MANAGING TECHNOLOGY WITHIN THE CONTEXT OF SUSTAINABILITY TRANSITIONS: AN INTEGRATED FRAMEWORK

Imke Hanlu de Kock

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Supervisor: Prof AC Brent

Co-supervisor: Prof SS Grobbelaar

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DECLARATION

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third-party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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ABSTRACT

There is an increasing awareness and understanding that addressing the numerous sustainability challenges that we face on a global scale poses a grand challenge. Addressing the sustainability challenges without innovative technologies will be difficult, and thus the development and diffusion of technologies that contribute towards addressing sustainability challenges are deemed to be among the main pathways towards a sustainable future.

However, technologies that could contribute towards increasingly sustainable socio-technical systems face a number of challenges; for example, 'sustainable' technologies may not offer the same (often economic) benefits as traditional, 'unsustainable' technology(ies). Nevertheless, the role that technology plays in achieving sustainability, its prospects and possible contributions (both positive and negative), its dynamics, and the technology-related factors that influence the progression of a socio-technical system towards sustainability, must all be understood in order to govern such transitions. It is evident, however, that the grand societal challenges and quest for sustainability pose substantial challenges for the management of technology within these contexts, and in turn also highlight the need to consider the management of technology within the context of socio-technical transitions towards sustainability.

A bibliometric and linkage analysis was performed to confirm or refute the disconnect that exists in the literature between that pertaining to technology management, and that pertaining to socio-technical transitions. On the basis of the findings of the bibliometric and linkage analysis, it thus was concluded that the integration of socio-technical transitions, approaches, concepts, frameworks and aspects with those of technology management theories and practices, and vice versa, are not addressed adequately in the literature. Given the role of technology, and the management thereof, to address the grand challenges, more research efforts are required across these bodies of knowledge to enable a just transition towards sustainability.

The aim of this research was thus twofold: firstly, to provide a premise for the integration of technology management and the concept of socio-technical transitions, and secondly, to provide the basis for the definition and identification of technology management considerations within the context of socio-technical transitions. This study can be described as a theory-building or model-building study and, due to the nature of this research, a constructivist philosophical perspective was embraced, and a primarily qualitative and deductive research strategy was followed.

The Integrated Technology Management-oriented Sustainability Transitions (ITMST) framework, as a designed result of the requirement specification, consists of five key features that collectively provide the premise for the integration between technology management and socio-technical transitions. The features are: (i) transition value creation, (ii) collective and individual consideration of transition progress, transition capability and system performance, (iii) co-management of incumbent and emerging/alternative technology domains, (iv) contextual specificity, and (v) contribution-requirement view. Given the conceptual nature of the ITMST framework and the stated importance of practical utility, the proposed framework was operationalised by translating the framework into a methodology.

The ITMST methodology, in contrast with the conceptual framing of a premise for the integration between technology management and the concept of sustainability transitions in the ITMST framework, outlines the practicability of the framework to provide decision support pertaining to considerations for the management of technology within the context of a sustainability transition. The ITMST methodology thus addresses the second part of the research aim, which was to provide the basis for a robust analysis to identify and define technology management considerations within the context of sustainability transitions.

The evaluation of the developed ITMST framework and methodology looked to address (i) whether the ITMST framework provides a premise for the integration of technology management, and (ii) whether the ITMST methodology provides the basis for the definition and identification of technology management considerations within the context of socio-technical transitions. The evaluation was addressed through a review of literature, a theoretical verification, and the operationalisation of the framework with a case study – on the required transition of the electricity sector of South Africa. The case study addressed whether the framework and methodology are implementable. The findings of the case study showcased that the ITMST methodology provides a basis for the definition and identification of technology management considerations within the context of sustainability transitions. And the evaluation of the validity and applicability of the ITMST framework, along with the theoretical verification, highlights that the ITMST framework provides a premise for the integration between technology management and socio-technical transitions.

UITTREKSEL

Daar is toenemende bewustheid en begrip dat die aanpak van die talle volhoubaarheidsuitdagings waarmee ons wêreldwyd te kampe het, ’n geweldige uitdaging inhou. Dit sou moeilik wees om daardie volhoubaarheidsuitdagings sonder innoverende tegnologieë aan te pak, en daarom word die ontwikkeling en verspreiding van tegnologieë wat tot die aanpak van volhoubaarheidsuitdagings bydra, as een van die belangrikste weë na volhoubare toekomste beskou.

Tegnologieë wat tot toenemend volhoubare sosio-tegniese stelsels kan bydra, staan egter voor ’n aantal uitdagings; onder meer dat “volhoubare” tegnologieë waarskynlik nie dieselfde (dikwels ekonomiese) voordele as tradisionele “onvolhoubare” tegnologie(ë) bied nie. Nietemin moet tegnologie se rol in die bereiking van volhoubaarheid, die vooruitsigte en moontlike bydraes (positief en negatief) daarvan, die dinamika daarvan, en die tegnologie-verwante faktore wat die vordering van ’n sosio-tegniese stelsel na volhoubaarheid beïnvloed, in geheel verstaan word vir die beheer-en-bestuur van sodanige oorgange. Dit is egter duidelik dat die grootskaalse maatskaplike uitdagings van en strewe na volhoubaarheid wesenlike uitdagings vir tegnologiebestuur binne hierdie kontekste inhou, en op hulle beurt ook die behoefte beklemtoon om oorweging aan tegnologiebestuur binne die konteks van die sosio-tegniese oorgange na volhoubaarheid te skenk.

Voorlopige navorsing dui daarop dat daar beperkte pogings is wat die gesamentlik oorweging van tegnologiebestuur en sosio-tegniese oorgange betref. Gevolglik is ’n bibliometriese en skakelontleding uitgevoer om die oënskynlike onsamehang wat in die literatuur bestaan tussen dít wat met tegnologiebestuur en dít wat met sosio-tegniese oorgange te make het, te bevestig of te weerlê. Op grond van die bevindinge van die bibliometriese en skakelontleding is daar tot die gevolgtrekking gekom dat die integrasie van sosio-tegniese oorgange, benaderings, konsepte, raamwerke en aspekte met dié van tegnologiebestuursteorieë en -praktyke, en omgekeerd, nie voldoende in die literatuur aangeroer word nie. Gegewe die rol van tegnologie en die bestuur daarvan in die aanpak van hierdie uitgebreide uitdagings, is meer navorsingspogings oor al hierdie kennisgroepe heen nodig om ’n regverdige oorgang na volhoubaarheid te verseker.

Die doel van hierdie navorsing is daarom tweeledig: eerstens om ’n uitgangspunt te bied vir die integrasie van tegnologiebestuur en die konsep van sosio-tegniese oorgange; en tweedens om die grondslag vir die definiëring en identifisering van tegnologiebestuuroorwegings binne die konteks van sosio-tegniese oorgange te bied. Hierdie studie kan as ’n studie van teorie- of modelbou beskryf word, en as gevolg van die aard van die navorsing, word ’n konstruktivisties-filosofiese perspektief omarm, terwyl ’n hoofsaaklik kwalitatiewe en deduktiewe navorsingstrategie gevolg word.

Die raamwerk vir geïntegreerde tegnologiebestuur-gerigte volhoubaarheidsoorgange (ITMST), as ’n ontwerpte resultaat van die vereistespesifikasie, bestaan uit vyf sleutelkenmerke wat gesamentlik die uitgangspunt voorsien vir die integrasie tussen tegnologiebestuur en sosio-tegniese oorgange. Die kenmerke is: (i) die skepping van oorgangwaardes; (ii) kollektiewe en individuele oorweging van oorgangsvordering, oorgangsvermoë en stelselprestasie; (iii) medebestuur van gevestigde en opkomende/alternatiewe tegnologie-domeine; (iv) kontekstuele spesifisiteit; en (v) ’n bydrae-vereiste-beskouing. Gegewe die konseptuele aard van die ITMST-raamwerk en die verklaarde belang van praktiese nut, is die voorgestelde raamwerk geoperasionaliseer deur die raamwerk na ’n metodologie om te skakel.

Die ITMST-metodologie, in teenstelling met die konseptuele raamwerk van ’n uitgangspunt vir die integrasie tussen tegnologiebestuur en die konsep van volhoubaarheidsoorgange in die ITMST-raamwerk, gee ’n uiteensetting van die uitvoerbaarheid van die raamwerk ter ondersteuning van die oorwegings vir tegnologiebestuur binne die konteks van ’n volhoubaarheidsoorgang. Die ITMST-metodologie spreek daarom die tweede deel van die navorsingsdoel aan, naamlik om die grondslag te bied vir ’n robuuste ontleding ten einde tegnologiebestuursoorwegings binne die konteks van volhoubaarheidsoorgange te identifiseer en te definieer.

Die evaluering van die ontwikkelde ITMST-raamwerk en -metodologie spreek die vraag aan of (i) die ITMST-raamwerk ’n uitgangspunt vir die integrasie van tegnologiebestuur bied; en (ii) die ITMST-metodologie die grondslag vorm vir die definiëring en identifisering van tegnologiebestuursoorwegings binne die konteks van sosio-tegniese oorgange. Die evaluering is aan die hand van die literatuur, teoretiese verifikasie, die operasionalisering van die raamwerk en die gevallestudie aangepak. Die gevallestudie spreek die kwessie aan of die raamwerk en metodologie implementeerbaar is. Die bevindinge van die gevallestudie toon dat die ITMST-metodologie ’n grondslag vir die definiëring en identifisering van tegnologiebestuursoorwegings binne die konteks van volhoubaarheidsoorgange bied. Die evaluering van die geldigheid en geskiktheid van die ITMST-raamwerk, tesame met die teoretiese verifikasie, beklemtoon dat die ITMST-raamwerk ’n uitgangspunt vir die integrasie tussen tegnologiebestuur en sosio-tegniese oorgange bied.

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DEDICATIONS

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Johan and Doedels Willemse
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Piet and Johanna van der Merwe

I look forward to discussing this dissertation with you one day.

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Nomenclature

Acronyms

AP	Attention points
ASCII	American standard code for information interchange
BA	Bibliometric analysis
BC	Boundary conditions
CoPs	Complex product systems
CSP	Concentrated Solar Power
DEA	Department of Environmental Affairs
DoE	Department of Energy
DPE	Department of Public Enterprises
DR	Design restrictions
DTI	Department of Trade and Industry
EIST	Environmental Innovation and Societal Transitions
EITM	European Institute of Technology
ETI	Energy Transition Index
FR	Functional requirements
GDP	Gross Domestic Product
GP	Guiding principle
GQ	Guiding question
IEEE	Institute of Electrical and Electronics Engineers
IJTM	International Journal of Technology Management
IRP	Integrated Resource Plan
IPP	Independent Power Producers
ISAEP process framework	Identification, selection, acquisition, exploitation and protection (ISAEP) process framework

ITMST framework	Integrated Technology Management-oriented sustainability transitions framework
LA	Linkage analysis
LEP	Large engineering projects
LTS	Large technical systems
MLP	Multi-level perspective
NERSA	National Energy Regulator of South Africa
NDP	National Development Plan
NIS	National innovation systems
OECD	The Organisation for Economic Co-operation and Development
PICMET	Portland International Conference on Management of Engineering and Technology
PV	Photovoltaics
REIPPP	Renewable Energy Independent Power Producer Procurement Programme
RIS	Regional innovation system
RF	Required force
RO	Research objective
RST	Resilience of sustainability transitions
R&D	Research and development
SIS	Sectoral innovation systems
SME	Subject matter expert
SNM	Strategic niche management
STT	Socio-technical transitions
TASM	Technology Analysis and Strategic Management
TIS	Technological innovation system
TFSC	Technological Forecasting and Social Change
TM	Technology management

UR	User requirements
UK	United Kingdom
US	United States

Symbols

A_{Ti}	Adaptability from a technological perspective for the incumbent technology domain
$A_{Te/a}$	Adaptability from a technological perspective for the emerging/alternative technology domain
A_{Si}	Adaptability from a social perspective for the incumbent technology domain
$A_{Se/a}$	Adaptability from a social perspective for the emerging/alternative technology domain
E	Entry
e	Edit distance of string
e/a	Emerging/alternative
i	Incumbent
R	References
P_{Ti}	Progress from a technological perspective for the incumbent technology domain
$P_{Te/a}$	Progress from a technological perspective for the emerging/alternative technology domain
P_{Si}	Progress from a social perspective for the incumbent technology domain
$P_{Se/a}$	Progress from a social perspective for the emerging/alternative technology domain
S_{Ti}	Stability from a technological perspective for the incumbent technology domain

$S_{Te/a}$	Stability from a technological perspective for the emerging/alternative technology domain
S_{Si}	Stability from a social perspective for the incumbent technology domain
$S_{Se/a}$	Stability from a social perspective for the emerging/alternative technology domain
v	Similarity value

Terminology

Guiding principles	A set of guiding principles is proposed that forms the basis upon which an integrated meta-perspective (i.e., the integration strategy) between socio-technical transitions and technology management is developed. Thus, any concept, construct and/or framework that aims to provide a helpful premise for integration between technology management and socio-technical transitions are guided by these principles.
Guiding questions	Two key guiding questions, that must be addressed when further conceptualising the abovementioned concept, are proposed in this research. These questions, along with the set of guiding principles, form the basis from which operational links between technology management and socio-technical transitions are be explored and elaborated on.
Integration strategy	The integration strategy acts as a bridge between the concepts of technology management and socio-technical transitions. This integration strategy is formulated in the form of a set of requirement specifications
Socio-technical system	Geels (2004:900) defines a socio-technical system in an abstract, functional way, stating that it can be defined as the *"linkages between elements necessary to fulfill societal functions"*. A socio-technical system thus represents the complex interrelatedness and interactions between technological innovations and society (Hekkert *et al.*, 2007). Socio-technical systems consist of elements, such as: actors, institutions, material, artefacts, and knowledge. These elements are interrelated and interact to serve a specific purpose or to address a specific need in society (Geels, 2004).
Socio-technical transitions	Socio-technical transitions are large-scale transformations of socio-technical systems that involve long-term processes and shifts to 'novel' socio-technical configurations; the common understanding is that these

	processes have an undeniable orientation towards sustainability (Loorbach, 2014; Markard, Raven and Truffer, 2012).
System performance	Given that (the need for) a transition is brought about by the unsustainability of one or more system performance elements (for example, the environmental unsustainability of a socio-technical system), the overlap between transition progress and system performance is that transition progress will thus (ideally) bring about change in system performance (i.e., making it more sustainable
Technology domain	Technology domain is the term used to refer to the technology as well as the system(s) within which such a technology exists. Thus, it includes the networks, organisations, policies, institutions, etc. that are present, or which are required to support the success of such a technology in fulfilling societal functions.
Transition progress	Transition progress is the extent to which a system has transformed, and it is also a dimension that contributes towards transition capability. For instance, a system that holds higher transition capability will show greater advancement in transition progress than a system with a lower level of transition capability.
Transition resilience	Schilling *et al.* (2018) developed the resilience of sustainability transitions (RST) concept and proposed (i) transition progress, (ii) stability, and (iii) adaptability as three dimensions that, when the overall transition process itself is regarded as a procedural entity, are essential for the success (and thus the resilience) of goal-oriented sustainability transitions.
Transition capability	Transition progress is well defined in the literature, and the concept of transition resilience (Schilling, Wyss and Binder, 2018) is argued to serve as an appropriate proxy for transition capability. Transition capability is then conceptualised as the capability of a socio-technical system to transition, and for the transition to progress and hence not fail.
Technology management	Technology management, as defined by the European Institute of Technology (EITM)[1], *"…addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies (product, process and infrastructural) needed to maintain a market position and business performance in accordance with the company's objectives".*

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[1] See: http://www-mmd.eng.cam.ac.uk/ctm/eitm/index.html

Chapter 1.

Definition of the research

In this chapter, the background to the research is provided in order to highlight the need for this research, and the problem statement, research aim and objectives are discussed. The research gap is emphasised, and the research approach is outlined. The scope of the research is subsequently discussed, and the chapter concludes with a brief outline of the dissertation chapters.

1.1 Introduction

There is an increasing awareness and understanding that addressing resource scarcity, and the numerous sustainability challenges that we face on a global scale pose a grand challenge. A widely accepted definition of 'sustainability' is that it is a balanced integration of environmental resilience, economic performance, and social justice, for the benefit of current and future generations (Brundtland, 1987; Elkington, 1998); 'sustainable development', in turn, has been defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987). The increasing need to fulfil the promise of sustainable development highlights the need for continued research that will improve our ability to comprehend the dynamics between societal and technological elements in socio-technical systems. Lachman (2013) argues that without an in-depth understanding of how to influence sustainability transitions, 'sustainable development' will remain a *'fata morgana'*.

The deep structural changes that are required to achieve the environmental and developmental improvements to address the grand challenge adequately, are referred to as sustainability transitions or socio-technical transitions towards sustainability (Grin, Rotmans and Schot, 2010; Geels, 2011; Van Den Bergh, Truffer and Kallis, 2011). A socio-technical transition can be described as a set of processes that leads to a fundamental transformation of, or shift in, socio-technical systems (Geels, 2004). Transitions are multi-actor, multi-factor systems, and typically unfold over a considerable number of years (Markard, Raven and Truffer, 2012); moreover, they are seen as co-evolutionary processes between technological and societal factors (Geels, 2012).

A number of approaches to sustainability are proposed in the literature, ranging from radical policy transformations to fundamental changes in socio-cultural dimensions. However, throughout the literature there is a consensus that aiming to address sustainability challenges without technology will be difficult, with the leading authors being Jeffrey Sachs[2] and Gunter Pauli[3]. Technological innovation is regarded as an indispensable element of the quest to solve global challenges like sustainability, and the mounting public concern and demands for intergenerational justice for future societies are putting pressure on policymakers to support technological innovations in order to realise environmental sustainability, economic sustainability, and social sustainability (Ittipanuvat *et al.*, 2014). It is evident that the development, diffusion, and management of technology that contribute towards addressing sustainability are deemed one of the key pathways towards sustainable futures (Paredis, 2011). Ittipanuvat *et al.* (2014) argue that broader analytical perspectives and a clear understanding of the linkages between technology and social issues are fundamental when aiming to address and respond to complex global challenges such as sustainability, and subsequently highlight the interrelationship between technology and socio-technical transitions.

Geels (2002:1257) states: "*Technology, of itself, has no power, does nothing*". This statement highlights the fact that only in conjunction with society, institutions, governing bodies, and organisations can technological innovation fulfil its function, and contribute towards sustainable development. Technology is an essential component of modern society, a key driver of innovation, and a driver of sustainable business growth (Phaal *et al.*, 2011; Dolata, 2013); moreover it contributes (both positively and negatively) towards the (un)sustainability of socio-technical systems (Geels, Hekkert and Jacobsson, 2008). Significant advances in technologies across the globe, as well as the rate and scope of change of such technological advances, and the application thereof, pose multiple challenges for individuals, organisations, and society, in terms of the increasing cost, complexity and risk of technology investments, especially against a background of increasing global competition (Smith and Stirling, 2008). An uncontested fact, however, remains that technology, irrespective of the objective of employing the technology, has to be managed.

Technology management, as defined by the European Institute of Technology (EITM)[4], *"…addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies (product, process and infrastructural) needed to maintain a market position and business performance in accordance with the company's objectives".* From this definition of technology management, one can already infer that technology management focuses primarily on the performance or competitive advantage of an organisation and/or the system within which it exists (Jin and von Zedtwitz, 2008).

1.2 Knowledge gap

Why should we then be interested in studying the level (dis)connection between the literature pertaining to technology management and the literature pertaining to socio-technical transitions? Smith, Stirling and Berkhout (2005) state that the analytical lens in sustainability studies has retracted from the organisational level, and that it is increasingly focusing on the wider socio-technical system. This systems-level focus recognises that technology(ies) are embedded within socio-technical systems. This embeddedness of technology within socio-technical systems, and the need for such systems to transition towards a higher state

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[2] http://jeffsachs.org/category/topics/sustainable-development/

[3] http://www.gunterpauli.com/Home.html

[4] See: http://www-mmd.eng.cam.ac.uk/ctm/eitm/index.html

of sustainability (Schilling, Wyss and Binder, 2018), highlight the need for the management of technology within the context of socio-technical transitions.

Additionally, there is a general agreement, as well as a sense of urgency throughout the literature, that technological change is required at the socio-technical system level for sustainable development. However, technologies that could contribute towards increasingly sustainable socio-technical systems face a number of challenges (Alkemade *et al*., 2009); for example, 'sustainable' technologies may not offer the same (often economic) benefits as traditional 'unsustainable' technology(ies). Nevertheless, the role that technology plays in achieving sustainability, its prospects and possible contributions (both positive and negative), its dynamics and technology-related factors that influence the progression of a socio-technical system towards sustainability, must all be understood in order to govern such transitions. It is, however, evident that the grand societal challenges and quest for sustainability pose substantial challenges for the management of technology within these contexts (Cetindamar, Phaal and Probert, 2016), and in turn also highlight the need to consider the management of technology within the context of socio-technical transitions towards sustainability.

Furthermore, a popular opinion in the literature is that a single discipline is no longer adequate to solve progressively complex (sustainability) challenges. Within the context of socio-technical transitions, researchers thus urge that further crossover and integration between disciplines are needed to improve the understanding of and insight into the dynamics of socio-technical transitions, and into how such transitions can be fostered, influenced and even possibly be managed (Geels, Hekkert and Jacobsson, 2008; Tran, 2014). The contribution of inter- and trans-disciplinary research is expected to be significant for numerous contemporary challenges. Additionally, the integration of disciplines is envisaged to open up new paths for innovation, as these will create linkages between established disciplines and identify new opportunities for innovation (Ittipanuvat *et al*., 2014).

A preliminary review of the literature indicated that there exists a disconnection between technology management and the field of socio-technical transitions. In order to confirm or refute this seeming disconnection, a comprehensive two-part investigation was done (see Chapters 3 and 4). Indeed, in this two-part investigation, no concrete evidence was found of significant integration and/or overlap in the foundational concepts that transcend these two separate bodies of literature.

However, even though the background research that considers technology management in the light of socio-technical transitions and vice versa is very limited, when turning to the literature, there is a rising interest and sense of urgency in the importance of managing technology within the context of sustainable development (Brent and Pretorius, 2008; Jovanovic *et al.*, 2019). Further evidence of a knowledge gap may be found in statements from researchers such as Philbin (2013) who argue that frameworks and constructs are required to provide approaches that will support the implementation of technology, coupled with improved decision-making and the management thereof that can support the societal and environmental needs of societies.

A research opportunity was thus identified to investigate the extent to which technology management and socio-technical transitions have been integrated, and subsequently to identify effective ways of pursuing such integration in order to contribute towards increasingly effective and efficient management practices within the context of socio-technical transitions.

1.3 Problem statement

Sustainability, and thus socio-technical transitions, challenges our traditional view of technology and how we create value through technology; it also challenges our traditional view of how we manage technology. It calls for more informed, nuanced and sophisticated constructs about the management of technology within the context of socio-technical transitions than what previously existed.

The preliminary research indicates that there have only been limited efforts to consider technology management and socio-technical transitions together. From a theoretical perspective, these two fields have not been integrated at a conceptual or theoretical level. From a practical perspective, the role of technology management is still primarily geared towards creating value for organisations and for the system within which such organisations exist. Therefore, there is a need to extend the value creation of technology management to the transition process. Moreover, there is currently no satisfactory theory of technology management within the context of socio-technical transitions.

1.4 Aim and objectives

In broad terms, the aim of this research is to contribute towards increasingly effective and efficient management practices within the context of socio-technical transitions. Even though such explicit management practices and tools do not fall within the scope of this dissertation, the conceptual and methodological propositions that are introduced herein lay the foundation for the development of such management practices. The specific aim of this research is twofold: firstly, to provide a premise for the integration of technology management and socio-technical transitions, and secondly, to provide the basis for the definition and identification of technology management considerations within the context of socio-technical transitions.

The aim of this research is thus to present the motivation and conceptual basis for research that links the management of technology with socio-technical transitions, thereby addressing the need for interdisciplinary studies targeting the integration of these concepts. Such integration is not the end in itself, but rather the value that such an integration may add to the problem-solving context when sustainability transitions are considered.

The research objectives (ROs) and sub-objectives that support the attainment of the research aim are presented in Table 1. It should be noted that the research is path-dependent in the sense that, should the outcome of RO2 (i.e., the extent to which a disconnection exists between the two relevant bodies of literature) had been that the management of technology within the context of socio-technical transitions has been adequately captured in the literature, the need to provide a premise for such integration would not have been identified.

Table 1. Research objectives, sub-objectives and corresponding chapters

RO NUMBER	RESEARCH OBJECTIVE DESCRIPTION	CORRESPONDING CHAPTER
RO1	To contextualise technology management and socio-technical transitions, as well as the challenges that face these two fields of research, from a theoretical and practical perspective in order to support the rationale of this research.	Chapter 2
RO2	To establish the extent of either integration or disconnection between the concepts of technology management and socio-technical transitions to elucidate the level of and extent to which these bodies of literature have been integrated. The sub-objectives for RO2 are:	
	RO2.1 To investigate and compare the structures of the scientific networks in the technology management and socio-technical transitions literature through a bibliometric analysis in order to explore the interfacial layer between the two bodies of literature.	Chapter 3
	RO2.2 To explore existing linkages between technology management and socio-technical transitions through a linkage analysis in order to elucidate the extent to which there exists an overlap, and to what extent these two bodies of literature share intellectual roots.	Chapter 4
RO3	To develop a proposition in the form of an integration strategy that transcends technology management and socio-technical transitions in order to articulate the conceptual notions from which to develop a premise for the integration of technology management and socio-technical transitions. The sub-objectives for RO3 are:	
	RO3.1 To identify and define the elements around which an integrated meta-perspective can be articulated – this will inform the objective to establish and elaborate on a common understanding and rationality about the transcending phenomena to inform a strategy for integration between technology management and socio-technical transitions.	Chapter 5
	RO3.2 To formulate an integration strategy that transcends technology management and socio-technical transitions.	Chapter 6
RO4	To develop and evaluate a conceptual framework and methodology that transcends technology management and socio-technical transitions in order to contribute towards increasingly effective and efficient management practices within the context of socio-technical transitions. The sub-objectives for RO4 are:	
	RO4.1 To develop a conceptual framework that provides the conceptual framings of a premise for the integration of technology management and socio-technical transitions.	Chapter 7
	RO4.2 To operationalise the developed conceptual framework through the development of a methodology that outlines the practicability of the framework.	Chapter 8
	RO4.3 To verify and validate the developed framework and methodology in order to evaluate whether the developed framework and methodology are fit for their intended purpose and are practicable.	Chapter 9

1.5 Research approach

This study can be described as a ‘theory-building or model building study’ as defined by Mouton (2013). The typical applications of such research are theoretical and conceptual studies aimed at developing new models, frameworks and/or theories or aimed at refining existing theories, frameworks and/or models (Mouton, 2013). Due to the nature of this research, a constructivist philosophical perspective is embraced, and a primarily qualitative and deductive research strategy is followed.

1.5.1 Philosophical perspective

The purpose of scientific research is the unearthing of 'truth' (Gay and Weaver, 2011; Mouton, 2013). However, every researcher has pre-existing views (philosophical perspectives or paradigm) as a result of certain assumptions and/or beliefs regarding the nature of reality and 'truth' and the way that this may be investigated – and, such philosophical perspectives should therefore be made explicit (Lincoln, 2010; Ungerer, 2015) .

Four key philosophical perspectives are highlighted in the literature – positivism, post-positivism, critical theory and constructivism. They can be distinguished based on their ontological perspective, epistemic perspective, methodological perspective, and axiological perspective. For the sake of brevity, not all of these philosophical perspectives are described and discussed, but only the philosophical perspective embraced throughout this research, i.e., constructivism; in addition, the alignment between the methodological perspective associated with constructivism and the current research is highlighted.

Constructivism, as employed by Ungerer (2015) and as seminally described by Guba and Lincoln (1994), is also sometimes referred to as interpretivism or naturalistic inquiry; it is a philosophical perspective that advocates ontological and epistemological relativism rather than realism. Guba and Lincoln (1994) emphasise that in constructivism *"realities are apprehendable in the form of multiple, intangible mental constructions, socially and experientially based, local and specific in nature … Constructions are not more or less 'true' in any absolute sense, but simply more or less informed and/or sophisticated"*. In other words, constructions are thus alterable, in line with the realities and contexts that are associated with such constructs. Constructivism is primarily qualitative in nature and pursues the improved understanding of phenomena with the belief that an absolute truth is unlikely to be found, but that increased understanding, nuance and sophistication are nonetheless possible, and that multiple truths exist.

The research context of the management of technology and that of socio-technical transitions is complex and dynamic, and allows for ambiguity and uncertainty. Consequently, constructivism is deemed fitting, given that (i) the nature of the research is exploratory, (ii) constructivism seeks to understand phenomena better, and (iii) the research aims to provide for more informed, nuanced and sophisticated constructs about the management of technology within the context of socio-technical transitions than what previously existed. The importance of practical utility, not only in the field of (Industrial) Engineering but in all problem-solving arenas, cannot be stressed enough. Gay and Weaver (2011) argued that *"what makes one theory preferred over another is the significant (albeit incremental) progression and advancement of knowledge toward the truth… Yet, 'truth' (i.e., theory) merely for the sake of truth, absent practical usefulness (scientific or pragmatic), is rarely sufficient"*. A key objective, albeit secondary (i.e., secondary to the establishment of the theoretical framing of a premise for the integration of technology management and the concept of socio-technical transitions), is therefore not only to make a theoretical contribution, but a practical one as well. Therefore, as is the aim with RO3.2, the constructivist paradigm is complemented by a practical utility orientation.

The philosophical perspective of constructivism and the identified need for a practical-oriented approach together thus influenced the research paradigm and the subsequent research design.

1.5.2 Research design and strategy

Mouton (2013) provides a broad classification of research designs; research efforts are categorised as either empirical or non-empirical. Empirical studies are further classified based on the data used - primary data or existing (secondary) data. Non-empirical research includes philosophical analysis, conceptual analysis, theory building and literature reviews. Mouton (2013) maps these research design types based on whether the research is empirical or non-empirical, and whether primary or secondary data is used – see Figure 1.

Given the nature of the problem statement and the research aim, the current research is geared towards theoretical and conceptual research that aims to develop new conceptual frameworks and theories and/or to refine existing theories and models. The intended outcome of this research is a conceptualisation of a construct (or constructs) that provides a premise for the integration of technology management and the concept of socio-technical transitions.

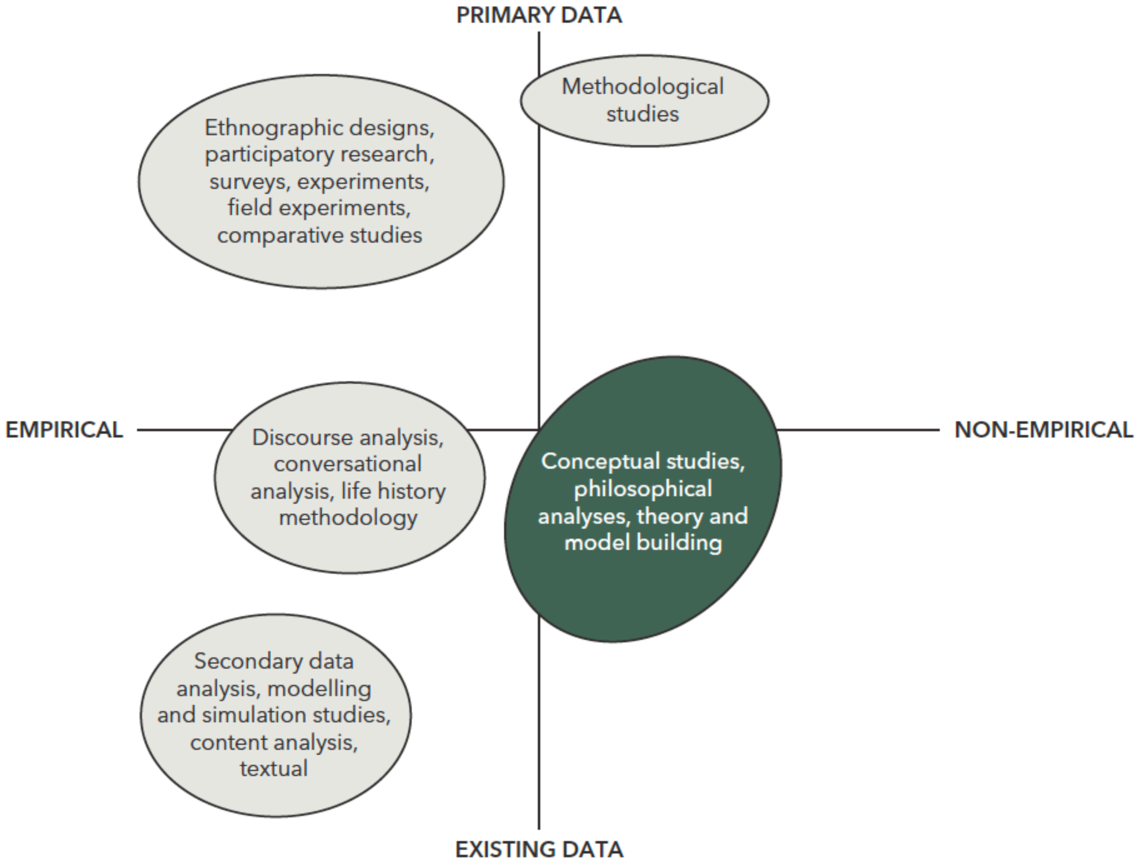

Figure 1. Mapping of research designs (adapted from Mouton, 2013:144)

This research inquiry thus aims to develop theory through the development of a conceptual framework. A theory is defined as an *"organised body of concepts and principles intended to explain a particular phenomenon"* (Leedy and Ormrod, 2013). The normal cycle of theory building research is an iterative process between description, explanation, and testing along with the development of models and frameworks in order ultimately to develop theory. This process is shown in Figure 2. The iterative process results in the development of conceptual or descriptive models, which are expanded into explanatory frameworks and then tested against reality to ultimately develop theories (Meredith, 1993).

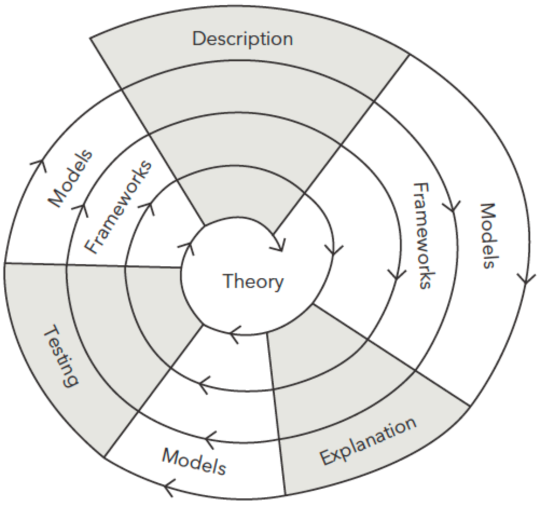

Figure 2. The research cycle (adapted from Meredith, 1993:4)

A model is defined as a "*simplified representation or abstraction of reality"* (Turban and Meredith, 1994). A model aims to imitate or describe a real event, process, object or phenomenon. However, it does not explain such event, process, object or phenomenon A concept is defined as having a number of meanings and characteristics associated with a real event, process, object or phenomenon. Concepts are used to represent, identify or understand these events, processes or phenomena. A conceptual model is thus a collection of concepts used to represent or describe a real event, process, object or phenomenon. However, as stated above, a conceptual model does not explain the phenomenon, but merely describes it (Meredith, 1993). Conceptual frameworks aim to explain an event or phenomenon through observed relationships between the elements of a system. Here the aim is not only to describe the phenomenon, but also to explain how and why it occurs (Meredith, 1993).

This process of theory building by developing conceptual models and subsequent conceptual frameworks through an iterative process of description, explanation and testing was used in this research inquiry. The research began by investigating the extent of integration or disconnection between the concepts of technology management and socio-technical transitions. A conceptual model was then developed in the form of an integration strategy. This conceptual model was subsequently expanded into a conceptual framework to provide a premise for the integration of technology management and the concept of socio-technical transitions. As mentioned earlier, the practical utility of any developed conceptual framework is regarded as highly important, and the developed framework is thus operationalised by developing a methodology that provides the basis for the definition and identification of technology management considerations within the context of socio-technical transitions.

Crabtree and Miller (1999) and (Patton, 2002) suggested that, for an inquiry into complex phenomena that are not easy to measure or research quantitatively, qualitative research provides a good way of exploring complex phenomena and generating the required understanding and insights into such complex problems. This research study was thus predominantly qualitatively based, but supported by quantitative methods where necessary.

The research strategy associated with the process of theory building outlined above is further supported and justified by the deductive mode of reasoning used in this research. Deductive forms of reasoning typically follow a process where a set of postulates is formulated, and theoretical propositions are subsequently deductively derived. This process culminates into a comprehensive set of theoretical propositions that are then tested against empirical data (Mouton, 2013) – which is in line with the overarching research strategy followed in this research (excluding of course RO1, namely, investigating the extent of integration or disconnection between the concepts of technology management and socio-technical transitions).

The detailed research methodologies employed throughout the dissertation and the research objectives are outlined in the respective chapters.

1.6 Scope of the research

The delimitations and limitations of the research are set out below.

1.6.1 Delimitations

The following delimitations are highlighted:

i. The focus and scope of this research are specifically on unsustainable regimes (unsustainability being primarily due to incumbent technologies) as well as on new or alternative technologies (developed in niches) that hold the potential of a more sustainable system; and
ii. The research focuses on technology management and socio-technical transitions in general, and is thus non-specific with regard to technology and sector.

1.6.2 Limitations

The following limitations confine the research to a reasonably contained area to ensure greater focus and achievability:

i. Explicit management practices, tools and techniques do not fall within the scope of this dissertation; the aim is that the conceptual and methodological propositions that are developed herein lay the foundation for the development of such management practices;
ii. The development of policies and/or interventions falls outside of the scope of this study – but the integration strategy, framework subsequent methodology may be used to facilitate, support and enable the associated development processes;
iii. A number of design restrictions are highlighted in Chapter 7 that also serve as limitations, and these include:
    a. The conceptual framework and its operationalisation are not meant to include an exhaustive set of tools and methods to elucidate the technology management requirements or transition capabilities in each transitional phase at any of the possible levels of analysis;
    b. The framework is intended for a systems level analysis, but may be applicable to an analysis at a lower and/or higher level of analysis;
    c. The framework is not a policy or regulatory guide, and input required for such items should be obtained from specific subject matter experts. However, the framework is intended to support the development of systems-level interventions to support sustainability transitions,

and can therefore also contribute towards policy and regulatory development processes; and

d. The framework does not guarantee an improved transition capability or transitional change due to a multitude of factors that would influence such an outcome. However, it does aim to provide principles and guidelines that will allow it to contribute towards the capability of a socio-technical system to transition, and for a transition to be resilient from a technology management perspective.

1.7 Document structure and outline

The research may be conceptualised as comprising four parts. Part I (Chapters 1 and 2) defines and contextualises the research. Part II (Chapters 3 and 4) presents a meta-analysis of the literature pertaining to technology management and socio-technical transitions in order to elucidate the extent to which these two bodies of literature are connected and/or overlap. In Part III (Chapters 5 to 9) a premise for the integration between technology management and socio-technical transitions are developed. And lastly, the research is concluded in Part IV (Chapter 10). The chapter layout is shown in the schematic in Figure 3.

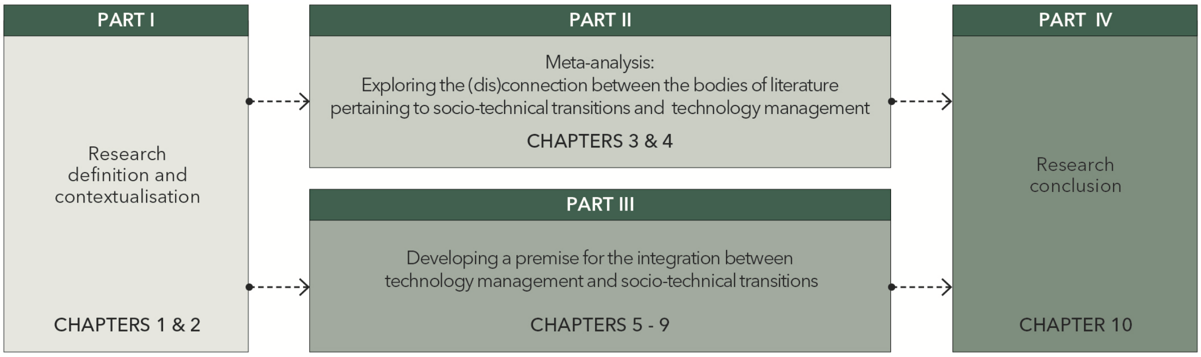

Figure 3. Chapter layout schematic

In Figure 4 below, a more detailed chapter layout provides insights into how the research progressed. Table 2 provides a brief overview of the chapters in this dissertation and highlights how chapters relate to one another.

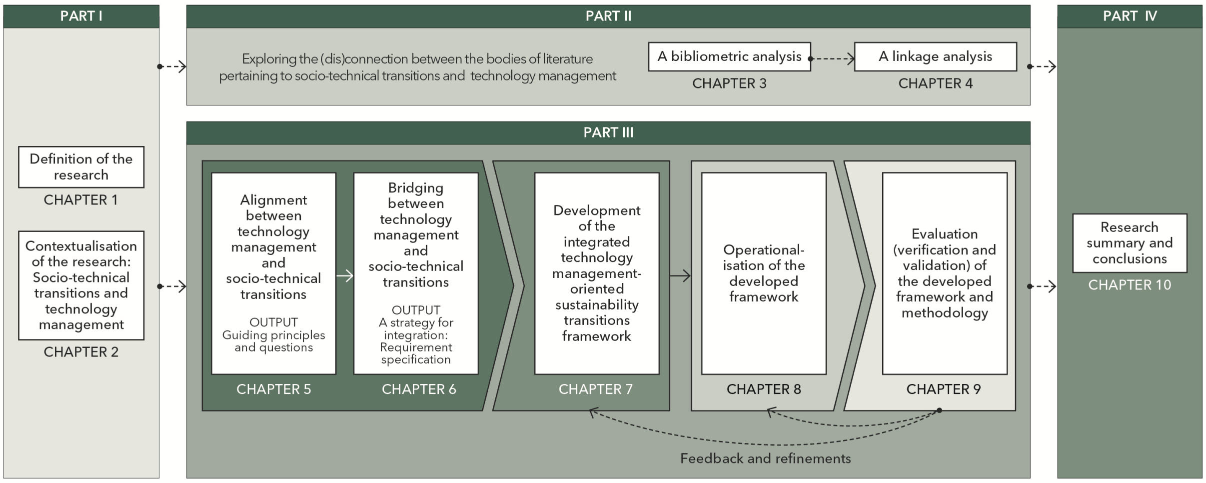

Figure 4. Detailed chapter layout schematic

Table 2. Chapter outline

PART	CHAPTER	CHAPTER TITLE
PART I	Chapter 1	*Definition of the research* In Chapter 1, the background to the research is provided to highlight the need for this research. The problem statement, research aim and objectives are articulated. The research gap is emphasised, and the research approach is outlined. Finally, the scope of the research and a brief outline of the dissertation chapters are discussed.
	Chapter 2	*Contextualisation: Socio-technical transitions and technology management* In Chapter 2, the theoretical foundations of technology management and socio-technical transitions are introduced. This contextualisation provides the rationale for the investigation into the (dis)connection between the bodies of literature pertaining to the management of technology and socio-technical transitions (Chapters 3 & 4) and provides the initial guidance for the alignment between technology management and socio-technical transitions (Chapter 5).
PART II	Chapter 3	*Exploring the (dis)connection between the bodies of literature pertaining to socio-technical transitions and technology management (Part A): A bibliometric analysis* In Chapter 3, a bibliometric analysis is used to elucidate the seeming disconnection that exists between the literature pertaining to socio-technical transitions and technology management respectively. Throughout this chapter, a number of areas of overlap are identified. However, the only key area of overlap that emerged from this analysis is that of innovation, and to a lesser extent sustainability and the focus on technology. Yet, no concrete evidence has been found of integration or significant similarity in foundational concepts used in both bodies of literature The findings serve as motivation that, in order to better articulate the level of integration in terms of conceptual framings and intellectual roots, a further analysis, in the form of a linkage analysis, is necessary – see Chapter 4.
	Chapter 4	*Exploring the (dis)connection between the bodies of literature pertaining to socio-technical transitions and technology management (Part B): A linkage analysis* In order to investigate the areas where the two concerned bodies of literature overlap and possibly integrate, in Chapter 4, the linkages between the socio-technical transitions and technology management bodies of literature are explored further, based on the references used by each set of documents, as described in detail in Chapter 3. The literature bases (i.e., the references used by each article) of both document sets are compared, and this detailed comparison is used to identify overlaps in the literature that are used as basis for the research in the bodies of literature. The aim of this approach is to elucidate the extent to which there exists an overlap, and to what extent these two bodies of literature share intellectual roots.

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PART III	Chapter 5	*Towards an integration strategy: Alignment between technology management and socio-technical transitions* *Given the rationale and the need highlighted in Chapters 1 and 2 for research efforts that consider the management of technology within the context of socio-technical transitions, and the disconnection that exists between these two fields of research, Chapter 5 – building on the research and findings discussed in Chapter 2 – begins the process of unearthing the foundational steps to develop a premise for the integration of technology management and the concept of socio-technical transition.*
	Chapter 6	*An integration strategy: Bridging between technology management and socio-technical transitions* In Chapter 6, the proposal for creating a bridge between the concepts of technology management and socio-technical transitions is set out. This integration strategy, in the form of a set of requirement specifications, concludes the background research and the synthesising of the literature to support the development of a premise for integration between technology management and the concept of sustainability transitions. The requirements are established. Even though the set of requirement specifications is formalised in this chapter, the investigation into and analysis of the literature presented in Chapters 5 and 6 form part of the requirements analysis.
	Chapter 7	*A dynamic framing of the management of technology in socio-technical transitions: The integrated technology management-oriented sustainability transitions (ITMST) framework* In Chapter 7, a conceptual framework is presented that aims to provide a premise for the integration of the management of technology and socio-technical transitions. The framework development is guided by the set of requirement specifications outlined in Chapter 6.
	Chapter 8	*Operationalisation of the integrated technology management-oriented sustainability transitions (ITMST) framework* Chapter 8 is dedicated to the operationalisation of the framework developed in Chapter 7. In the initial sections of the chapter an overview of the operationalisation is presented, followed by a detailed discussion and explanation of the various analytical perspectives and phases that constitute the operationalisation.
	Chapter 9	*Evaluation of the ITMST framework and methodology* Chapter 9 deals with the verification and validation of the developed framework and methodology. The former verifies the set of requirements that was developed in Chapter 6, before discussing the process of theoretical validation and refinement of the framework that was followed to provide confidence in the applicability and practicability of the developed framework and methodology. The chapter concludes with reflections on the framework and methodology
PART IV	Chapter 10	Research summary and conclusions Chapter 10 concludes the study by giving an overview of the study, drawing conclusions regarding the premise for the integration between technology management and socio-technical transitions. It outlines the theoretical and practical contributions of the developed framework and methodology. And lastly, possibilities for future research are highlighted.

1.8 Conclusion: Chapter 1

The research has been formally defined in this chapter; the background to the research has been provided, and the research aim and objectives and the problem statement were articulated. The research approach, research gap, scope and limitations and lastly the document structure and outline were also presented.

Chapter 2.

Contextualisation: Socio-technical transitions and technology management

In this chapter, the theoretical foundations of technology management and socio-technical transitions are introduced and the aim is thus to contextualise the study. The contextualisation provides a rationale for the In this chapter, the theoretical foundations of technology management and socio-technical transitions are introduced, with the aim of contextualising the study. This contextualisation provides a rationale for the investigation into the (dis)connection between the bodies of literature pertaining to the management of technology and socio-technical transitions (Chapters 3 and 4), and guides the alignment between these two fields (Chapter 5). This chapter first focuses on the theory, approaches and frameworks relating to technology and the management thereof, as well as the challenges facing technology management in light of sustainability and socio-technical transitions. Thereafter, the theory, approaches and frameworks relating to socio-technical transitions are considered, as well as the challenges associated with the field of socio-technical transitions, in order to elucidate the logical basis for this research.

2.1 Technology and technology management: Theories, approaches and frameworks

Before considering the management of technology, it is important to understand what is meant by ‘technology’ and how it is defined in literature. There are a significant number of definitions and meanings for the term ‘technology’, and technology means a variety of things to different groups of people, depending on the perspective, the environment, and the professional and personal experiences from which they view technology. Khalil (2000) offers a broad definition, stating that technology is: *“all the knowledge, products, processes, tools, methods, and system employed in the creation of goods or in providing services”*. Burgelma *et al.* (2001) propose that: *“technology refers to the theoretical and practical knowledge, skills, and artefacts that can be used to develop products and services as well as their production and delivery systems”*. When considering these definitions, the inextricability of a technology and the product(s) within which such technology manifests is evident (Taylor and Taylor, 2012). Howells (2005) states that definitions of technology are often linked to the specific environment or discipline within which, or for which, a definition was developed. Even though the first thoughts regarding technology are often concerned with the physical instruments that enable everyday tasks, it is indisputable that technology includes a range of elements, components, and stakeholders that are interdependent, codetermining, and equally important (Zeleny, 1986). Technology is widely described, and commonly acknowledged, as consisting of interacting resources and components (Fleck and Howells, 2001; Grübler, 2003; Haines and Sharif, 2006; Zeleny, 1986) working towards a goal (Howells, 2005). It is commonly agreed that technology is multifaceted and complex (Fleck, 2008), or at the very least complicated.

Haines and Sharif (2006) and Fleck and Howells (2001 evaluated written definitions of technology from a number of professions, disciplines and environments[5]. In their comparison of disciplinary definitions of technologies, Fleck and Howells (2001) concluded that, in every definition of technology, there is a hardware (artefactual) component embedded within human activity, as well as within an organisational or social context. In turn, Haines and Sharif (2006) concluded that the common components that technology definitions refer to include: physical components (artefacts, hardware, tools, machines and objects), human components *("the person-embodied art-of-doing-type skills technologies, like ingenuity, craftsmanship, and talent")*, a knowledge component *("the primary source of human creativity related to a tool-based task"),* and a social component *("organisation, relationship, action, process, technique, or methodology").* Roberts and Grabowski (1996) also evaluated a number of definitions, and concluded that technology consists of mechanical technologies *("physical machines, tools and equipment used to produce goods")*, human technologies *("skills and physical energy involved in producing goods and services")*, and knowledge technologies *("abstract meanings and concepts used in production").* It is further acknowledged that all components coexist within systems or organisations (Roberts and Grabowski, 1996). In addition to Fleck and Howells (2001), Haines and Sharif (2006) and Roberts and Grabowski (1996), a number of other researchers contextualised technology, and offered definitions that group the elements that form part of any given technology into three or four sub-sets of elements. Grübler (2003), for example, states that technology consists of three primary components: hardware (such as machinery or a manufacturing plant), software (know-how, human knowledge and skills), and factor inputs (labour, energy, raw materials, capital). Pacey (1983) and Hughes (1987) take a broader system view of technology and include aspects such as culture and legislation. Pacey (1983), for instance, propose a view of technology that includes three main aspects: technical, organisational, and cultural aspects. Hughes (1987) defines the components of technological systems as physical artefacts, organisational comportments, and legislative artefacts. When considering all these definitions, the differences in the delimitation and definition of technology are already evident.

From the above analysis of the definitions, the overlaps within the definitions of technology, and the components of technology considered in each definition, are clear. However, some elements are distinct, and when considered holistically, the range of elements that are included and used to define technology differs. This is in line with the process that led to the development of the 'technology complex', developed by Fleck and Howells (2001) as a conceptual device that aims to embody all sub-definitions of technology. The technology complex lists the distinctive elements and/or components that comprise the various different sub-definitions of technology. The elements are ordered from 'physical' elements to 'cultural' elements, and can be used to relate broad, general definitions, to the sub-definitions included in a number of technology definitions. Technologies may then be described by using the elements of the technology complex.

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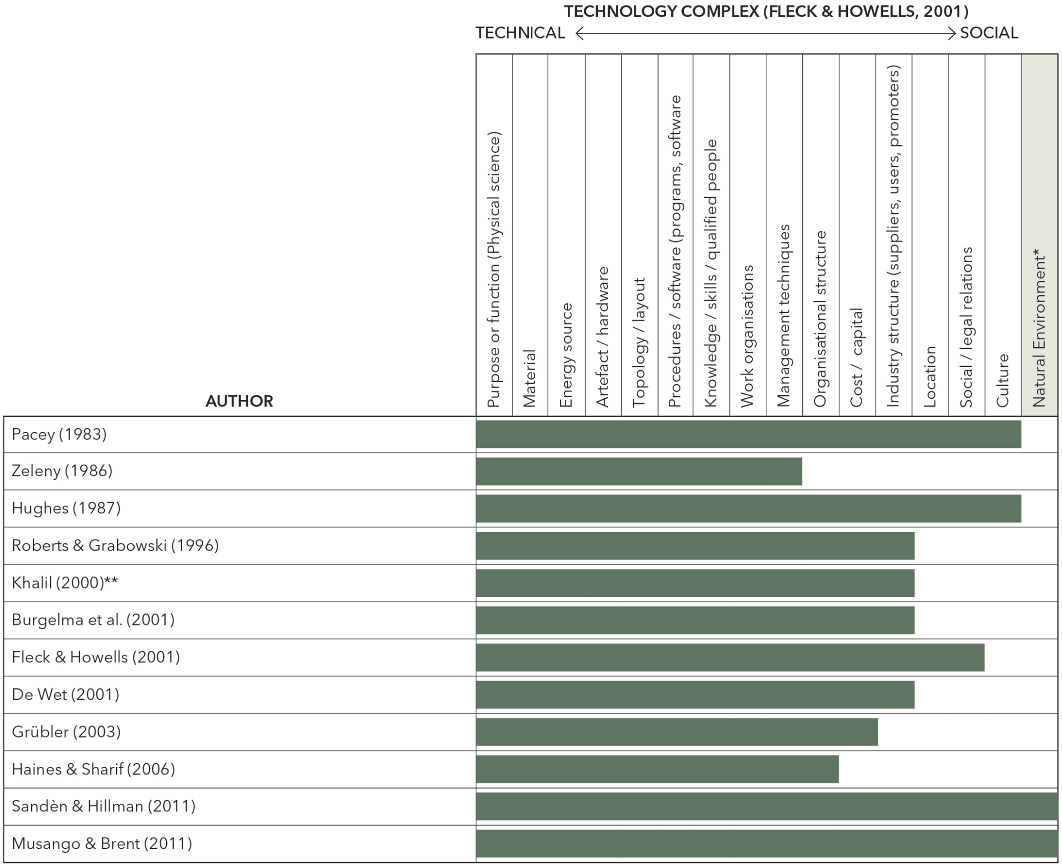
[5] See Haines and Sharif (2006) and Fleck and Howells (2001) for a comprehensive study of the definitions of technology across a number of environments.

The written definitions, though not an exhaustive list, and more specifically the proposed components and elements that collectively define technology, are compared with each other, as well as with the concept of the technology complex (see Figure 5), with the aim of highlighting the importance of differentiating between the definition of technology and the broader system, namely, 'technology practice' (Pacey, 1983) and 'technological systems' (Hughes, 1987). Pacey's (1983) definition of 'technology practice', which is shown in Figure 6, encapsulates a broader view of technology that goes beyond the 'restricted' view of technology. However, the 'restricted view' of technology does not only refer to physical artefacts or hardware. The 'technical aspect' of technology practice incorporates social aspects too, such as knowledge and skills. Hughes (1987), for instance, states that: *"technological systems contain messy, complex, problem-solving components; they are both socially constructed and society shaping"*. He further states that technological systems are comprised of four components, namely: physical artefacts, organisations, legislative artefacts, and natural resources – thus, the environment. Musango and Brent (2011) argue that technology is always embedded within the subsystems of the economy, the society, and the natural environment. This 'embeddedness' essentially refers to the interaction of technology with these subsystems, and thus also supports the notion that technological systems comprise physical, organisational (societal), legislative, and environmental components.



*The technology complex (Fleck & Howells 2001) did not include the natural environment
** Khalil (2000) expands on the proposition of Zenely (1986) by adding "Know-how" as a fourth component to the definition proposed by Zeneley.

Figure 5. Definitions of technology compared against the 'Technology Complex' concept

Evidently, written definitions of technology are wide and varying (Fleck and Howells, 2001; Haines and Sharif, 2006), which highlights the complexity of technology. However, even though there is a large degree of overlap and similarity between the components, aspects, and elements that form part of technologies, for the aim of defining technology, written definitions lack somewhat the descriptive power of conceptual or diagrammatic models. In addition to the abovementioned contextualisation of technology, a number of researchers have also offered conceptual and diagrammatic models to enhance these definitions (De Wet, 2001; Haines & Sharif, 2006; Pacey, 1983).

As mentioned, Pacey (1983) developed a diagrammatic definition of 'technology' (shown in Figure 6) that embodies the organisational, technical and cultural aspects of technology. It is important to note that, as mentioned earlier, Pacey's definition of 'technology' defines the concept of 'technology practice'. Here, technology-practice refers to the 'broader' practice of using technology to achieve a certain goal. De Wet (2001) developed a schematic representation (shown in Figure 7) of the definition of technology that enhances Pacey's model of technology. De Wet (2001) proposed that, in addition to the broad, high-level definition of technology developed by Pacey, 'technical' aspects of the definition of technology could be further defined. In addition, De Wet's conceptual model represents the interactive nature of the technical aspects of technology, and highlights the multi-component characteristics of technology (De Wet, 2001). This representation enhances the definition of technology that states that, within the broad context of technology practice or a technological system, the technical aspects can be defined in terms of *"technical knowledge, people, and physical tools",* and they include *"all knowledge, products, processes, tools, methods, and systems employed in the creation of a product or service"* (De Wet, 2001). This, to some extent, addresses the notion of treating technology as a black box within the larger system, namely: technology-practice or the technological system. This definition of technology, shown in Figure 6, focuses on the technical aspects; nonetheless, however, this is valuable in that the technology triangle, shown in Figure 7, enables a definition of technology within technology-practice and/or a technological system.

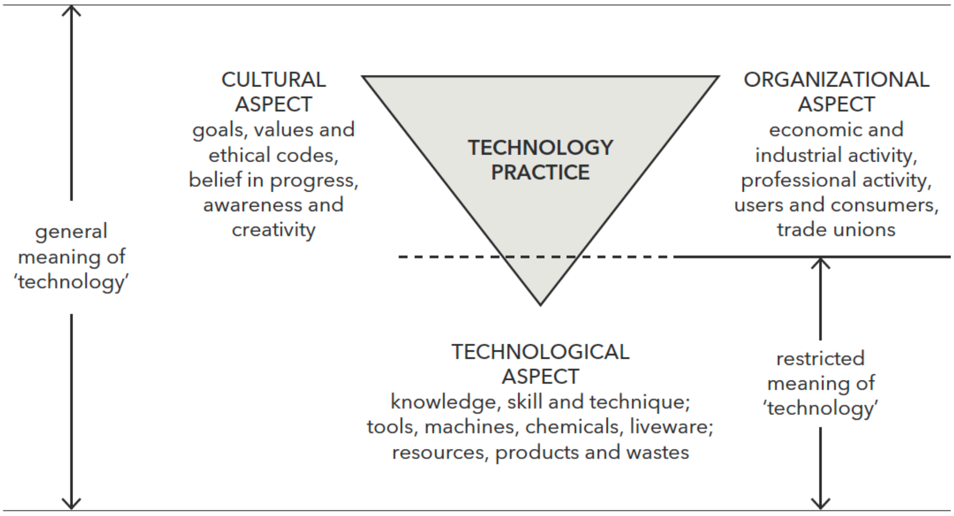


Figure 6: Diagrammatic representation of the definitions of 'technology' and 'technology practice' (reproduced from Pacey 1983).

Pacey's broader definition of technology, or technology practice, is aligned with the definition that Hughes (1987) proposes for technological systems, in that the technology is defined as part of a broader system. Technological systems (Hughes, 1987) are defined as having four components: physical artefacts, organisations, legislative artefacts, and natural resources. Both Pacey and Hughes thus highlight the 'technical' side of technology being embedded within a larger system.

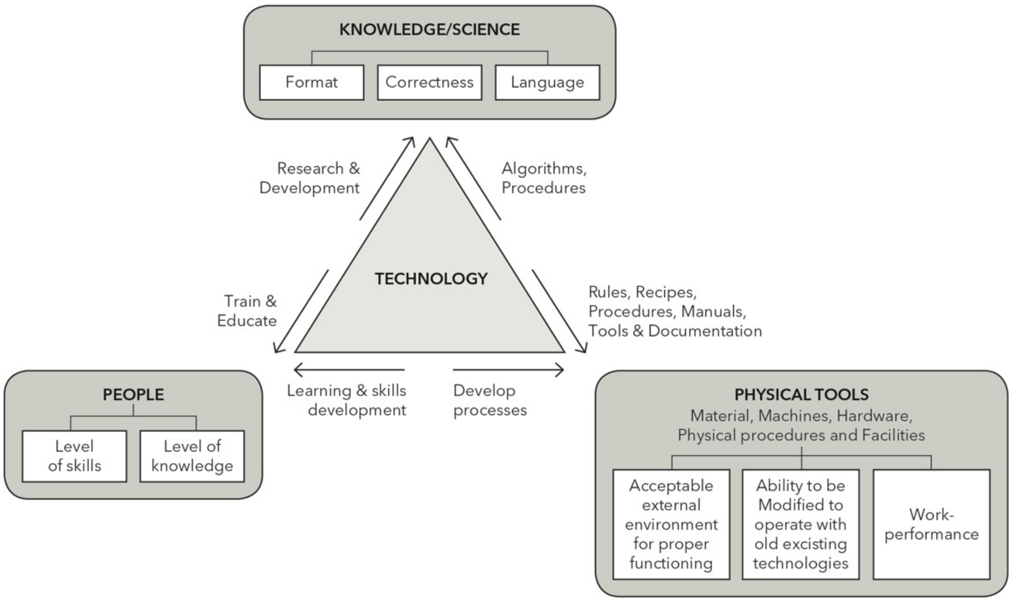


Figure 7. The technology triangle (adapted from (De Wet, 2001)

Sandén and Hillman (2011:405) go on to define technology as a socio-technical system; they state that technology is a combination of upstream and downstream value chains, thus a "*system of socio-technical elements organised in bundles of value chains*". Geels (2004:900) defines a socio-technical system in an abstract, functional way, stating that it can be defined as the *"linkages between elements necessary to fulfill societal functions"*. A socio-technical system thus represents the complex interrelatedness and interactions between technological innovations and society (Hekkert *et al.*, 2007). Socio-technical systems consist of elements, such as: actors, institutions, material, artefacts, and knowledge. These elements are interrelated and interact to serve a specific purpose or to address a specific need in society (Geels, 2004). The similarities between the definitions of a socio-technical system and the definitions of technology are evident. However, it is here that the argument, namely, to differentiate between technology, technology-practice and technological systems, and a socio-technical system, has to be made. And it is here that the work done by De Wet (2001), which complements the diagrammatic definition of technology practice developed by Pacey (1983), plays a vital role. De Wet (2001) argues that the socio-technical aspects involved in technology are incorporated into the definition of technical aspects of technology, while still allowing for the differentiation between technology and socio-technical systems.

Furthermore, Murmann and Frenken (2006) found that there are significant inconsistencies when considering the unit of analysis of studies concerned with technology. It is this, at least in part, that this research aims to address, by clearly defining the level of analysis that will be used when the management of technology is considered within the context of socio-technical transitions.

It is evidently possible to examine technology at several levels of analysis. And when the aim is to consider a specific technology, and not a technological system more generally, the importance of delving into the technical aspects of technology becomes apparent. Here, the technical aspects of technology do very well by including the components as per the definitions of technology. Within these 'technical aspects' of technology, the cultural and organisational aspects of technology practice/technological systems are, to an extent, included within the detailed description of technology, as defined by the technology triangle developed by De Wet (2001). However, this would be at the level of the technical artefact. This is what makes this definition of technology especially valuable for this research inquiry, in that it clearly addresses the distinction between technology and the larger system that may be studied.

In addition to the written definitions, and the conceptual and diagrammatic models that have been offered to define technologies, the typologies used to group types of technologies, and the concepts used to describe the interactions among technologies, are useful concepts when seeking to understand technology better.

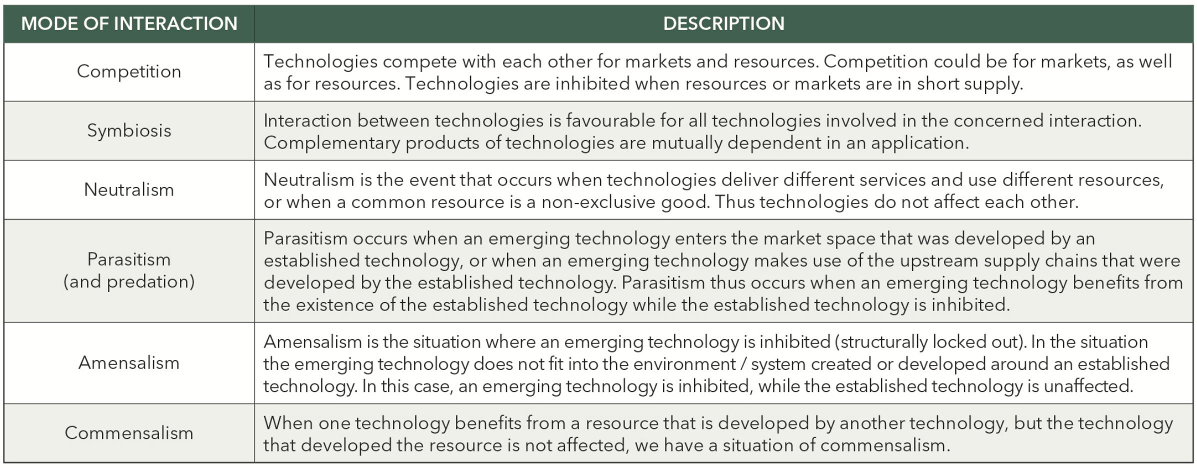
2.1.1.1 Interactions among technologies

The interactions among technologies are a relevant feature in the literature. However, these interactions are often described in terms of the competition between technologies. Pistorius and Utterback (1997) described three major modes of interactions between technologies, namely: pure competition, symbiosis, and predator-prey. However, these modes of interactions are primarily concerned with the competition between technologies. Sandén and Hillman (2011) similarly state that, until 2011, the literature on technology interaction focussed on competition, and that the characteristics of each of these modes of interactions between technologies differ. It is commonly accepted that the modes of interaction between technologies can shift from one mode to another, and it is suggested that specific technology management strategies must be developed for each mode of interaction (Pistorius and Utterback, 1997). It is also important to note that multi-mode interactions between technologies are possible, and that technologies can interact according to a number of modes.

As interactions between technologies go beyond ‘competition’, researchers have offered more detailed and nuanced descriptions of technology interactions. However, such interactions are also grounded in the fact that technologies either positively or negatively influence a specific technology’s growth rate (amongst other factors) (Pistorius and Utterback, 1997).

Technologies consist of a hierarchy of value chains, upstream supply chains, and down-stream application chains. Products and processes form part of several value chains, and technologies are thus made up of a ‘bundle of value chains’ (Sandén and Hillman, 2011). The modes of interaction between technologies are then defined in terms of the shared elements in different parts of the value chains, with six modes of interaction being defined (see Table 3). Sandén and Hillman (2011) provide an account of the range of possible interaction modes between technologies, including: (i) competition, (ii) symbiosis, (iii) neutralism, (iv) parasitism, (v) amensalism, and (vi) commensalism.

Table 3: Six modes of interaction between technology (based on Sandén and Hillman, 2011)



MODE OF INTERACTION	DESCRIPTION
Competition	Technologies compete with each other for markets and resources. Competition could be for markets, as well as for resources. Technologies are inhibited when resources or markets are in short supply.
Symbiosis	Interaction between technologies is favourable for all technologies involved in the concerned interaction. Complementary products of technologies are mutually dependent in an application.
Neutralism	Neutralism is the event that occurs when technologies deliver different services and use different resources, or when a common resource is a non-exclusive good. Thus technologies do not affect each other.
Parasitism (and predation)	Parasitism occurs when an emerging technology enters the market space that was developed by an established technology, or when an emerging technology makes use of the upstream supply chains that were developed by the established technology. Parasitism thus occurs when an emerging technology benefits from the existence of the established technology while the established technology is inhibited.
Amensalism	Amensalism is the situation where an emerging technology is inhibited (structurally locked out). In the situation the emerging technology does not fit into the environment / system created or developed around an established technology. In this case, an emerging technology is inhibited, while the established technology is unaffected.
Commensalism	When one technology benefits from a resource that is developed by another technology, but the technology that developed the resource is not affected, we have a situation of commensalism.

Musango and Brent (2011) investigated the role that the interdependence of technologies plays in respect of the implementation of large-scale socio-technical changes; they state that socio-technical systems cannot be analysed in terms of a single technology, but that they should be considered in terms of the interactions and relationships between coexisting technological, institutional, and social change.

2.1.1.2 Technology typologies

In order to establish the similarities and differences between typologies describing technologies with specific characteristics, typologies concerned with multiple technologies that interact and/or work together in a system- or network-type configuration were evaluated (see Table 4).

Technology clusters refer to agglomerations of firms within a specific technology-oriented industry (Casper, 2013). An example of this would be Silicon Valley. In turn, competence blocs refer to the *"total infrastructure needed to create, select, recognize, diffuse, and exploit new ideas"* (Eliasson and Eliasson, 1997). Both technology clusters and competence blocs are thus concerned with networks of technology, skills and organisations, and not purely focussed on the technology itself. Technological systems, as discussed in Section 2.1, are concerned with all the actors within the system within which a technology exists, which also highlights the absence of a focus on technology in this typology.

When the description of complex product systems (CoPS) is considered, it is clear that this typology focuses on technology, whether that be a network, a product, a system or a construct. However, even though the impact of society on CoPS, and vice versa, is acknowledged, this typology is purely focused on the technical aspects – as defined by De Wet (2001) and Pacey (1983) – of a technological system.

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Table 4. Typologies describing groups of technologies

		DESCRIPTION	STRUCTURE	EXAMPLE
Complex technologies (Rycroft & Kash, 1998; Rycroft & Kash, 2002)		Complex technologies cannot be understood in detail by an individual expert, and cannot be precisely communicated among experts across time and distance.	Numerous interacting components, produced and supplied by a range of producers and suppliers.	Aircrafts, automobiles, computers, telecommunications equipment, and the internet.
Technological systems (Alkemade, 2009; Aunger, 2010; Bijker et al., 1987)		Hughes (1987) states that "Technological systems contain messy, complex, problem-solving components. They are both socially constructed and society shaping". He further states that technological systems comprise four components, namely: physical artefacts, organisations, legislative artefacts and natural resources (i.e., the environment).	Technological systems consist of, and contain, several interdependent subsystems that function in a coherent manner. The specific combination of subsystems, and the interdependencies between them, represent the performance of the overall system. Technological systems have both an aggregate-level functionality, as well as each component having a specific function.	Worldwide web, electrical power systems, telecommunication systems, transportation systems.
Complex product systems (CoPS) (Hobday, 1998; Hobday, 1999; Ren & Yeo, 2004) CoPS include complex products and complex systems.		CoPS are defined as high-cost, engineering-intensive products, systems, networks and constructs. Embedded within CoPS are high-technology product components. These product components are usually also complex systems or subsystems. CoPS's inherent complexity is due to the large number of complex product components, activities and human interactions that result in a source of project risks and uncertainty. CoPS represent major national and commercial capital asset development, and are critical to national economic and social development and well-being.	CoPSs have elaborate structures, and consist of many interconnected sub-systems and components. CoPS have a comparatively high degree of system hierarchy.	Commercial aircrafts, telecommunication networks, precision machines, nuclear power plants and intelligent buildings (such as hospitals). CoPS are typically found in aerospace and defence industries, high-tech manufacturing, chemical and petrochemical industries, pharmaceutical industries, infrastructural development of airport, seaports and mass rapid transit, electricity generation and distribution and environmental systems.
	Complex products	Complex products are considered as a network of components that, in order to function as a whole, share technical interfaces (or connections).		Aircrafts, high-speed trains, turbines, computers, aircraft engines.
	Large technical systems (LTS)	LTS, as described by Hughes (1987) under 'technological systems' above, are made up out of a number of CoPS that functions as the command, control and communication components of LTS. CoPS thus shape, facilitate and in some instances constrain the development of LTSs. LTSs can be considered as one single CoPS or as consisting of several CoPS.		Telecommunications network, electronic road pricing system, air travel, the internet.
	Large engineering projects (LEP)	LEPs are mainly infrastructural constructs, and constitute one of the most important and significant business sectors in local and international economies. LEPs may also, similar to LTS, incorporate complex products. Most LEPs can be considered as a CoPS or considered to incorporate CoPS components.		Mainly infrastructure constructs: Airports, urban transport systems, oil/gas field development, power systems.
	Large IT/Software Projects	Large software projects (large enterprise information systems or embedded engineering software systems) can be single CoPS by themselves, or a critical part of a larger CoPS. When compared to complex engineering systems, software development activities are largely human centered, craft-based and individualistic in nature.		Large ERP, software systems.
Competence blocs (Carlsson et al., 2002; Eliasson & Eliasson, 1997)		Competence blocs are defined as the total infrastructure required to create, select, recognise, diffuse, and exploit new ideas in clusters of firms. It is thus a set of related products and artefacts that work towards a particular function. A competence bloc thus includes a wide range of technologies and actors that are configured to stimulate the growth of an industry.	Competence blocs and technology clusters consist of parts of several technological systems supplying technological innovations that are applicable and related to a specific sector or industry. A competence bloc or technology cluster will include a large range of technologies.	Silicon Valley and the South German luxury car production cluster.
Technology clusters (Grübler, 2003)		A technology cluster is defined as a group of interconnected organisations, companies, research institutions, and other stakeholders in a particular knowledge field or industry that are linked by certain commonalities.		Silicon Valley and the Milwaukee water technology cluster.

2.1.1.3 Level of analysis

The level of analysis at which technology is considered provides valuable insights into the concept of 'technology' and how it should be managed. Carlsson et al. (2002), for instance, found that at least three levels of analysis are possible when a systems approach is used: at the level of technology in the sense of a knowledge field; at the level of a product or artefact; and lastly at the level of a set of related products, technologies or artefacts aimed at fulfilling a specific function. However, 'a set of related products' in this sense refers to the level of analysis being at the level of a competence block, technology cluster, or technological system. Complex technologies, and complex technological systems (in the broad, all-inclusive sense), typically consist of components, sub-systems and systems as a nested hierarchy (Murmann and Frenken, 2006). Considering the level of analysis in terms of the nested hierarchy of components that constitute technology and technological systems, as well as the importance of the distinction between technology and technology practice or technological systems, the level of analysis when aiming to manage technology is evident. Thus, in order to delineate the adequate level of analysis when aiming to understand how to manage technology within the context of socio-technical transitions, involving the level and granularity of analysis must be considered; Murmann and Frenken (2006:934) argue that: *"at the most detailed level of analysis, no two artifacts are the same; at the coarsest level of analysis, every two artifacts are the same"*.

2.1.2 The management of technology

"Technology, of itself, has no power, does nothing" (Geels, 2002:1257). This suggests that only in conjunction with society, institutions, governing bodies, and organisations can technological innovation fulfil its function (Geels, 2002). Moreover, the extensive integration of technology within such systems, as we have witnessed over the last couple of decades, has resulted in technology becoming an indispensable part of modern society. Technology is also a key driver of innovation (Dolata, 2013), it embodies an important basis of competitive advantage and growth (Cetindamar, Phaal and Probert, 2010), and it has the ability to contribute towards the promise of sustainable futures (Smith and Stirling, 2008). But, unfortunately it also plays a significant part in the unsustainable practices embedded within modern society. Technology can mean different things to different people, thus giving rise to a number of definitions (Fleck and Howells, 2001; Haines and Sharif, 2006). Nonetheless, technology has to be managed in order to realise the specific objectives that it aims to achieve.

As in the case of 'technology', there are numerous definitions of 'technology management' too. For instance, it is defined by the National Research Council (1987) as *"a process, which includes planning, directing, control and coordination of the development and implementation of technological capabilities to shape and accomplish the strategic and operational objectives of an organization"* (National Research Council, 1987). According to Gregory (1995), technology management *"addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies needed to maintain a stream of products and services to the market"*. A study by Jin and von Zedtwitz (2008:328) defines technology management as the *"capability to make effective use of technical knowledge and skills, not only in an effort to improve and develop products and processes but also to improve existing technology and to generate new knowledge and skills in response to the competitive business environment"*. The European Institute of

Technology (EITM)[6] defines technology management as follows: *"Technology management addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies (product, process and infrastructural) needed to maintain a market position and business performance in accordance with the company's objectives"*. From these definitions of technology management, one can already infer that its focus is primarily on the performance or competitive advantage of an organisation (Jin and von Zedtwitz, 2008).

Phaal *et al*. (2004) proposed a framework that supports technology management in the manufacturing sector, at the firm level. However, this framework (shown in Figure 8) is of such a nature that it is considered to be a representation of technology management in a broader application, throughout different types of organisations and organisational contexts (Cetindamar, Phaal and Probert, 2009). The technology management framework illustrates that the activities that constitute technology management (identification, selection, acquisition, exploitation and protection of technology) are embedded within, or linked to, the strategic, innovation and operational business processes of an organisation (Phaal *et al*., 2004). The framework further shows that the internal and external context of organisations influences and determines the technology management issues and challenges within an organisation. Even though it is not specifically mentioned, time is an important dimension in the technology management framework, in terms of ensuring that, within the context of evolving markets, products and technology, technological developments and capabilities are synchronised with business objectives and requirements (Cetindamar, Phaal and Probert, 2009). The framework also highlights the knowledge flows and interchange that must occur between the technological and commercial functions of an organisation, if technology management is to be effective (Phaal *et al*., 2004).

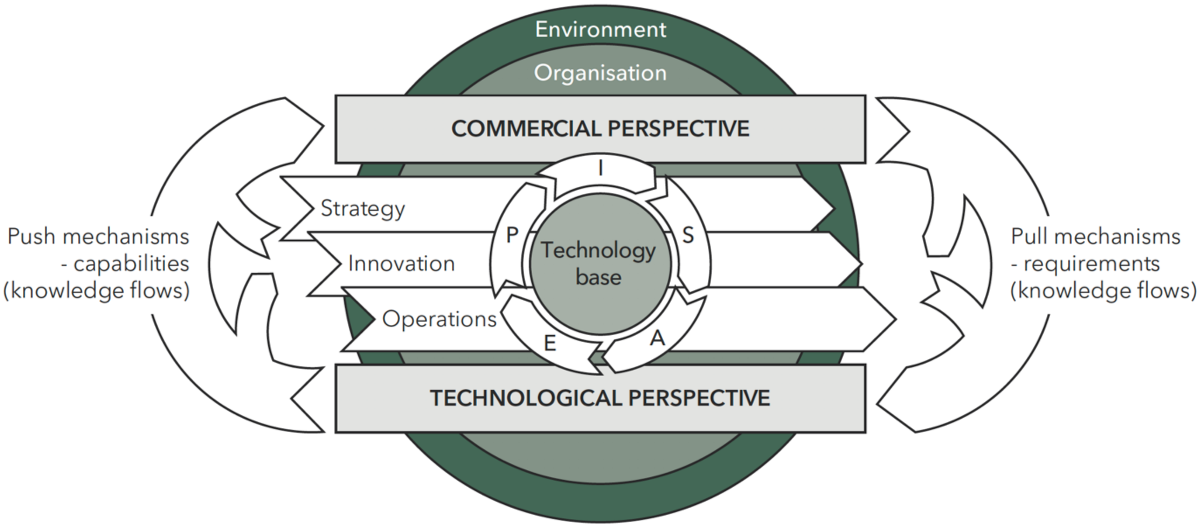

Figure 8: Technology management framework (adapted from Phaal et al. *(2004)*

Gregory (1995) put forward the identification, selection, acquisition, exploitation and protection (ISAEP) process framework as a conceptualisation of technology management (see Gregory (1995) for a

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[6] See http://www-mmd.eng.cam.ac.uk/ctm/eitm/index.html

comprehensive discussion of this framework). Kerr *et al*. (2013) elaborated on the framework developed by Gregory (1995) by placing technology (technological resources) at the centre of the framework. This resonates with the technology management framework shown in Figure 8, where technology is a resource, and the technology base represents the technological knowledge that must be transformed into services, products and processes through the technological capabilities that are developed through the effective management of technology (Cetindamar, Phaal and Probert, 2010). In addition to placing technology central to the framework, Kerr *et al*. (2013) also placed the protection process around the technology base, while the other four activities (identification, selection, acquisition and exploitation) are represented as gears, to show that these activities must be configured within an organisation. Kerr *et al*. (2013) then also add that co-ordination of activities is important, as this will allow the activities to be integrated into a system that, together, aims for the effective management of technology. Lastly, the three core business processes (innovation, operations, and strategy) are shown around the outside of the framework; they provide the required connections between the technology management activities and processes within an organisation and the wider business context (Kerr *et al*., 2013).

Ultimately, the framework shown in Figure 9 draws on the framework proposed by Gregory (1995) and Phaal *et al*. (2004) to show that technology management is concerned with *"establishing and maintaining the linkages between technological resources and company objectives"*. In addition, technology management is a "multifunctional and multidisciplinary field", which *"deals with all aspects of integrating technological issues into business decision-making and is directly relevant to a number of core business processes including strategy, innovation, new product development and operations management"* (Phaal *et al*., 2004). The goal of technology management is thus to facilitate the efficient and effective synergy and collaboration between all the elements within an organisation (i.e., research, development, planning, engineering, machines, software, production, and communication) to achieve long-term firm profitability and growth (Hamilton, 1997; Kim, 2013; Li-Hua and Khalil, 2006). Philbin (2013:35) summarises technology management as follows: *"Technology management provides the structures, processes and tools to allow this technological resource to be deployed in order for an organisation's strategic objectives to be delivered"*.

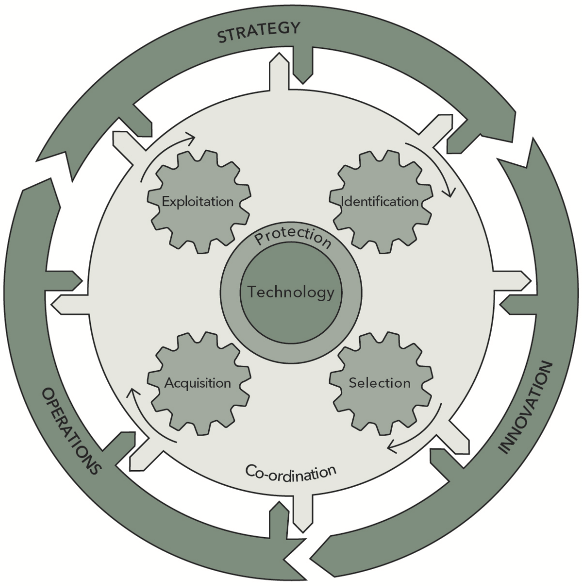


Figure 9: STM framework wheel (adapted from Kerr et al.*, 2013)*

2.1.3 Technology management as a dynamic capability

Teece, Pisano and Shuen (1997) define dynamic capabilities as *'the ability to integrate, build, and reconfigure internal and external competencies to address rapidly-changing environments'*. Changes in technology are constantly creating new challenges and opportunities, and such opportunities have to be identified and translated into value through effective and dynamic technology management (Cetindamar, Phaal and Probert, 2009). Technology management overlaps with disciplines such as innovation management, knowledge management and project management – a Venn diagram employed by Cetindamar, Phaal and Probert (2009) shows these overlaps, but also highlights the distinctive nature of technology management (see Figure 10).

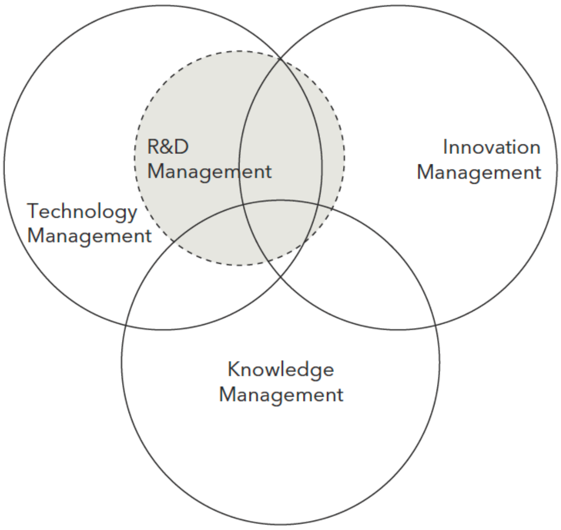


Figure 10. Technology management and related disciplines (adapted from Cetindamar, Phaal and Probert, 2009).

2.1.4 Challenges facing technology management

The technology management literature provides numerous frameworks, tools and activities that have proven to be indispensable for understanding technology management, addressing the technology management challenges, and improving the technological capabilities of an organisation. A number of contemporary challenges relating to technology management are discussed throughout the literature (La Nauze and Shodde, 2004; Phaal, Farrukh and Probert, 2006; Cetindamar, Phaal and Probert, 2009, 2016; Kim, 2013, 2015; Philbin, 2013; Syryamkin and Syryamkina, 2015; Lee *et al.*, 2016; Jovanovic *et al.*, 2019). These challenges are predominantly compounded by factors that relate to either the changing environment within which technology has to be managed, or to the ever-increasing need to manage our resources in a way that would ensure a sustainable future. This section thus discusses the challenges faced by technology management, from both a theoretical and a practical perspective.

When the challenges that face technology management are considered, these challenges can be attributed to the fact that technologies and markets are highly dynamic, and hence are we seeing on-going changes in core business processes, and it is these changes that are having, and will have, an impact on the management of technology (Cetindamar, Phaal and Probert, 2016). The primary cause of the significant changes required in terms of technology management is due to the rapidly changing global technological and market environments (Kim, 2015), and the fact that technology management encompasses multiple dimensions and components results in it constantly evolving (Jovanovic *et al.*, 2019). The intellectual development of the discipline of technology management can be seen elsewhere in the literature (Linton and Thongpapanl, 2004; Cetindamar, Phaal and Probert, 2009; Thongpapanl, 2012). However, technology management must adapt to such changing environments. Cetindamar *et al*. (2016) created a list of challenges in the three key business processes, i.e., innovation, operations and strategy, and subsequently found that the challenges in these areas can be attributed to changes in innovation types and processes, sustainability challenges, the integration of services with products, and finally the impact of these changes on organisational strategy as the key challenges that face modern technology management.

2.1.4.1 Changes in innovation

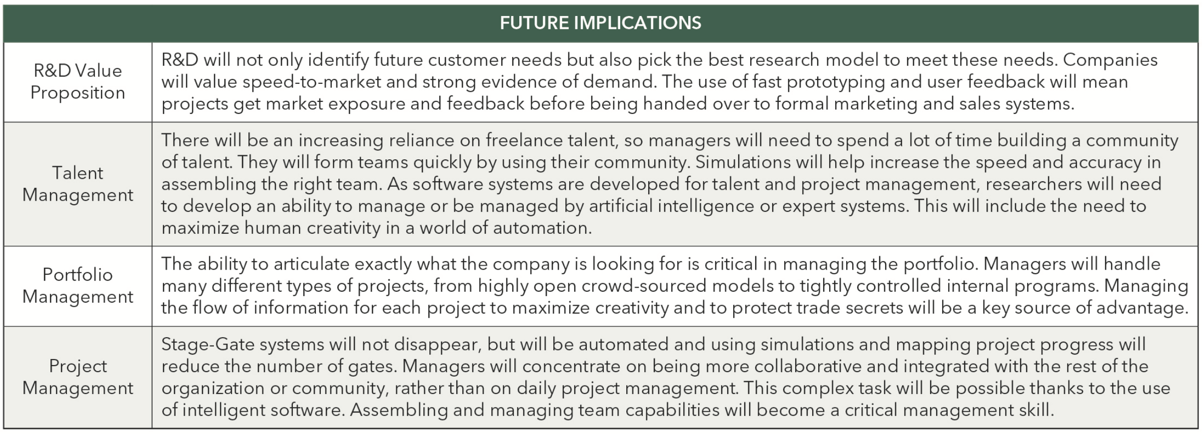
Researchers highlighted the changes in the types of innovation that are being developed, as well as the transformations seen in innovation processes (Berg *et al*., 2015; Horwitch and Stohr, 2008); these changes pose significant challenges for the technology management discipline (Cetindamar, Phaal and Probert, 2016).

Several types of innovation exist (see OECD [2005] and Tidd and Bessant [2013] for a full account of these). Recently, however, new types of innovations, with noteworthy implications for technology management, have emerged (Cetindamar, Phaal and Probert, 2016). These include eco-innovation (Schiederig, Tietze and Herstatt, 2012), reverse innovation (Zeschky, Winterhalter and Grassmann, 2014), social innovation (Horwitch and Stohr, 2008), and design-driven innovation (Tidd and Bessant, 2013). These are diffusing into numerous areas of application in a number of different ways, which will require the application of technology management to be widened into areas such as social, environmental and sustainability problems (Cetindamar, Phaal and Probert, 2016). Moreover, they are contributing to the fact that technology management must increasingly focus on social and environmental challenges. In addition, technology management will have to apply across cultures and geographies, which is highlighted by innovations that focus on resource-constrained customers in emerging markets (Cetindamar, Phaal and Probert, 2016; OECD, 2005).

However, the technologies that could contribute to sustainability face a number of challenges; the future performance of such technological innovations is often uncertain, and societal preference might in fact change during the transition period (Alkemade *et al*., 2009). Such innovations, which are developed or aimed at emerging or developing (often resource constrained) markets, are typically products that may seem inferior when compared with their advanced counterparts, in that their features might not be as extensive or their performance may not be as high level (Hang, Chen and Subramian, 2010). Nonetheless, such innovations are likely to have other characteristics, such as low cost, ease of use, simplicity, and low-cost material. And these (alternative) characteristics may result in them outperforming advanced technologies in the specific market contexts (Cetindamar, Phaal and Probert, 2016). Cetindamar *et al*. (2016) also highlight the importance of understanding the local context, of making sure that the innovations align with, and are sensitive to, these contexts, and that these new sources of innovation will require technology managers who are able to work across geographies and cultures.

Farrington and Crews (2013) conducted a study that considered the shape of R&D in the next 25 years, with the aim of understanding how the trends we are seeing today might affect research and the management of technology in 2038. This study developed sets of scenarios that sought to improve our vision of what technology managers might face in about 20 years' time. The study identified four implications for research and technology management, which are summarised in Table 5 below.

Table 5. Future implications for technology management related fields (Farrington and Crews, 2013)



FUTURE IMPLICATIONS	
R&D Value Proposition	R&D will not only identify future customer needs but also pick the best research model to meet these needs. Companies will value speed-to-market and strong evidence of demand. The use of fast prototyping and user feedback will mean projects get market exposure and feedback before being handed over to formal marketing and sales systems.
Talent Management	There will be an increasing reliance on freelance talent, so managers will need to spend a lot of time building a community of talent. They will form teams quickly by using their community. Simulations will help increase the speed and accuracy in assembling the right team. As software systems are developed for talent and project management, researchers will need to develop an ability to manage or be managed by artificial intelligence or expert systems. This will include the need to maximize human creativity in a world of automation.
Portfolio Management	The ability to articulate exactly what the company is looking for is critical in managing the portfolio. Managers will handle many different types of projects, from highly open crowd-sourced models to tightly controlled internal programs. Managing the flow of information for each project to maximize creativity and to protect trade secrets will be a key source of advantage.
Project Management	Stage-Gate systems will not disappear, but will be automated and using simulations and mapping project progress will reduce the number of gates. Managers will concentrate on being more collaborative and integrated with the rest of the organization or community, rather than on daily project management. This complex task will be possible thanks to the use of intelligent software. Assembling and managing team capabilities will become a critical management skill.

Cetindamar *et al*. (2016) summarise the findings of Farrington and Crews (2013) by stating that technology management professionals have to take note of the paradigm shift taking place within technological innovation, and to understand the implication of these shifts on the practice of technology management. In addition, this also highlights the expansion of the scope of innovation and technology management, which was traditionally focussed on products and services, but now extends to business models and societal innovations (Groen and Walsh, 2013; Horwitch and Stohr, 2008). These changes in innovation processes, unsurprisingly, result in an increased number of stakeholders within the innovation and technology management activities and processes (Cetindamar, Phaal and Probert, 2016).

2.1.4.2 Sustainability

There is a rising interest (and sense of urgency) in both the theoretical and the methodological perspectives of technology management, as well as in practice, to manage technology within the context of sustainable development (Brent and Pretorius, 2008; Jovanovic *et al.*, 2019). Technology management must provide the tools and techniques that will support the implementation and improved decision-making in terms of technology, and the management thereof, to meet the societal and environmental needs of current and future generations (Philbin, 2013). In addition, the ever-increasing focus on sustainability contributes to the complexity of technology management, and according to the NaturalEdge Project[7], the next wave, and possibly future waves of innovation too, will be driven by the need concurrently to address productivity as well as to safeguard society and the environment (Cetindamar, Phaal and Probert, 2016). However, it is common knowledge that sustainability is not only about technology, but that in order to realise the promise of sustainable development, sustainable products, systems, services and supply chains are necessary; more

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[7] http://www.naturaledgeproject.net/Keynote.aspx licensed under http://creativecommons.org/licenses/by/3.0/

importantly, all of this has to be managed towards sustainability (Cetindamar, Phaal and Probert, 2016). An important concept to keep in mind here is that the total life-cycle should be taken into consideration, and only when this holistic approach is followed, will it become conceivable to decrease the negative impact of production and consumption on the environment and society effectively and efficiently, while maintaining profitability (Cetindamar, Phaal and Probert, 2016). The ideal approach is not only to reduce the negative impacts, but also to identify, exploit and manage the potential positive impacts of technological innovations on society and the environment.

Brent and Pretorius (2008) concluded that sustainability aspects are not adequately addressed in technology management theories and practices, and subsequently developed a framework that coupled technology management tools and techniques as these relate to sustainable development (Brent and Pretorius, 2008). Numerous environmental policies and regulations such as R&D support and economic incentives have seen the light. According to Jacobsson and Bergek (2011). However, these 'general' policies are not enough to stimulate sustainable development; they further argue that technology-specific policies are required. Developing technology-specific policies will require the processes that are critical for success to be identified, as well as an in-depth understanding of the dynamics and prospects of such a technology. The importance of technology-specific policies to aid the transitioning to sustainability in turn highlights the importance of managing technology within this context. Aside from the need for technology-specific policies, the lack of sustainability aspects being addressed in technology management reiterates the need for an approach to amalgamate the management of technologies with the theories that support the facilitation of sustainable futures.

2.1.4.3 Integration of services with products

In recent years, the service sector has become a significant application area for both engineering and technology management, and currently represents between 60% and 70% of the GDP in developed countries (Berg *et al*., 2015). There are numerous examples of how technological innovation has transformed service industries, including healthcare, insurance and education (Cetindamar, Phaal and Probert, 2016). This integration of services and technological innovations further highlights the fact that technology management will have to support the dynamics of both manufacturing and service industries. In addition, technology management will most likely have to support new business models, focus on improving business processes and reduce costs and risks (Cetindamar, Phaal and Probert, 2016). This all calls for different, alternative, and additional sets of capabilities to succeed in the integration of products and services, all of which is essential to ensure the long-term competitiveness and effectiveness of organisations (Cetindamar, Phaal and Probert, 2016). Cetindamar *et al*. (2016) further propose that, within the context described above, technology managers, and thus also the field of technology management, will increasingly need to improve abilities that relate to cross-disciplinary communication, multidisciplinary team management, and service management.

2.1.4.4 Strategy

The changes in innovation and the environments within which organisations exist affect all aspects of business, and require a reform, or at least a revised approach, to most aspects of an organisation, including its strategies (Cetindamar, Phaal and Probert, 2016). Previous research clearly demonstrated that emerging regimes have an advantage when a new business model threatens an existing technological system or market (Utterback, 1995).

Digitalisation is an example of an emerging business model that challenges the status quo. The digitalisation of business processes, content and transactions, and the effect thereof on economic growth, is compared with that of the industrial revolution (Brynjolfsson and McAffee, 2014). This digitalisation of 'just about everything' furthermore facilitates processes of continuous improvement and improved understanding of complex processes and systems, due to the vast volumes of information being available, thus resulting in increased transparency. In addition to the creation of new business models, it also highlights the importance and value of big data in this 'new' way of conducting business (Cetindamar, Phaal and Probert, 2016).

The numerous 'new' technologies that are emerging are, undoubtedly, creating opportunities for a number of role players, but strategic approaches to dealing with these technologies, especially given their sets of characteristics, are still lacking (Groen and Walsh, 2013). Also, existing approaches do not take into account all the aspects of commercial, ethical, societal, and environmental perspectives (Groen and Walsh, 2013). Moreover, the commercialisation of technologies that are directed at societal and environmental problems remains challenging, and highlights the need for technology managers to have these skills (Cetindamar, Phaal and Probert, 2016).

Centidamar *et al*. (2016) argue that, in order to deal with the strategic challenges faced by the discipline of technology management, improved entrepreneurial skills, design-thinking, and cross-cultural perspectives are required. This resonates with the skills required to address some of the other challenges facing technology management, namely: cross-disciplinary communication, multidisciplinary team management, and service management, and the need to amalgamate the management of technologies with the theories that support the facilitation of sustainable futures.

2.2 Socio-technical transition: Theory, approaches and frameworks

The field of socio-technical transitions is built on the notion that technology is socially contingent and a *'terrain of struggle'* (Ahlborg *et al.*, 2019:23) with social, political and environmental consequences (Ahlborg *et al.*, 2019; Bijker, Hughes and Pinch, 1989; Smith and Stirling, 2010). This section starts by first considering socio-technical systems and then outlining socio-technical transitions and related topics, such as the role of technological innovations in socio-technical transitions, the analytical frameworks associated with socio-technical transitions, transition pathways, and the challenges faced by the field of socio-technical transitions.

2.2.1 Socio-technical systems

Socio-technical systems represent the complex interactions and interrelatedness between technology and societies (Hekkert *et al.*, 2007), and can be defined as the *"linkages between elements necessary to fulfil societal functions"* (Geels, 2004:900). Economics, innovation and science and technology scholars identified a number of structural elements that constitute socio-technical systems (see Hughes, 1987; Carlsson *et al.*, 2002; Geels, 2004; Bergek *et al.*, 2008); socio-technical systems primarily consist of three inter-related elements: (i) a network of actors and social groups, (ii) formal, cognitive, and normative rules that guide the activities of actors, and (iii) material and technical elements, such as artefacts and infrastructures. All of these elements interact to serve a specific purpose or address a specific need within a society (Geels, 2004).

The literature pertaining to the economics of innovation and science and technology studies has identified a number of structural elements that constitute a socio-technical system (Hughes, 1987; Carlsson *et al.*, 2002; Geels, 2004; Bergek *et al.*, 2008). Sandén and Hillman (2011) elaborated on the work of these scholars by grouping the structural elements into three key categories, namely: artefacts, actors and schemata. Sandén and Hillman (2011:405) state that, "*By 'schemata' we refer to virtual properties, regularities that can be abstracted from artefacts and actors, such as knowledge and rules. Correspondingly we may say that the technology, understood as a socio-technical system, extends in a multidimensional space with material, organisational and conceptual dimension".* Furthermore, some socio-technical systems exist as complete systems that extend across all dimensions and that are well developed or mature from a material, organisational and conceptual perspective, while other socio-technical systems are 'embryos' – or, as Sandén and Hillman (2011:405) describe it, "*as a piece of knowledge scribbled on the back of an envelope or as an expectation held by a few individuals".* Geels (2004) provided the schematic, shown in Figure 11, of the basic elements and resources found in socio-technical systems.

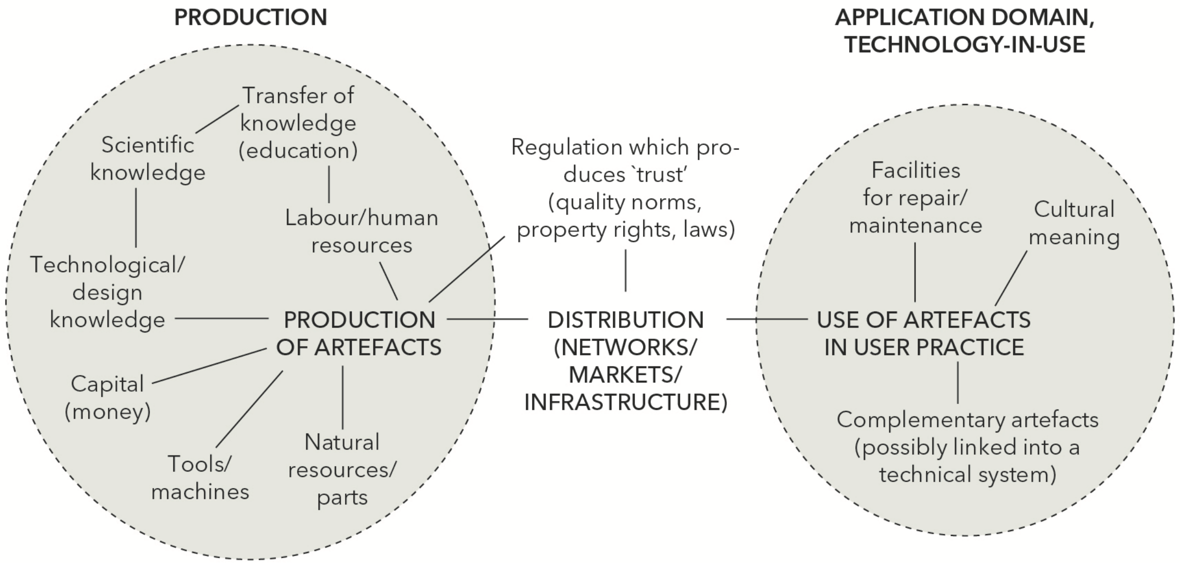

Figure 11. Basic elements and resources of socio-technical systems (adapted from Geels, 2004)

2.2.2 Socio-technical transitions

Given the overview of socio-technical systems, socio-technical transitions can then be explained as large-scale transformations of socio-technical systems that involve long-term processes and shifts to 'novel' socio-technical configurations; the common understanding is that these processes have an undeniable orientation towards sustainable futures (Loorbach, 2014; Markard, Raven and Truffer, 2012). The concept of 'transitions' and the momentum that it gained in the field of 'sustainable development' during the 1990s was partly due to the momentum of 'sustainable development' triggered by the World Commission of Environment and Development in 1987. This resulted in an increasing interest in studies on the transition towards sustainable futures (Lachman, 2013). Socio-technical transitions towards sustainable futures are different from historical transitions. History provides numerous examples of transitions, for example, sail boats to steam engines, horse carriages to automobiles, and the transition from cesspool passed evacuation of waste water to sewer systems (Geels, 2005). In hindsight, it is evident that some historic transitions were transitions to socio-technical systems that were more harmful to the environment and that did not promote sustainable development as it is understood today, i.e., from a perspective of the triple-bottom-line (Elkington, 1994).

Transition management theorists developed the multi-level approach (Geels, 2004) to delineate socio-technical systems (i.e., niches, regimes and landscapes), and to outline and accommodate the role of human agency on the part of innovators and entrepreneurs generating new knowledge and technologies, while also doing justice to the ways in which contexts shape and are shaped by novelty (Berkhout, Smith and Stirling, 2004). Geels (2004) identifies changes at the landscape level as the source of important tensions in regimes – in modern times, the negative consequences of the exploitation of natural resources and environmental services have introduced tensions to numerous embedded regimes. Examples include the carbon intensity of energy and transport systems and the chemical-intensive agriculture sector.

Socio-technical transitions are further considered purposive transitions associated with sustainability goals (Markard, Suter and Ingold, 2016). Such transitions can thus be defined as *"long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption"* (Markard, Raven and Truffer, 2012:965) In addition, the aim of a sustainability transition is to improve the overall sustainability of a socio-technical system through a technological, social, and/or political intervention (Rotmans, Kemp and Van Asselt, 2001; Markard, Suter and Ingold, 2016; Schilling, Wyss and Binder, 2018).

Three characteristics of sustainability transitions can be highlighted that differentiate this type of transitions from the historic examples. Transitions towards sustainability are, firstly, goal-seeking in that they aim to address the ever-increasing societal challenges (Smith, Stirling and Berkhout, 2005). The goal is related to a greater, collective good, i.e., achieving a sustainable future. Historic transitions were 'emergent', in that they were focussed towards exploring commercial opportunities and driving economic growth (Geels, 2011). Wagner, Bachor and Ngai (2014) add to this by explaining the paradox when defining sustainability as 'a bundle of public goods', and arguing that, for a firm that pursues sustainable development with the aim of economic profit, the true social benefit and 'greater' good might be questioned.

The second characteristic that differentiates sustainability transitions from historic ones is that the alternative socio-technical system that is aspired to, often does not offer obvious (economic) benefits to users compared to incumbent technologies (Geels, 2011). This highlights the fact that transitioning towards sustainable socio-technical systems will most likely have to be supported by changes in economic frame conditions. Such changes will, in turn, result in changes in policy (Geels, 2011).

The third characteristic that differentiates sustainability transitions from historic transitions, relates to the domains where transitions to sustainable practices are most needed, such as transport, energy and agri-processing. These socio-technical systems are characterised by incumbent firms, technologies and providers who also have 'complementary assets' to offer. Complementary assets include established, specialised services and products such as manufacturing, supply-chain, complementary technologies, and so forth, which reinforce their leading position relative to pioneers in the field of alternative, sustainable solutions (Geels, 2011). Geels (2011) states that, even though these established firms might not lead the way in terms of developing sustainable alternatives, their involvement in sustainability transitions can aid the acceleration and breakthrough of sustainability innovations, should their complementary assets and resources be supporting these innovations.

Transition studies focus on understanding socio-technical change or socio-technical transitions. Such transitions are referred to as 'systemic' or 'radical', meaning that the changes go beyond the ordering of the current system (Bergman *et al.*, 2008). There is an increasing movement of applying the concept and understanding of socio-technical transition to tackle the polycrisis of unsustainability by aiming to understand, conceptualise, explain and identify how socio-technical change towards more sustainable future states can be promoted (Elzen, Geels and Green, 2004).

The interrelatedness and interdependency of societal and technological systems and sub-systems are highlighted throughout transition studies literature. The societal systems have, over decades, created technological and innovation lock-ins and path dependencies that result in stability, cohesion and reinforcement of socio-technical systems (Smith, Stirling and Berkhout, 2005). Transitioning to sustainable socio-technical systems depends on both far-reaching technological and behavioural innovations (Tran, 2014), and cannot develop into a dominant regime without fundamentally rethinking economic and wider societal conditions (Van Den Bergh, Truffer and Kallis, 2011; Wagner, Bachor and Ngai, 2014).

Socio-technical transitions require inclusive, qualitative and systemic, societal and technological innovations, which will result in the reform of existing socio-technical systems. Researchers have outlined three continuously interacting levels within socio-technical systems. Dynamic interaction between such levels is necessary to bring about socio-technical transitions. These three levels are defined as niches, regimes and landscape levels, and are referred to as a "nested hierarchy" (Geels, 2002) (refer to Figure 12). Niches represent individual technologies on the periphery or outside of the regime (Geels, 2005; Smith, Stirling and Berkhout, 2005). The regime constitutes the current, paradigmatic core of a sector or system. Regimes are an outcome from the co-evolution of societal functions and technologies over time (Fuenfschilling and Truffer, 2013). Both niches and regimes are embedded within the broader landscape. The socio-technical landscape is defined as a configuration of broad political cultures, economic growth and institutional elements working together to support specific actions and agendas (Geels, 2002).

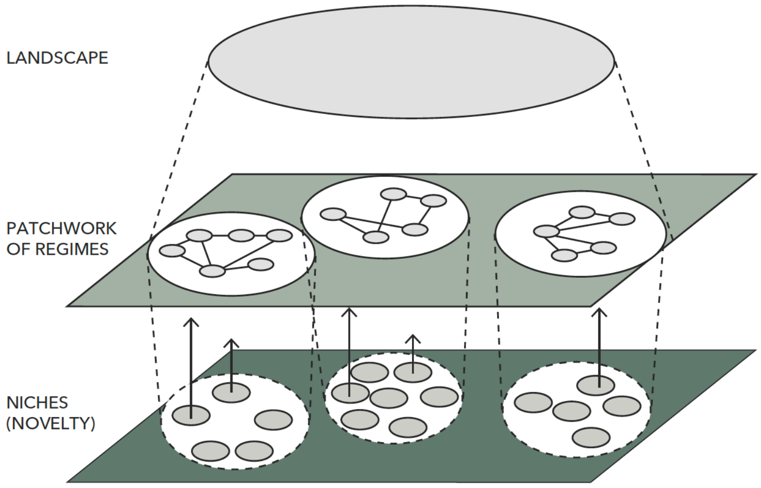

Figure 12: Multiple levels as a nested hierarchy (adapted from Geels, 2002)

For transitions to occur, developments across all three levels are necessary (Geels, 2002; Hekkert and Negro, 2011). Transitions occur along two possible routes, either through regime change or regime transformation. Regime changes occur when the current regime cannot adapt to the pressures from the landscape or niche levels, and are then as a result replaced by a new or alternative regime capable of dealing with the new conditions or requirements. Regime transformation occurs when the current regime responds to the pressures from niche and landscape levels and then changes or adapts some of the rules and practices within the regime to be able to accommodate the new conditions or required changes (Bergman *et al*., 2008).

Transition thinking requires a systems thinking approach; it is a broad term that includes theoretical frameworks and approaches to study socio-technical transitions. The literature on transitions promotes understanding how to address the challenges that current socio-technical systems face. However, the literature is less clear about the agents of transitions, and the specific activities and actions that can foster and promote transitions (Doci, Vasileiadou and Petersen, 2015).

2.2.3 The role of technological innovation in socio-technical transitions

The importance of technology and/or technological innovation in advancing towards sustainability is debated in the literature. For example, some authors argue that environmental regulation is more important than the role that technology might play in bringing about transitions (Popp, 2001; Jorgenson *et al.*, 2009). However, the opinion, viz., that aiming to address sustainability problems without innovative technologies will be difficult, remains popular, with the leading authors being Jeffrey Sachs[8] and Gunter Pauli[9]. The development and diffusion of technologies that contribute towards addressing the sustainability challenges (both environmental and developmental) are deemed one of the main pathways towards sustainable futures (Paredis, 2011).

Numerous environmental policies and regulations such as R&D support and economic incentives have seen the light. However, these ‘general’ policies are not enough to stimulate socio-technical transitions, according to Jacobsson and Bergek (2011), who argue that technology-specific policies are required. Developing technology-specific policies will require the processes that are critical to success to be identified, as well as an in-depth understanding of the dynamics and prospects of a technology to be developed.

The importance of technology-specific policies to aid the transitioning to sustainable socio-technical systems in turn highlights the importance of managing technology within this context. The technological innovation management process, or technology management, can be seen as a number of interrelated processes that must be managed to reach the ultimate goal of desired market diffusion. Four phases of the innovation process can be described as innovation stimulus, R&D, initial market adoption, and market diffusion (Spoerri *et al*., 2010). If a sustainable future, or contributing towards this, is the goal, then technology management or innovation management becomes a concern of greater good.

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[8] http://jeffsachs.org/category/topics/sustainable-development/

[9] http://www.gunterpauli.com/Home.html

2.2.4 Current state of the art: existing analytical frameworks

A number of multi-disciplinary approaches to study socio-technical transitions exist. Van den Bergh *et al.* (2011) state that the particular approaches that have thus far been used to study socio-technical transitions include: (i) the innovation systems approach, (ii) the multi-level perspective (MLP), (iii) strategic niche management, (iv) transition management (based on complex system analysis), and (v) evolutionary-economic views and multi-agent modelling of transitions. Lachman (2013) conducted a survey and review of the most widely used to study transitions and deems the following approaches to be the 'most notable' transition approaches: (i) the MLP, (ii) strategic niche management, (iii) transition management, (iv) innovation systems, (v) techno-economic paradigm, and (vi) socio-metabolic transitions. Markard *et al.* (2012) provide four frameworks that have achieved prominence in transition studies and that are considered central to the theoretical framing of socio-technical transitions, namely: (i) transition management, (ii) strategic niche management, (iii) multi-level perspective, and (iv) technological innovation systems (TIS).

In addition to the abovementioned, there is a broad range of alternative approaches that address the theoretical underpinnings of transitions. Some examples include evolutionary theory and actor network approaches. Approaches such as the social construct of technology, technology future studies, constructive technology assessment, to name but a few, deal more specifically with technologies. From the literature, however, it is evident that MPL, innovation systems (specifically technological innovation systems), strategic niche management, and transition management are the most prominent approaches of studying socio-technical transitions.

2.2.4.1 Multi-level perspective

The MLP is a theory that focuses on and conceptualises the dynamic patterns of socio-technical transitions. It aims to offer insights about the processes and factors that either hinder or enable the far-reaching adoption of technologies. MLP amalgamates concepts from a number of fields and disciplines, such as evolutionary economics, science and technology studies, neo-institutional theory, and structuration theory, in order to analyse the interplay between all stakeholders within a socio-technical system (Geels, 2012).

Socio-technical transitions are viewed as non-linear processes in the MLP. Transitions are seen as the interaction between, and development of, three analytical levels: micro-level or niche level (where technological innovations are developed and incubated and look to challenge the dominant or incumbent technologies in the regime), meso- or regime-level (the diverse elements of the established production and consumption practices and associated rules of the existing [often stable] existing regime), and landscape- or macro-level (the broader environment within which socio-technical regimes exist, the realm of governmental institutions, socio-demographic trends, conditions and pressures) (Cohen, 2012; Geels, 2005; Rip and Kemp, 1998). Each of these 'levels' comprises a diverse configuration of elements, and the stability increases from the niche level to the landscape level in terms of the number of actors and elements, as well as the degree of alignment between actors and elements (Geels, 2012).

The key focus of the MLP is to study and analyse the interactions and interplays between the new technological innovations (niche level) and the existing regime. These interactions and interplays between the niche and regime levels are situated within a macro environment (the landscape), which also has an influence on the regime (Geels, 2002; Verbong and Geels, 2007). Socio-technical transitions occur when processes across all three levels link up and reinforce each other (Geels and Raven, 2006). MLP has been used extensively to understand technological transitions, and subsequently socio-technical transitions.

2.2.4.2 Innovation Systems Approach

An 'innovation system' comprises networks of actors that influence, and ultimately determine, the direction and speed of technological change in socio-technical regimes. The innovation system approach takes a broader view than just technological change. The systemic context of technological innovations is deemed, taking into consideration innovating actors, interaction networks and their dependence and interdependence on various institutions (Edquist, 2005; Hekkert *et al*., 2007). The innovation systems approach has been extended and defined, based on the differences in system boundaries, at different levels of analysis, namely the National Innovation Systems (NIS), Sectoral Innovation Systems (SIS), Technological Innovation Systems (TIS), and Regional Innovation Systems (RIS) (Jacobsson and Bergek, 2011).

The TIS level focuses on, and studies, the characteristics of a system that is associated with a specific technological innovation. The aim is not only to identify and analyse the characteristics associated with the specific technologies' strengths and weaknesses, but also to compare the system with the dominant or competing technology in the existing socio-technical regime (Hekkert and Negro, 2011; Jacobsson and Johnson, 2000).

The interdependent nature of the innovation systems approach highlights and addresses the fact that technological change can be influenced by both collective and individual actions and activities of the actors within an innovation system. This approach thus aims to unpack innovation systems into their constituent elements, with the aim of identifying which of these do not realise their intended purpose or achieve their desired goals. Such elements will hamper the developmental process of the entire system (Jacobsson and Bergek, 2010).

2.2.4.3 Strategic Niche Management

Strategic niche management (SNM) focuses on the dynamics around the early adoption stages of technological innovations that could contribute towards sustainable development. The approach assumes that creating protected spaces for technological innovations, in which these can be developed and experimented with, can facilitate the developmental process of such technological innovations. The main question that SNM aims to answer is: "*how and under what circumstances is the successful emergence of a technological niche possible?"* (Schot and Geels, 2008:540). The aim is ultimately to align a technological innovation through a process of SNM to bring about a regime shift. SNM facilitates this through a process of learning-by-doing and doing-by-learning to gain insights from the transition experiments, and subsequently to evaluate the required measures to increase the probability of a niche technology replacing the existing incumbent technology within a socio-technical system – and in this way, bringing about a socio-technical transition (Raven and Geels, 2010).

2.2.4.4 Transition Management

Transition management aims to work towards sustainability and adds to on-going dynamics to help steer and build bottom-up initiatives. The aim is thus strategically to exploit on-going development processes and dynamics to guide systems towards a sustainable future or selected sustainable development goals. A goal might be the use of a particular technological innovation or a performance indicator. Existing and alternative policies are subsequently evaluated to identify the impact on the immediate gains, as well as the contribution of such policies towards fostering a socio-technical transition (Elzen, Geels and Green, 2004).

Transition management is geared towards achieving system improvement and system innovation. This process-focussed approach supports dealing with the complexity and uncertainty in a constructive way. It is based on a process management philosophy that directs an existing or new process towards a set of goals or desired futures. The key elements of transition management include long-term thinking, back-casting, multi-level thinking, multi-domain thinking and analysis, a focus on learning, an orientation towards system innovation, and an evaluation of various scenarios (Elzen, Geels and Green, 2004).

In summary, the main aim of transition management is to identify and analyse the opportunities, enabling factors, limitations and conditions under which transition management has to be set up to influence a socio-technical system effectively in order to foster a transition.

2.2.5 **Transition pathways**

A number of different transition paths have been defined. Geels and Schot (2007) provided a typology of these, and Geels *et al.* (2016) reformulated this initial typology by differentiating it "*through the lens of endogenous enactment, identifying the main patterns for actors, formal institutions, and technologies"* (Geels *et al.*, 2016:896). Essentially, they defined four transition pathways: transformation, technological substitution, reconfiguration, and de-alignment and re-alignment. The key constructs of the pathway typology are the timing and nature of multi-level interactions. Table 70 in Appendix A summarises the different transition pathways defined by Geels and Schot (2007). Berkhout *et al*. (2004) presented a fourfould typology of transitions contexts based on two differentiating factors: (i) the first dimension considers whether or not change is envisaged and coordinated at the level of the regime, or whether change is an emergent outcome of the normal behaviours of agents within the regime – this dimension distinguishes between intended and unintended transformations; (ii) the second dimension is concerned with the degree to which the resources necessary to respond to the landscape pressures are available within the regime (or can be coopted by the regime), or whether a response depends on resources only available outside of the regime. If the resources needed to respond to the landscape pressures are available inside of the regime, change is more likely to be incremental and the regime is less likely to transition to a new regime. The four 'ideal-type' transformations outlined by Berkhout *et al*. (2004), and shown in Figure 13, include:

i. Endogeneous renewal: Here, the resources required are internally available to respond to the pressures, and the change is coordinated at the level of the regime, thus regime actors make a consious effort to find ways of responding to the perceived threats to the regime (i.e., tensions brought about by the landscape pressures). Given that innovations are steered from within the regime, the transition will be steered by prevailing values, cognitive structures, and problem-solving abilities of the existing regime. In such instances, transformations, over the long term, tend to be incremental. An example of this kind of transformational process is the radical scaling up of the thermal capacity of steam-generating plants over the course of the 20th century. Even though this was constituted by a significant number of individual organisational and engineering innovations, it resulted in a radical transformation in the character of the electricuty regime (Hughes, 1987).

ii. Reorientation of trajectories: Similarly to i, the response to landscape pressures and tensions is formed from within the regime. However, the stimulus for reorientation is a shock that originates inside or outside of the regime. An example is the wide-scale adoption of combined cycle gas turbines, especially in the UK. This transformation of both technical and operational characteristics was not anticipated or intended, but nevertheless emerged through the combination of a number of uncoordinated technological opportunities, market regulation changes, and alternatives, such as coal and nuclear, facing a number of difficulties. But still, the adoption and diffusion of gas turbines were managed from within the incumbent regime, rather than being executed from outside of the regime.

iii. Emergent transformation: This type of transformation develops from uncoordinated pressures for change, and the responses for such change is based on resources that are located outside of the incumbent regime. These transitions are generally associated with scientific activity that produces 'solutions' to the pressures experienced within the regime, and it is often challenging to identify which of these solutiuons will be successful, and which will not. An example of this is Carbon Capture and Sequestration (CCS) of Use (CCU) to address the carbon emissions in the fossil fuel industry.

iv. Purposive transitions: Even though emergent transitions have an autonomous quality, purposive transitions are distinguished from these in that they are, in some sense, intended and pursued to *"reflect the expectations of a broad and effective set of interests"* (Berkhout, Smith and Stirling, 2004:70) Tensions are perceived in the regime, and actors coordinate actions to respond to such pressures. The resources required to respond to the pressures are not available inside of the regime. An example of such transformation processes is the transition to the greater use of renewable energy technologies.

It is important to note that not all purposive transitions – imagined, planned, and excecuted – necessarily generate social and enviormental benefits (Berkhout, Smith and Stirling, 2004). This highlights the importance of (i) taking a broad view of sustainability, and thus considering all dimensions of sustainability, and (ii) taking a systems perspective, thus considering the impact and consequences of the solution on other elements and actors within the socio-technical system.

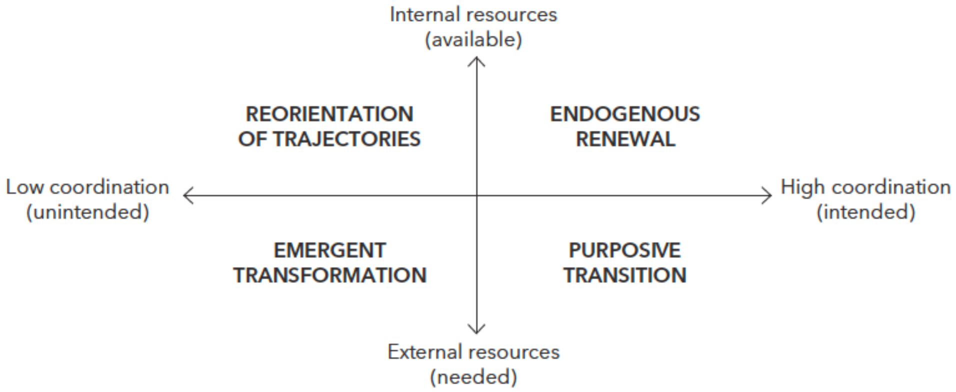

Figure 13. Four transition contexts and transformation processes (adapted from Berkhout, Smith and Stirling, 2004)

2.2.6 Shaping socio-technical transitions: Analytical challenges

The literature on sustainability and socio-technical transitions has developed several concepts that are indispensable for understanding the transition from one socio-technical system to another. However, this section discusses the challenges faced by the literature on socio-technical transitions, frameworks and approaches. It should be noted that this is not an extensive list of the challenges and concerns raised throughout the literature, but rather an overview of the challenges that could perhaps be addressed by reflecting on technology management.

To date, multiple approaches and frameworks are available to support the evaluation and analysis of socio-technical transitions. However, the contending perspectives frame socio-technical systems in incommensurable ways, typically have different views on the orientation of desirable pathways towards sustainability, and take different views on the virtues and weaknesses of the different socio-technical practices (Smith and Stirling, 2008). Ulli-beer (2013) argues that the multiple approaches and perspectives pose a challenge for the application or selection of an approach or framework for a specific real-world context and problem. The question that arises is thus "which is the most applicable framework or approach to use given a particular socio-technical system or transition?" This leads to another challenge, a challenge that is not unique to the specific environment of socio-technical transitions: multiple frameworks and approaches hinder the accumulation of a consistent knowledge stock (Ulli-beer, 2013). In addition, the bounding, segregating and ordering of a socio-technical system under consideration is challenging (Smith, Stirling and Berkhout, 2005), and researchers have concluded that transition management requires collaboration and consensus-building (Smith and Stirling, 2008). However, the question of how to achieve this remains unanswered. This calls for standardisation, a level of normative consensus, or simplification across the different socio-technical approaches and frameworks. However, critics warn that, when simplification, although necessary, is considered, it risks masking and reifying more than what would actually be revealed and explained about socio-technical systems and transitions (e.g., Shove and Walker, 2007). The challenge is to simplify without being simplistic and one-dimensional, to be clear on what basis one is simplifying, and to ensure that one substantiates any conclusions that are drawn (Smith and Stirling, 2007).

An on-going discussion about how some of the socio-technical transition frameworks and approaches could be operationalised and institutionalised is evident in the literature (Smith, 2009). The operationalising of key transition concepts can be ambiguous (Genus and Coles, 2007), highlighting the sensitivity of transitions research to analytical framings; however, the high stakes, instrumental purpose and pressing timelines associated with socio-technical transitions emphasise the implications (Smith and Stirling, 2008). A key challenge to operationalising and institutionalising the concepts of transitions is the fact that the transitions literature supports our understanding of how to address the challenges and issues that socio-technical systems face, although it is less clear on the particular activities and actions that are required to promote and stimulate socio-technical transitions (Doci, Vasileiadou and Petersen, 2015). Multiple factors and processes are posed as elements that steer system evolution in the socio-technical transitions literature, however the question still remains how they can be explicated for a concrete action context.

Ulli-beer (2013) states that a shortcoming of the encompassing storyline of socio-technical transitions, and thus also that of the approaches to study socio-technical transitions, is that it lacks a theoretical micro-foundation for actor behaviour, i.e., the driving forces that can contribute towards transitioning to sustainable socio-technical systems are not explicated by these approaches. This again highlights the fact that the relationship between the frameworks and approaches, which tend to be conceptual in nature, and the practical tools, which focus on action, is important when considering the management of socio-technical systems towards sustainability. It is paramount that practical tools, techniques and methods be established and articulated to link the very tangible need of transitions with the development, use and application of approaches and frameworks concerned with socio-technical transitions.

The analysis performed by Coenen and Díaz López (2010) concludes by stating that the differences between socio-technical transition approaches hamper knowledge integration and crossover between different socio-technical transitions perspectives to support the investigation of both drivers and barriers of sustainability transitions and improved competitiveness in socio-technical systems. Ulli-beer (2013:37) provides examples of questions that existing framework do not address, i.e., *"How can emission reduction targets be met in time? How can we stay competitive during socio-technical transitions?"* This in turn, as mentioned earlier, also highlights the fact that, in order to advance the field of socio-technical transition studies, it is important to go beyond the existing models, and to expand and elaborate on the existing frameworks and approaches. Even though there are numerous theories, perspectives, frameworks and approaches concerning socio-technical transitions, the challenges and critiques raised throughout the literature suggest that a drawback of the socio-technical transitions literature, and thus also that of the approaches to study socio-technical transitions, is that they do not offer a set of practical devices (i.e., methods, processes, techniques and tools) to support the theoretical framings. In fact, the multiple different perspectives result in confusion on the processes and activities that transition activists and managers need to conduct, in order to manage and ultimately foster socio-technical transitions.

It is acknowledged that many of the above-mentioned challenges are readily apparent to transition researchers and scholars. However, here we interpret these challenges to be ones that could potentially be addressed, or at least discussed, in terms of how technology management frameworks structure the elements that support the development of a premise to integrate technology management and the concept of socio-technical transitions, rather than attempting a fundamental reconceptualisation of approaches to study socio-technical transitions.

2.3 Conclusion: Chapter 2

Given the shared base in context, i.e., the fact that technology exists within socio-technical systems, and that it plays a significant role in the (un)sustainability of socio-technical systems, it is argued that a sufficient and appropriate premise of how to link the concepts of technology management and socio-technical transitions pose value for both fields of study – from a practical, methodological and theoretical perspective. The investigations into the challenges faced by the respective bodies of literatue further support the rationale for this research, in that it emphasised that, by taking a socio-technical transitions perspective of technology management, and vice versa, important and useful insights may be uncovered regarding the potential and value of an integrative framework to increase the potential for innovative and less (environmentally, economically and socially) destructive practices to emerge.

As highlighted, the fields share similarities, although there are important differences that call for a cautious approach. The focus of socio-technical transitions research is different from technology management in a number of respects: objects, objectives, structure or function, and level of analysis. Hence, there are challenges related to conceptualisation and integration across these fields. However, it is argued that, given the background and contextualisation provided throughout this chapter, the insights gained and lessons learnt from the socio-technical transitions and technology management literature, there is a need to develop a concept that transcends the two bodies of knowledge, as a unifying aspect that needs to be addressed for sustainability transitions.

Furthermore, the preliminary investigation (highlighted in Section 1.2) highlights the limited efforts that explicitly consider both technology management and socio-technical transitions as a key focus. This further supports the rationale to investigate and develop a premise for integration between these two fields, while also highlighting the need for a more in-depth investigation into the extent to which the concepts of technology management and socio-technical transitions have been considered together in, and integrated in, the literature. Chapter 3 therefor presents an in-depth investigation into the (dis)connection between the bodies of literature pertaining to socio-technical transitions and technology management.

Chapter 3.

Exploring the (dis)connection between the bodies of literature pertaining to socio-technical transitions and technology management (Part A): A bibliometric analysis

This chapter considers a specific relation within the technology-social context, namely: the link between technology management and socio-technical transitions. A socio-technical perspective to sustainability is based on the contextual understanding of technology (Grin, Rotmans and Schot, 2010), and in order to develop, diffuse, and employ technology to foster and facilitate sustainability, such technologies and/or technological innovations that have the prospect of contributing towards sustainable development, have to be managed accordingly. It is argued that the exploration and identification of the overlap and integration, or lack thereof, of socio-technical transitions literature and the technology management literature is a vital consideration when the aim is to ultimately develop a premise for the integration between these two bodies of literature. Singular reviews have been conducted that consider literature pertaining to technology management (Pilkington and Teichert, 2006; Pilkington, 2014; Sarin, Haon and Belkhouja, 2018) and socio-technical transitions (Chappin and Ligtvoet, 2014; Hansen and Coenen, 2014; Savaget *et al.*, 2019), but no such reviews or bibliometric studies were focused on unearthing the level of integration, or lack thereof, between the bodies of knowledge of technology management and socio-technical transitions.

To, ultimately, contribute towards the development of a premise for the integration between technology management and socio-technical transitions, it is important to understand if integration between the two fields has been established, and if so, where and to what extent has this been achieved.

3.1 Introduction: Bibliometric analysis

Literature, information and knowledge tend to be segmented and discipline-specific, making it difficult and challenging for experts (within a certain field/discipline) to comprehend the ‘big picture’ or direction of knowledge (Ittipanuvat *et al.*, 2014). And when sustainability is considered, it is generally agreed that a holistic, systems view of socio-technical systems is required when transitions of such systems are studied. Scientific research has evolved over the last couple of decades to be increasingly interdisciplinary, and has resulted in improved fundamental understanding of how to address problems of which the solutions lay outside the boundaries of a single field of research, practice, or discipline (Porter and Rafols, 2009; Chappin and Ligtvoet, 2014). Nevertheless, the constant growth and evolution of research and knowledge have resulted in the boundaries between disciplines and/or fields of research becoming increasingly unclear, adding to the challenge of delimiting the overview of a specific problem under consideration (Ittipanuvat *et al*., 2014). Given this, Ittipanuvat *et al*. (2014) state that an interfacial layer[10] exists between disciplines and/or fields of research, but that the internal structure of such a layer is often not visible or is unclear. However, it is argued that an investigation into this 'interfacial layer' through bibliometric research or analysis is an effective way to gain insight into the integration or overlap between disciplines and/or fields of research (Chappin and Ligtvoet, 2014). A bibliometric analysis is an approach used for extracting information about a field (or fields) of research from bibliographic databases, and to subsequently perform qualitative and quantitative analyses to explore the knowledge structure, research trends, emerging areas of research, patterns and development of research fields based on the analysis of related published documents, primarily scientific research (Daim *et al*., 2006). Bibliometric research includes the application of information technology to efficiently extract, analyse, and interpret useful information from the current knowledge databases (Ittipanuvat *et al*., 2014). Put differently, this form of research investigates information relating to fields of research and/or scientific networks through the use of a number of indicators, such as publications, references, authors, keywords, citations, co-citations, authors, author affiliation and geographic location, and related characteristics that could possibly improve our understanding of the landscape of scientific networks (Daim *et al*., 2006).

Identifying the areas of integration (and disconnect) between the scientific networks of socio-technical transitions and technology management, holds potential benefits to both these fields of research (De Kock and Brent, 2017a, 2017b). The inclusion of sustainability aspects, thus concurrent consideration for the coherent consideration for environmental sustainability, social sustainability, and economic sustainability in technology management theories and practices has been argued. In 2008, Brent and Pretorius concluded that sustainability aspects were not adequately addressed in technology management theories and practices, and subsequently developed a framework that coupled technology management tools and techniques as they relate to sustainable development (Brent and Pretorius, 2008). And in recent years, the discipline of engineering and technology management increasingly engages with issues of sustainable development (Bocken *et al.*, 2014; Ittipanuvat *et al.*, 2014). However, the overlap and integration of the respective scientific networks of technology management and socio-technical transitions have not been evaluated. The objective of this chapter is thus to investigate and compare the structures of the scientific networks in the technology management and socio-technical transitions literature in order to explore the interfacial layer between the two bodies of literature; Chapter 4 subsequently has the objective to identify to what degree these two bodies of literature overlap and to what extent the concepts of the two bodies of literature are mutually included in the respective fields.

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[10] The interfacial layer refers to the common boundary(ies) that exist between scientific networks and across which two (independent) systems 'meet'. Ittipanuvat et al. (2014) use the term 'interfacial layer' to illustrate that there is not only an interface or 'link' between disciplines, but that this interface may be a 'layer', thus it has depth and possibly a structure. The internal structure of the interfacial layer then refers, in the context of research disciplines or scientific networks to the content, relationships, etc. that constitute the interfacial layer.

3.2 Methodology: Bibliometric analysis

Bibliometric analysis was introduced in 1969, and has continued to be widely used to evaluate the characteristics of research areas, and to identify patterns of research and collaborations (Wang, Wei and Brown, 2017). Given the ever-expanding nature of academic literature, bibliometrics is considered "*one of the most important and efficient methods to research libraries of published information*" (Wang, Wei and Brown, 2017:58). For this reason, a bibliometric analysis is selected as an appropriate approach to explore the disconnect between the literature that respectively focuses on technology management and socio-technical transitions.

The methodology employed to explore the (dis)connection between the bodies of literature pertaining to socio-technical transitions and technology management (as the chapter heading suggests) consists of two parts, Parts A and B – of which this chapter is Part A. In Part A the level of integration or disconnect between literature pertaining to technology management and socio-technical transitions is analysed through a bibliometric analysis (BA), and has two phases; phase one is concerned with the collection of data of the scientific networks, and phase two with the analysis of extracted bibliometric data (see Figure 14). Similar approaches have been used throughout literature (Klavans and Boyack, 2006; Sakata *et al.*, 2013; Chappin and Ligtvoet, 2014; Ittipanuvat *et al.*, 2014). Initially the scientific networks are analysed individually and then compared across a number of dimensions. The aim of this analysis is to create an academic landscape of each scientific network to improve the understanding of the structure of each network, and how these structures compare, while the BA is aimed at the collection and comparison of the data concerned with each of the two datasets obtained for the two scientific networks.

In order to justify and substantiate the selection of a bibliometric analysis, the method was cross-checked with well-known methodological approaches presented by Tranfield *et al.* (2003), Pittaway *et al.* (2004), and Centobelli *et al.* (2018) – all widely used approaches to conduct literature reviews on managerial topics. The methodology used in this study is similar to phases 0, 3, 6, 7 and 8 of the methodology presented in Tranfield, *et al,* (2003). Essentially, the stages I – III, as set out by Tranfield *et al.* (2003), serve as a comprehensive guide for a systematic literature review – which is different from the aim of the research efforts presented in this dissertation. In the research efforts presented in this chapter, the focus is on understanding the 'interfacial layer' between technology management and socio-technical transitions rather than performing a systematic review of the internal structure and content of the respective bodies of knowledge. Similarly, Pittaway *et al.* (2004) performs a systematic literature review (concerned with the status of entrepreneurship research) and Centobelli *et al.* (2018) employs the method proposed by Pittaway *et al.* (2004) in order to perform a literature review. Although we acknowledge that this approach is an exceptional approach when conducting a structured review, it is argued that a bibliometric analysis is an appropriate approach when aiming not to unpack the internal structure of a body of knowledge, but rather to elucidate the extent of overlap or disconnect between two bodies of literature.

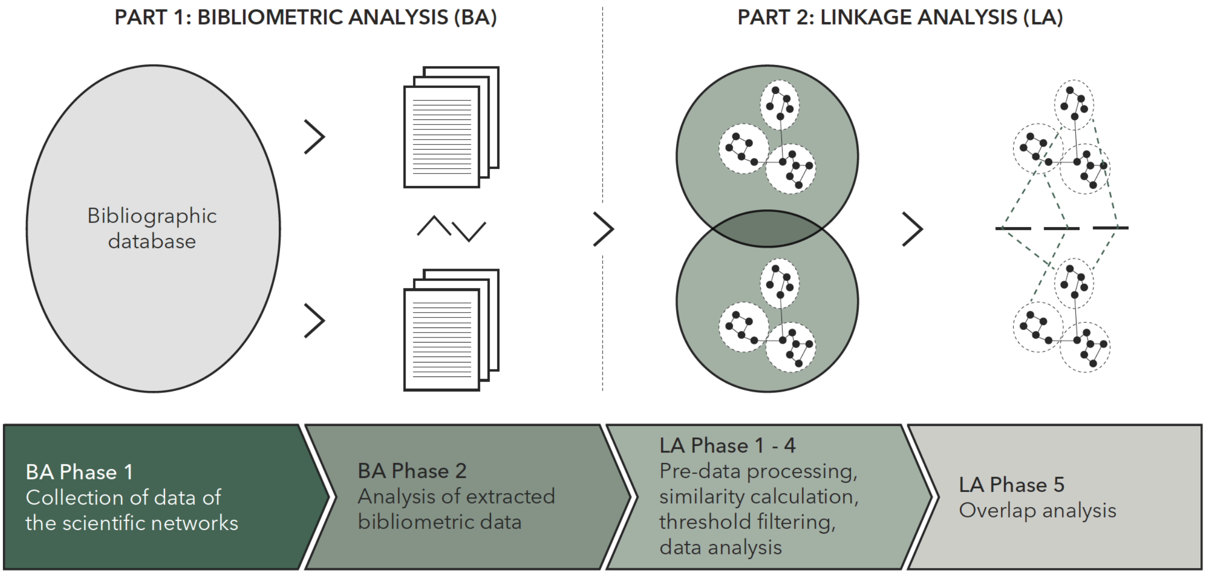

Figure 14. Schematic representation of the bibliometric analysis and linkage analysis methodology

3.2.1 BA Phase 1: Collection of data of the scientific networks

In order to grasp the academic landscape of both technology management and socio-technical transitions, a structured keyword-based search was used to identify and collect documents that constitute the scientific networks of the ‘socio-technical transitions’ and ‘technology management’ literature. The BA is based on the approach proposed by Chappin and Ligtvoet (2014) who performed a bibliometric analysis of the scientific fields researching socio-technical change, specifically relating to socio-technical transitions and transformations. The keyword analysis conducted by Chappin and Ligtvoet (2014) was used as the starting point of the keyword selection for this research inquiry, but adapted to fit this study more specifically. The keywords ‘socio-technical transition’ and ‘technology management’ were not used in isolation, but the keyword sets were expanded; the keywords, as shown in Table 6, were thus selected for the document collection. Table 7 shows the keywords used in the respective searches. It should be noted that the use of loose phrases[11] (i.e. searching for loose phrases in Scopus using double quotation marks) allows for wildcards and lemmatisation; thus finding, for example, both singular and plural forms.

Table 6. Keywords

KEYWORD	EXPANDED SET OF KEYWORDS
Socio-technical transitions set	Sociotechnical transition, socio-technical transformation, sociotechnical transformation, socio-technical change, sociotechnical change
Technology management set	Management of technology

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[11] https://blog.scopus.com/posts/6-simple-search-tips-lessons-learned-from-the-scopus-webinar

Table 7. Keywords used in the respective searches

	SEARCH TERMS INCLUDED							
	"socio-technical transition"	"sociotechnical transition"	"socio-technical transformation"	"sociotechnical transformation"	"socio-technical change"	"sociotechnical change"	"technology management"	"management of technology"
Socio-technical transitions set	x	x	x	x	x	x	-	-
Technology management set	-	-	-	-	-	-	x	x
Combined search	x	x	x	x	x	x	x	x

The keywords were searched for in the titles, abstracts and keywords of documents, further restricting the results to all articles published before 2016 to allow for repeatability. The same 'combined search' (as per Table 7) was conducted at the end of 2019, and only two additional documents that were published since the start of 2016, and thus not included in the dataset, resulted from the *combined search* (i.e. De Kock and Brent, 2017a, 2017b) – both documents by the author of this thesis. The keywords were used in a number of combinations as shown in Table 7.

All keywords were searched for as loose phrases in Scopus, and thereafter the bibliographic data used in this analysis were obtained from Scopus. The search was done with no other restrictions on publication year, subject area, or document type. A structured keyword-based search was thus used to identify and collect documents, authors, and citations in the fields of 'socio-technical transitions' and 'technology management'. Keywords directly liked to sustainable development and innovation management were deliberately not used in order to let the relevance of technology management and socio-technical transitions to sustainable development and innovation management emerge from the analysis. The identification and delineation of a scientific network by searching literature databases by keywords is challenging, because results depend significantly on the selected keywords. To counter this, full transparency about the choices that were made throughout this inquiry is provided

Scopus was used since, according to Elsevier[12], it is the largest abstract and citation database of peer-reviewed literature. Scopus covers peer-reviewed journal articles and other publications from the life sciences, health sciences, physical sciences, social sciences and humanities (Ballew, 2009). Scopus is considered one of two premium periodical databases – the other being Web of Science/Knowledge[13]. The coverage and functionality of Scopus made it a reasonable choice.

3.2.2 BA Phase 2: Analysis of extracted bibliometric data

For all the documents identified during Phase 1 of the BA, the data that was extracted for all documents found in both scientific networks included: (i) title and keywords; (ii) authors; (iii) number of citations; (iv) source of publication; (v) mode of publication; (vi) geographical representation; (vii) subject area; and (viii) references/citations.

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[12] https://www.elsevier.com/en-in/solutions/scopus

[13] www.webofknowledge.com

For the BA of the extracted data, the data listed in i – vii above was used. The references (viii) were used primarily in the linkage analysis (Part B) of this investigation (discussed in Chapter 4).

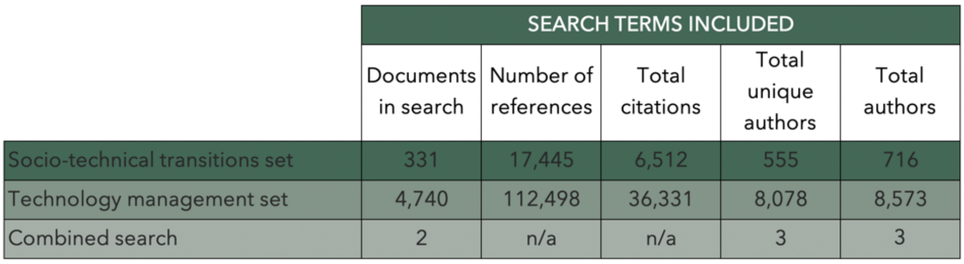
3.3 Bibliometric analysis: Results and analysis

In this section, an overview of the results is provided, followed by a discussion of the key findings with regards to the key contributing authors, keyword analysis, sources and modes of publication, and the geographical representations.

3.3.1 Overview of the results

An overview of the search statistics is shown in Table 8. The literature search (BA Phase 1) resulted in 331 documents for the socio-technical transition scientific network, and 4,740 documents for the technology management scientific network. As mentioned, only two articles (Dolata, 2013; Wells and Lin, 2015) were found to be present in both networks. Also, as stated in Section 3.2.1, only two additional documents (thus that were published since the start of 2016 and thus not included in the original dataset) considered both technology management and socio-technical transitions (i.e. De Kock and Brent, 2017a, 2017b). However, due to this overlap of only two documents, the two sets were expanded to include the references used within the two scientific networks respectively. This resulted in the socio-technical transitions set being expanded to include 17,445 references, and the technology management set expanded to include 112,498 references. The references in the respective sets of documents were primarily used in Part B in the linkage analysis (discussed in Chapter 4).

Table 8. Search statistics



	SEARCH TERMS INCLUDED				
	Documents in search	Number of references	Total citations	Total unique authors	Total authors
Socio-technical transitions set	331	17,445	6,512	555	716
Technology management set	4,740	112,498	36,331	8,078	8,573
Combined search	2	n/a	n/a	3	3

It is clear that the network of scientific documents in the technology management literature is significantly larger than that of socio-technical transitions. The number of publications per year is shown in Figure 15. It is also clear that the technology management field is an ‘older’ and more established field of research or discipline than that of socio-technical transitions; not only in that publications concerned with technology management commenced earlier than those of socio-technical transitions, but also the frequency of publications started to increase a couple of decades before the frequency of publications concerned with socio-technical transitions started to increase. The total number of citations within the technology management and socio-technical datasets is 36,331 and 6,512 respectively. The bibliometric analysis is thus based on 5,071 documents (the combined number of documents found in the bibliographic database).

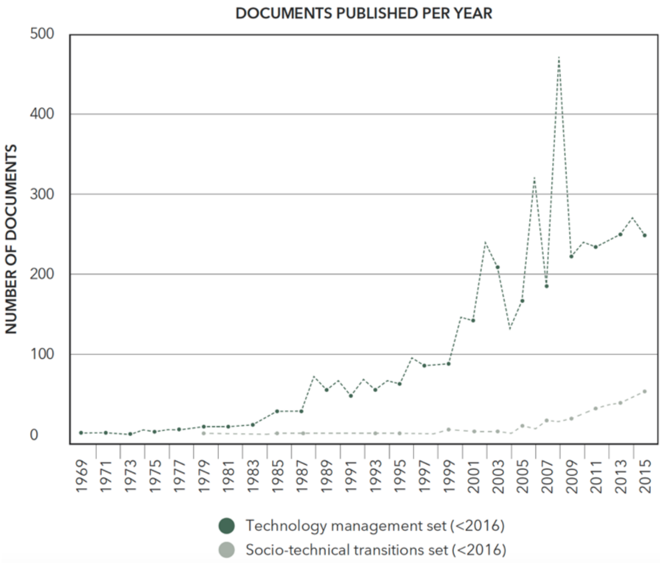


Figure 15. Number of publications per year

The data retrieved form the bibliometric database was subsequently analysed and various elements considered and compared across the two scientific networks. These included contributing authors, keywords, title words, sources of publication, subject areas, modes of publication, and geographical representation.

3.3.2 Key contributing authors

When the authors that contribute to the respective scientific networks are considered, as can be expected, more distinct/unique authors are found in the technology management network than in the socio-technical transitions network (8,087 authors vs. 555 authors). It should be noted that there exist inconsistencies in the metadata found in the bibliographic database. However, these inconsistencies have been addressed as well as possible by reviewing the author metadata and combining the metadata that clearly refers to the same author.

Since the primary objective is to investigate the level of integration and overlap between the two identified scientific networks, the authors that contributed towards the two fields respectively were compared to identify the authors that contributed to both sets of documents. Aside from the three authors that are the authors of the two papers that are in both sets of documents (Dolata, 2013; Wells and Lin, 2015) and excluding the authors De Kock and Brent (2017a; 2017b) that are the only two others that have published articles since the start of 2019 that consider both technology management and socio-technical transitions, there are an additional 33 authors that have contributed to documents in both the technology management and the socio-technical transition sets of documents. These authors are shown in Table 10. Interestingly, four of these authors also feature on the lists of most prominent authors that contribute to either the technology management or socio-technical transition body of literature. These authors are (also highlighted in Table 9 and Table 10):

i. *Prof Ulrich Dolata* (‘Dolata U’ in the tables below), from the University of Stuttgart, Department of Organisational Sociology and Innovation Studies. His key areas of focus include technology, economic sociology and organisation studies, innovation research, technology policy, sociology and political economy of the internet.

ii. *Prof Alan Porter* (‘Porter A.L.’ in the tables below), from Georgia Institute of Technology, School of Public Policy. His key areas of research include science, technology and innovation policy.

iii. *Prof Harald Rohracher* (Rohracher H. in the tables below), from Linköping University, Technology and Social Change and Department of Thematic Studies. His work focuses on a better understanding of the co-evolution of technology and society, as well as strategies to promote socially and environmentally sound technologies, and the consequences of strategies aiming to transition to more sustainable socio-technical systems.

iv. *Prof Peter Wells* (Wells P. in the tables below), from Cardiff Business School. He is a professor of business and sustainability, and the head of logistics and operations management sections. His research focuses on alternative local economies, automotive industry, celebrities, wealth and sustainability, corporate strategy, government transport and environment policy, mobility, sustainable business models and transitions to sustainability.

The most prominent authors in the respective scientific networks, in terms of the number of documents that each author contributed towards, are shown in Table 9 and Table 10.

Table 9. Authors that contributed to both scientific networks

AUTHORS THAT CONTRIBUTED TO BOTH BODIES OF LITERATURE					
Bock T.	Dolata U.*	Li Y.	Nam Y.	Rickne A.	Thissen W.
Chang K.-C.	Goulding J.	Lin X.*	Park J.	Rohracher H.	Wang C.-H.
Chang R.	Ho J.C.	Lin Y.-C.	Park S.	Rossini F.A.	Wells P.*
Cooke P.	Kim J.	Liu W.	Phillips F.	Schiavone F.	Yuan J.
Cresswell A.M.	Kim T.	Magnusson T.	Porter A.L.	Smith A.	Zhang J.
De Bruijn E.J.	Lee S.	Martin H.	Rees J.	Taylor R.	Zhao Z.

* Authors that contributed to the two papers that form part of both sets of documents

Table 10. Most prominent authors (number of documents)

SOCIO-TECHNICAL TRANSITION SET OF DOCUMENTS		TECHNOLOGY MANAGEMENT SET OF DOCUMENTS	
AUTHORS	NUMBER OF DOCUMENTS	AUTHORS	NUMBER OF DOCUMENTS
Geels, F.W.**	8	Probert, D	47
Smith, A.	8	Phaal, R.	41
Rohracher, H.	5	Farrukh, C.	24
Shin, D.H.	5	Daim, T.U.	21
Truffer, B.	5	Kocaoglu, D.F.	17
Voβ, J.P.	5	Pantano, E.	17
Wells, P.	5	Berg, D.	16
Bolton, R.	4	Garcia, R.	15
Dolata, U.	4	Brent, A.C.	14
Lopolito, A.	4	Schuc, G.	14
Markard, J.	4	Porter, A.L.	13
Morone, P.	4	Pretorius, L.	13
Morone, P.	4	Walsh	13
Newman, M.	4	Cunningham, S.W.	12
Papachristos, G.	4	Einspruch, N.G.	11
Seyfang, G.	4	Granstrand, O.	11
Upham, P.	4	Jun, S.	10
Berkhout, F	4	Subhan, A.	10

** Frank Geels is a prominent researcher and published author in the area of socio-technical transitions and has published a significantly larger number of documents in the timeframe considered. And, for that reason, it is important to highlight the scope and focus area of this bibliometric analysis. Within the search conducted (i.e. with a specific focus on socio-technical transitions and technology management, and as shown in Table 10, 8 documents authored by Geels was identified. However, during the timeframe of the search, Geels published 63 articles. In order to ensure that the search did bring to the fore the documents that is relevant to this study, the 63 articles were investigated. Of the 63 documents, 14 are books and 2 are editorials. These types of publications in Scopus typically do not have abstracts and keywords - an acknowledged drawback of the bibliometric data retrieved from such databases. In these 16 documents, of which only the titles are available in Scopus, none of them hold socio-technical transitions or related search terms. Of the remailing 47 documents, we searched for ‘transitions’, and 18 of these did not contain the word ‘transitions’ in the title, abstract or keywords – which then automatically means that it does not contain the search terms socio-technical transitions. Of the remaining 29 documents, 8 is concerned with technological transitions and does not contain the necessary search terms, 7 is not concerned with socio-technical perspectives per se even though it does mention ‘transitions’ in the title, abstract or keyword and is thus included in this set of 29 documents. Then there are the 8 documents that are concerned with socio-technical transitions and had socio-technical transitions or related search terms in the title, keywords or abstract (i.e. the 8 that is included in the bibliometric analysis and shown in in Table 10). The remaining 6 documents do not hold socio-technical transitions or related search terms in their keywords, titles or abstracts even though they are, some just broadly, concerned with socio-technical transitions. Again, arguably one of the known caveats of searching for documents using search terms. However, it is argued that given the aim of the research, that an article that is concerned with socio-technical transitions, but does not highlight the term in the title, keyword or abstract will likely not be concerned with the constructs and conceptual framings of the discipline. Furthermore, these fields of knowledge are dynamic and in continuous flux, and it is necessary to demarcate the temporal boundary of the study, to enable the analysis.

Table 11 and Table 12 show the most cited documents in the socio-technical transitions and technology management sets respectively. As is expected, the overlap in terms of authors, focus areas, and sources of publication, are limited to the extent that the only indication of overlap, in terms of these most cited documents in the respective bodies of knowledge, is that there are documents in both sets that are concerned with innovation, i.e. the works of Smith *et al*. (2010), Markard and Truffer (2008), Enkel *et al*. (2009) and Gann and Salter (2000) – however, these research efforts focus on different aspects of innovation in terms of the context as well as level and unit of analysis.

Table 11. Most cited documents in the socio-technical transitions set of documents

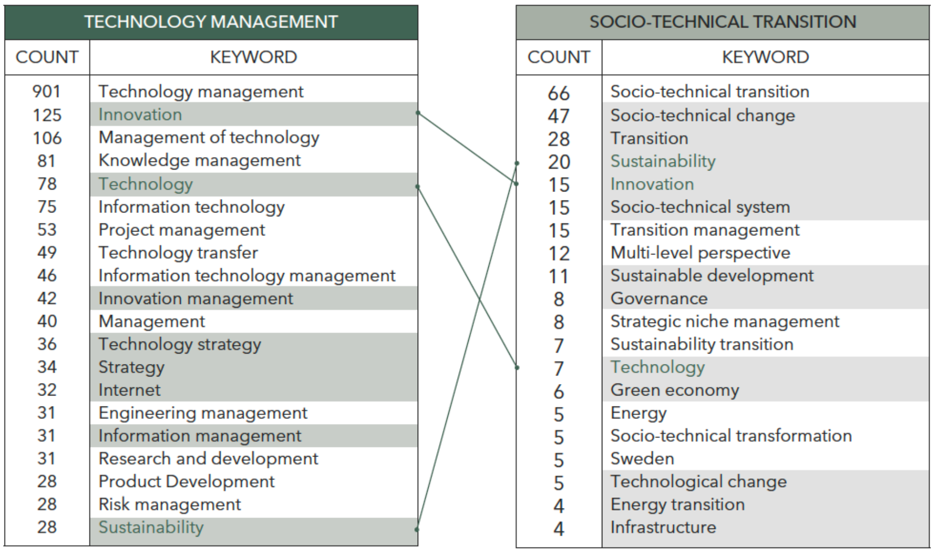
DOCUMENT TITLE	AUTHOR(S)	PUBLICATION YEAR	NUMBER OF CITATIONS
Typology of sociotechnical transition pathways	Geels, F.W., Schot, J.	2007	1,271
The governance of sustainable socio-technical transitions	Smith, A., Stirling, A., Berkhout, F.	2005	773
The multi-level perspective on sustainability transitions: Responses to seven criticisms	Geels, F.W.	2011	507
Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges	Smith, A., VoB, J.P., Grin, J.	2010	491
Technological innovation systems and the multi-level perspective: Towards an integrated framework	Markard, J., Truffer, B.	2008	415
Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective	Geels, F.W.	2010	398
Governing transitions in the sustainability of everyday life	Shove, E., Walker, G.	2010	292
Can cities shape socio-technical transitions and how would we know if they were?	Hodson, M., Marvin, S.	2010	278
What about the politics? Sustainable development, transition management, and long term energy transitions	Meadowcroft, J.	2009	276
Growing grassroots innovations: Exploring the role of community-based initiatives in governing sustainable energy transitions	Seyfang, G., Haxeltine, A.	2012	254

Table 12. Most cited documents in the technology management set of documents

DOCUMENT TITLE	AUTHOR(S)	PUBLICATION YEAR	NUMBER OF CITATIONS
A framework for quality management research and an associated measurement instrument	Flynn, B.B., Schroeder, R.G., Sakakibara, S.	1994	1,097
Examining the Technology Acceptance Model Using Physician Acceptance of Telemedicine Technology	Hu, P.J., Chau, P.Y.K., Liu Sheng, O.R., Tam, K.Y.	1999	886
A comprehensive conceptualization of post-adoptive behaviors associated with information technology enabled work systems	Jasperson, J., Carter, P.E., Zmud, R.W.	2005	738
Knowledge and the firm: Overview	Spender, J.-C., Grant, R.M.	1996	670
Open R&D and open innovation: Exploring the phenomenon	Enkel, E., Gassmann, O., Chesbrough, H.	2009	656
Innovation in project-based, service-enhanced firms: The construction of complex products and systems	Gann, D.M., Salter, A.J.	2000	644
Information technology acceptance by individual professionals: A model comparison approach	Chau, P.Y.K., Hu, P.J.-H.	2001	639
Generic knowledge strategies in the U.S. pharmaceutical industry	Bierly, P., Chakrabarti, A.	1996	523
Technologies of humility: Citizen participation in governing science	Jasanoff, S.	2003	513
Investigating healthcare professionals' decisions to accept telemedicine technology: An empirical test of competing theories	Chau, P.Y.K., Hu, P.J.-H.	2002	487

3.3.3 Keyword analysis

The twenty most frequently used keywords in both the technology management and socio-technical transitions scientific networks are shown in Figure 16. The keywords highlight the strong focus on sustainability and sustainable development within the socio-technical transitions set, whereas the focus of the technology management scientific network is mostly on the management of various subjects, as well as on innovation. The keywords shown in red (innovation, technology and sustainability) are the three keywords that are prominent (in the top 20 most frequently used keywords) in both scientific networks. As can be expected, 'technology' is a much more frequently used keyword in the technology management scientific network, and the same goes for 'sustainability' within the socio-technical transitions network. The fact that 'innovation' is the 2nd and 5th most frequently used keyword within the technology management and socio-technical transitions networks, respectively, indicates that the literature concerned with 'innovation studies' or just 'innovation' is an area where these two bodies of literature overlap. However, the keywords highlighted in grey are keywords that are present within both sets, however not used as frequently (i.e. not in the 20 most frequently used keywords).



TECHNOLOGY MANAGEMENT	
COUNT	KEYWORD
901	Technology management
125	Innovation
106	Management of technology
81	Knowledge management
78	Technology
75	Information technology
53	Project management
49	Technology transfer
46	Information technology management
42	Innovation management
40	Management
36	Technology strategy
34	Strategy
32	Internet
31	Engineering management
31	Information management
31	Research and development
28	Product Development
28	Risk management
28	Sustainability

SOCIO-TECHNICAL TRANSITION	
COUNT	KEYWORD
66	Socio-technical transition
47	Socio-technical change
28	Transition
20	Sustainability
15	Innovation
15	Socio-technical system
15	Transition management
12	Multi-level perspective
11	Sustainable development
8	Governance
8	Strategic niche management
7	Sustainability transition
7	Technology
6	Green economy
5	Energy
5	Socio-technical transformation
5	Sweden
5	Technological change
4	Energy transition
4	Infrastructure

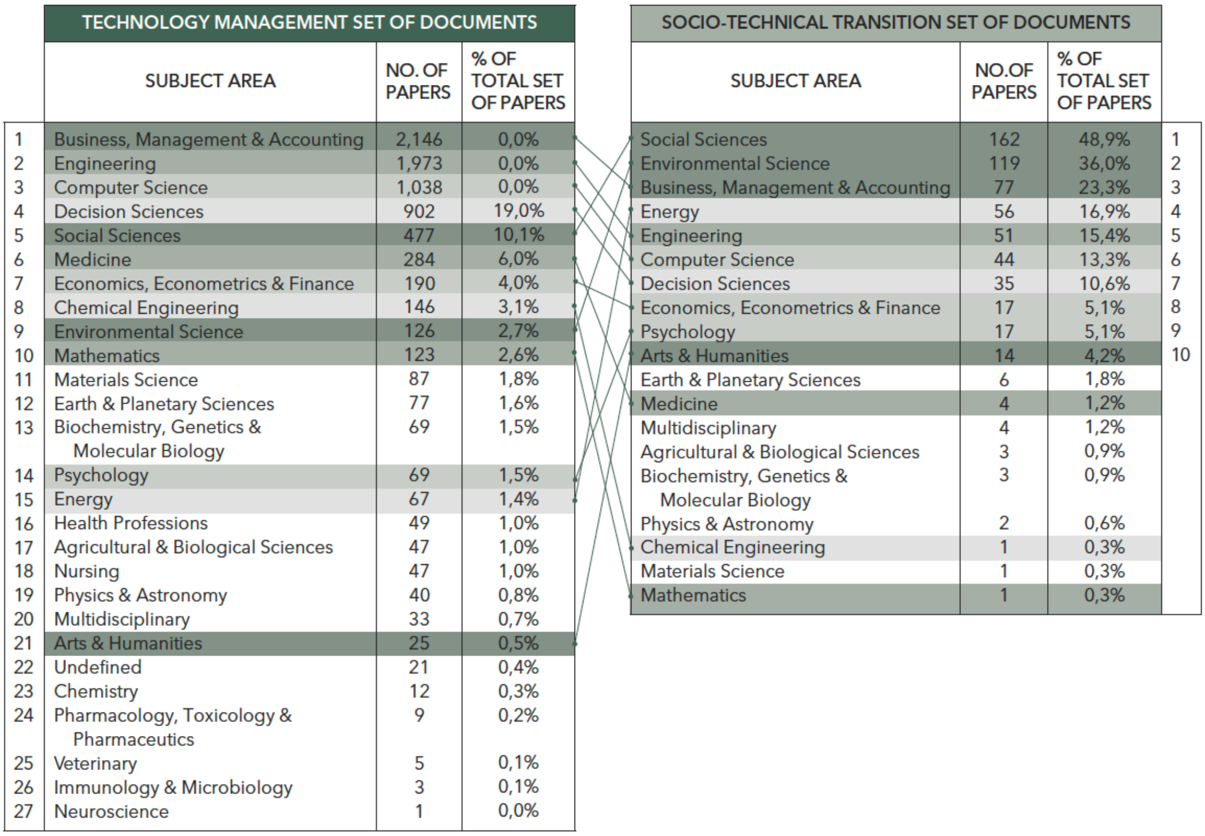
Figure 16. Most frequently used keywords

3.3.4 Sources of publication and subject area

Considering the sources of publication, six journals – Environmental Innovation and Societal Transitions (EIST), Technological Forecasting and Social Change (TFSC), Energy Policy, Research Policy, Environment and Planning, and Technology Analysis and Strategic Management (TASM) – emerged as the leading outlets for documents published on socio-technical transitions (see Figure 54 in Appendix B). The top ten sources of the socio-technical transitions documents account for 31% of the socio-technical transitions network. The six leading sources for technology management documents includes the Portland International Conference on Management of Engineering and Technology (PICMET) proceedings, International Journal of Technology Management (IJTM), IEEE Transactions on Engineering Management, Technovation, IEEE International Engineering Management Conference, and TFSC. The top ten sources of technology management documents account for 18% of the documents within the technology management network. When compared to the 31% of the socio-technical transitions documents published in the top six socio-technical transitions sources, it is clear that technology management literature is published across a wider range of sources, implying that the socio-technical transitions network is at this stage a more concentrated field of research. The only source that is amongst the most prominent sources of publication for both scientific networks is the TFSC journal. The only other journal that is amongst the top twenty sources in both fields is the Technology Analysis and Strategic Management journal. Within the top one hundred sources of both fields, twelve sources are present in both sets, from which one could infer that there is no significant overlap between these two fields of literature when the sources of publication are considered.

The key journals provide an indication of the broader scholarly communities within which technology management and socio-technical transitions are embedded, or to which they are related. It is evident that both fields of literature are trans- and multi-disciplinary. However, the scholarly communities for the respective fields differ quite significantly. These include, for technology management, the management of engineering, science and technology, decision-making or policy formulation for R&D, technological innovation, commercial utilisation of technology, as well as technological forecasting and planning tools for technology management as they relate to society, the environment and technological factors. The focus of the socio-technical transitions document sources includes innovation studies, sustainable development, environmental studies, technological factors, with a specific focus on energy within sustainable development, and policy studies.

From another perspective, the various subject areas that the documents on socio-technical transitions focus on, in comparison with those that the technology management documents focus on, were considered by looking at the percentage of documents that are concerned with any specific subject areas. It should be noted that in most cases documents address more than one subject area. From the analysis shown in Figure 17, it is evident that there exists an overlap in the subject areas that the two scientific networks address. Three of the five most frequently addressed subject areas are present in both fields – these include 'business management and accounting', 'engineering', and 'social sciences'. The most popular subject area addressed in the technology management documents is 'business, management and accounting', but this is the third most frequently addressed subject area in the socio-technical transitions scientific network. In addition, 'engineering', which is the second most frequently cited subject area for technology management, is the fifth most cited subject area for socio-technical transitions. The two most frequently addressed subject areas in the socio-technical transitions set of documents are 'social-sciences' and 'environmental science'. Figure 18 shows the extent of the overlap of subject areas addressed. It can be inferred from this figure that the extent to which the literature concerned with socio-technical transitions has ventured into the subject areas that are ‘traditionally’ considered to be more related to technology management are more extensive than the extent to which the literature concerned with technology management has ventured into subject areas that are ‘traditionally’ considered to be more related to socio-technical transitions.



TECHNOLOGY MANAGEMENT SET OF DOCUMENTS

	SUBJECT AREA	NO. OF PAPERS	% OF TOTAL SET OF PAPERS
1	Business, Management & Accounting	2,146	0,0%
2	Engineering	1,973	0,0%
3	Computer Science	1,038	0,0%
4	Decision Sciences	902	19,0%
5	Social Sciences	477	10,1%
6	Medicine	284	6,0%
7	Economics, Econometrics & Finance	190	4,0%
8	Chemical Engineering	146	3,1%
9	Environmental Science	126	2,7%
10	Mathematics	123	2,6%
11	Materials Science	87	1,8%
12	Earth & Planetary Sciences	77	1,6%
13	Biochemistry, Genetics & Molecular Biology	69	1,5%
14	Psychology	69	1,5%
15	Energy	67	1,4%
16	Health Professions	49	1,0%
17	Agricultural & Biological Sciences	47	1,0%
18	Nursing	47	1,0%
19	Physics & Astronomy	40	0,8%
20	Multidisciplinary	33	0,7%
21	Arts & Humanities	25	0,5%
22	Undefined	21	0,4%
23	Chemistry	12	0,3%
24	Pharmacology, Toxicology & Pharmaceutics	9	0,2%
25	Veterinary	5	0,1%
26	Immunology & Microbiology	3	0,1%
27	Neuroscience	1	0,0%

SOCIO-TECHNICAL TRANSITION SET OF DOCUMENTS

SUBJECT AREA	NO.OF PAPERS	% OF TOTAL SET OF PAPERS	
Social Sciences	162	48,9%	1
Environmental Science	119	36,0%	2
Business, Management & Accounting	77	23,3%	3
Energy	56	16,9%	4
Engineering	51	15,4%	5
Computer Science	44	13,3%	6
Decision Sciences	35	10,6%	7
Economics, Econometrics & Finance	17	5,1%	8
Psychology	17	5,1%	9
Arts & Humanities	14	4,2%	10
Earth & Planetary Sciences	6	1,8%	
Medicine	4	1,2%	
Multidisciplinary	4	1,2%	
Agricultural & Biological Sciences	3	0,9%	
Biochemistry, Genetics & Molecular Biology	3	0,9%	
Physics & Astronomy	2	0,6%	
Chemical Engineering	1	0,3%	
Materials Science	1	0,3%	
Mathematics	1	0,3%	

Figure 17. Subject areas

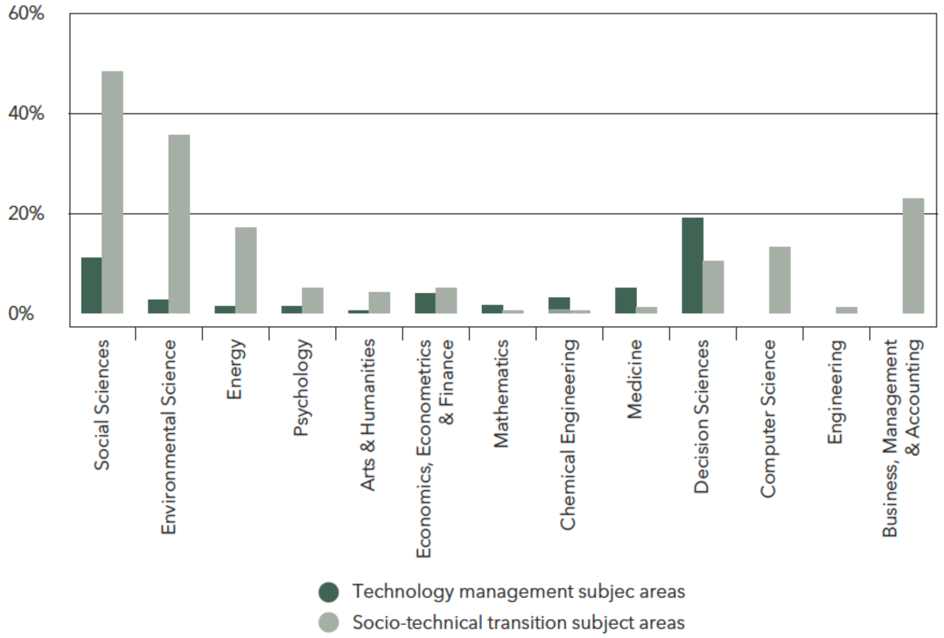


Figure 18. Subject area overlap comparison

3.3.5 Mode of publication

Considering the mode of publication, the two key differences between the two bodies of knowledge are: i) technology management documents are better represented across a wider range of document types, and ii) there is a significant difference in the number of academic conference papers and journal articles published for the two scientific networks respectively. Whereas 71.9% of the documents concerned with socio-technical transitions are published as journal articles, and 12.7% as conference papers, 45% of technology management documents are published as journal articles, and 41.8% as conference papers. This might be attributed to the socio-technical transitions field being relatively new, with the number of conferences that cater for research done on socio-technical transitions not being as established as those of technology management. Interestingly, there is not a significant difference in the percentage of books published between the two fields: 1.2% and 1.7% for socio-technical transitions and technology management respectively. Figure 19 shows the respective modes of publication.

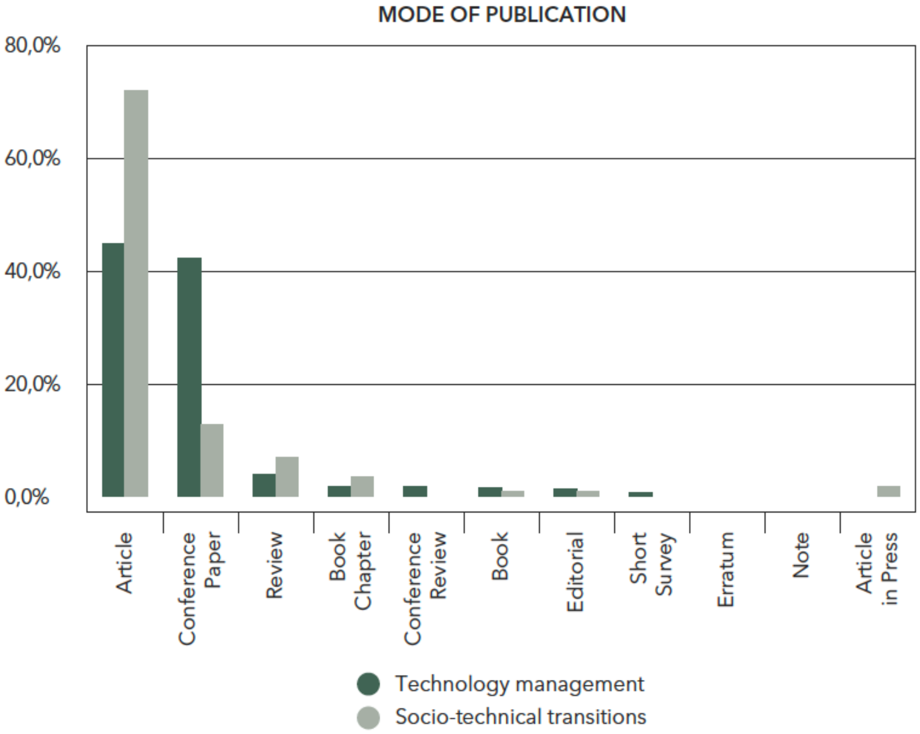


Figure 19. Respective modes of publication

3.3.6 Geographical representation

In geographical terms, the top five countries with research competency in the technology management field are the United States (US), the United Kingdom (UK), China, Japan and Germany. As a single country, it is notable that the US leads the others with more than a quarter of the documents within the technology management scientific network having an affiliation with the US. When all European countries are considered together, the research competency within Europe is equivalent to that of the US for technology management. When the research competency per country for the socio-technical transitions network is considered, the UK as a single country leads the others, with a quarter of the documents within the socio-technical transition network having affiliations with the UK. When all countries are considered, more than

67% of the documents within the socio-technical transitions network have a European affiliation, with only 3.8% of documents within this network having affiliations with BRICS[14] countries. This reinforces the statement made by Lachman (2013) who argues that the approaches that have been developed to study socio-technical transitions are heavily flavored by the context of developed countries – the environment within which they were developed, and thus might be less suitable for contexts such as developing countries. In addition, Tigabu *et al*. (2013) argue that most research concerned with a concept strongly related to socio-technical transitions – technological innovation systems (TIS) – as well as transitions in a more general sense was conducted in highly developed countries, and the applicability of approaches such as TIS to developing countries is still unclear. Markard *et al*. (2012) also added to these arguments by stating that there is a clear "European bias" in the current state of the socio-technical transitions field, which is to be expected, given the location of the researchers contributing to this field of research. Table 13 shows the geographical representation within the respective scientific networks.

Table 13. Geographical representation within the respective scientific networks

TECHNOLOGY MANAGEMENT SET OF DOCUMENTS		SOCIO-TECHNICAL TRANSITION SET OF DOCUMENTS	
GEOGRAPHICAL AREA	% OF DOCUMENTS	GEOGRAPHICAL AREA	% OF DOCUMENTS
United States (US)	26,0%	United Kingdom	25,0%
United Kingdom (UK)	6,0%	United States	12,0%
China	5,0%	Netherlands	11,0%
Japan	4,0%	Germany	6,0%
Germany	4,0%	Sweden	5,0%
Combined for European countries	25,8%	Combined for European countries	67,4%
BRICS countries	12,4%	BRICS countries	3,8%

3.4 Discussion

The bibliometric analysis highlights the most prominent areas of overlap, although limited, between the technology management and socio-technical transitions' bodies of literature. An overlap of two documents was found between the two bodies of literature (i.e. the work of Dolata (2013) and Wells and Lin (2015); the first quantitative indication that there exists a disconnect between these two bodies of literature. These two documents found in both sets of literature focus on the changes in socio-economic structures, institutions and actors under the influence of technology, and how they react to technology-induced pressures to change, and processes of change outside of the traditional context of technology policy and management respectively – highlighting that both consider technology within the context of change in socio-technical systems, but do not consider the integration or overlap of technology management and socio-technical transitions per se.

It was found that 36 unique authors (out of a possible 8,633) contribute to both bodies of literature, indicating that a small number (0.004%) of authors conduct research that is applicable to both bodies of literature.

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[14] BRICS is the terms / acronym for an association of five major emerging economies: Brazil, Russia, India, China and South Africa.

Interestingly, four out of the 36 unique authors that contribute towards both bodies of literature, are also present in the most prominent authors in terms of number of documents contributed to the two respective bodies of literature (refer to Table 9 and Table 10). When considering the focus areas of these authors, it is clear that their areas of research are in line with the areas of overlap found in the bibliometric analysis, namely: technology, innovation and sustainability. Other areas prominent in the research of these researchers, that are not noticeable from the bibliometric analysis, but evident from the linkage analysis performed and discussed in the subsequent chapter, is the focus on economics and policy.

From the keyword analysis it is evident that the three areas where the technology management and socio-technical transitions bodies of literature overlap are the areas of innovation, technology and sustainability. However, the prominences of these three areas in the respective fields differ. For example, sustainability is the fourth most prominent keyword in the socio-technical transitions body of literature, but only the twentieth most prominent keyword in the technology management body of literature. Technology is ranked higher in prominence in the technology management body of literature (fifth) while it ranks thirteenth in the socio-technical transitions body of literature. The keyword analysis indicates that innovation is an area that ranks relatively high in both bodies of literature, second for the technology management body of knowledge, and fifth for the socio-technical transitions body of literature, and is thus considered to represent the most significant overlap.

The only two sources of publication that are prominent sources of publication in both bodies of literature are TFSC[15] and TASM[16]. TFSC focuses on technological forecasting and future studies as planning tools since they interrelate social, environmental and technological factors. The focus of TASM is on linking the analysis of science, technology and innovation with the strategic needs of policymakers and management. Here it is evident that both technology management and socio-technical transition scholars, in addition to what has already been highlighted as overlaps between the two bodies of knowledge, engage in inter-, trans- and multidisciplinary research, with a strong focus on the role of technology in strategy and policy. This highlights the difference, generally speaking, in the level and unit of analysis of these two bodies of literature.

Given the nature of both technology management and socio-technical transitions – the inter-, trans- and multidisciplinary nature of both these disciplines – it is unsurprising that there is a seemingly significant overlap in the subject areas that are addressed. However, there is a difference in the order of prominence, in terms of the number of papers that are concerned with the subject areas. Business, management and accounting, social sciences, and engineering are among the top five subject areas for both bodies of literature; environmental science is the second most prominent in the socio-technical transitions body of literature, but only the ninth most prominent in the technology management body of literature – which is in line with the findings of De Kock & Brent (2017b) that technology management to date has not sufficiently veered into the realm of dealing with environmental challenges. From the analysis of the subject areas, and the overlap

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[15] https://www.journals.elsevier.com/technological-forecasting-and-social-change

[16] https://www.tandfonline.com/loi/ctas20

in such areas, it is then inferred that the extent to which the literature concerned with socio-technical transitions has ventured into the subject areas that are 'traditionally' considered to be more related to technology management, are more extensive than the extent to which the literature concerned with technology management has ventured into subject areas that are 'traditionally' considered to be more related to socio-technical transitions (see Figure 18).

When the geographical representation of the two bodies of literature is considered, it is clear that both disciplines are strongly linked with North American and European countries, with significantly less representation in countries with developing or emerging economies. A number of researchers (Markard, Raven and Truffer, 2012; Lachman, 2013; Tigabu, Berkhout and van Beukering, 2013) have raised concerns about the lack of representation in the research on issues such as socio-technical transitions and technology management from a non-western perspective – from which the applicability of developed concepts for other contexts are often brought into question.

3.5 Conclusion: Chapter 3

In this chapter, a bibliometric analysis is used to elucidate the seeming disconnect that exists between the literature pertaining to socio-technical transitions and technology management respectively. Throughout this chapter, a number of areas of overlap are identified. However, the only key areas of overlap that emerged from this analysis is that of innovation, and to a lesser extent sustainability and the focus on technology. Yet, no concrete evidence of integration or significant similarity in foundational concepts used in both bodies of literature is evident.

Even though there exists a disconnect between the two bodies of literature studied in this chapter, when turning to the technology management literature, there is a rising interest and sense of urgency to manage technology within the context of sustainable development (Brent and Pretorius, 2008; Jovanovic *et al.*, 2019). The requirement is for technology management frameworks and constructs to provide approaches that will support the implementation and improved decision-making in terms of technology, and the management thereof, of 'sustainable' technologies that can support the societal and environmental needs of societies (Philbin, 2013). However, as elucidated through the bibliometric analysis, technology management has not yet been integrated beyond broad themes (i.e. innovation, sustainability and technology) with socio-technical transitions. This is highlighted as a key area where future research should focus as socio-technical transitions are what is required for systems like energy, transport and agro-processing if sustainable futures are to be realised.

Further, although highlighting distinctions of frameworks and constructs that form part of the bodies of literature was not a key focus of the research effort presented in this chapter, it is acknowledge that such distinctions manifest more clearly for the socio-technical transitions body of literature (i.e. strategic niche management and multi-level perspective) than the distinctions in the technology management body of literature. However, the fact that these distinctions did not emerge in the bibliometric analysis serves as further motivation to conduct a linkage analysis to elucidate if, when further distinctions are considered at an increased level of granularity, new or alternative conclusions can be drawn about the nature and level of integration that exists between technology management and socio-technical transitions.

Although the results presented in this chapter may seem limited, it is argued that this in itself is of value in that the extent to which the overlap exists has not been 'quantified' up to now, and it is now evident that there exists a disconnect in the academic literature, and that we have clarity on where the overlaps, albeit limited and unsurprising, exist. These findings then also serve as motivation that, in order to better articulate the level of integration in terms of conceptual framings and intellectual roots, a further analysis is necessary.

It is thus proposed that the investigation into the (dis)connection between the bodies of literature pertaining to socio-technical transitions be enriched by a systematic, in-depth exploration of the literature bases (i.e. references used by the respective bodies of literature) in order to further insights into the concepts that underpin the respective fields of research. And to, ultimately, confirm or refute the highlighted disconnect that exists between socio-technical transitions and technology management

Chapter 4.

Exploring the (dis)connection between the bodies of literature pertaining to socio-technical transitions and technology management (Part B): A linkage analysis

The bibliometric analysis presented in Part A (Chapter 3) of this two-part investigation, considered 331 documents resulting from a keyword search focused on socio-technical transitions, and 4,740 documents resulting from a keyword search focused on technology management (see Table 6 and Table 7 in Chapter 3) - it emerged that only two documents are present in both sets of documents. Therefore, in order to further investigate the areas where the two concerned bodies of literature overlap and possibly integrate, this chapter explores the linkages between the socio-technical transitions and technology management bodies of literature, based on the references used by each set of documents (given the data sets extracted as shown in Table 8 and as described in Chapter 3), to elucidate the level of integration that exists between these two bodies of literature.

4.1 Introduction: Linkage analysis

Technology plays an undisputed role in the quest for sustainable development and the technology and innovation management literature provides many concepts that are central to understanding the role of technology for sustainable business development (Wagner, Bachor and Ngai, 2014), and the importance of technology management within the context of sustainable development has been argued in literature (Brent and Pretorius, 2008). Recently, scholars have argued the importance of not only understanding technology management within the context of sustainable development, but also the importance of integrating the concepts of technology management and socio-technical or sustainability transitions (De Kock and Brent, 2017a, 2017b). However, the bibliometric analysis conducted in Chapter 3, which compared the respective bodies of literature that pertains to technology management and socio-technical transitions, found "no concrete evidence of integration or significant similarity in foundational concepts used in both bodies of literature". It is thus proposed that the bibliometric analysis and subsequent findings be enriched with a systematic and in-depth assessment of the literature bases (i.e. references used by the respective bodies of literature) to further clarify the level of integration and overlap that exists between technology management and socio-technical transitions literature, in order to ultimately provide for the starting point for the development of an integration strategy between technology management an sustainability transitions.

4.2 Methodology: Linkage analysis

The methodology followed in the two-part investigation into the disconnect that exists between technology management and socio-technical transitions is showed in Figure 14. As mentioned above, a bibliometric analysis was conducted in Part A and included two phases; Part B deals with the linkage analysis (LA) and includes five phases. Similar approaches, to evaluate the landscape, overlap and integration of bodies of literature have been used throughout literature (Klavans and Boyack, 2006; Sakata *et al*., 2013; Chappin and Ligtvoet, 2014; Ittipanuvat *et al*., 2014). The remainder of this chapter this focuses on the LA, and the remainder of this section focuses on the LA methodology.

4.2.1 Linkage analysis method

For all the documents that were extracted and used in Part A (see Chapter 3), only two documents[17] formed part of the combined search (see Table 8). Thus, in order to evaluate the level of overlap and integration between the two sets of literature, the references associated with both scientific networks were evaluated to identify references in documents in both the technology management and socio-technical transitions scientific networks. The linkage used in this research inquiry refers to the cross-network method that is applied to reveal the linkage between the two scientific networks.

Due to the fact that only two documents fall within both data sets, the references used in the socio-technical transitions and technology management documents respectively were compared with the aim of identifying the references that are used in both scientific networks. Thus, the two datasets exported form Scopus (containing 331 documents and a resulting 17,445 references in the socio-technical transitions network, and 4,740 documents and a resulting 112,498 references in the technology management network)[18] were used in the LA.

The input data for the linkage analysis was exported from the Scopus website, using the .txt output format. Each ‘Entry’ (i.e. document resulting from the search) in the input file has a title, author list and bibliography list. Each bibliography list contains multiple items, referred to here as ‘References’. The comparison of the datasets was done in two separate exercises, both comparing the references found in each dataset with the references found in the other dataset with the aim of achieving two respective outputs:

i. A list of references from the technology management set of documents that are also present in the socio-technical transitions set of documents; and
ii. A list of references from the socio-technical transitions set of documents that are also present in the technology management set of documents.

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[17] Two documents that are present in both the TM and STT primary document sets are: *Spontaneous emergence versus technology management in sustainable mobility transitions: Electric bicycles in China* (Wells and Lin, 2015), and *The transformative capacity of new technologies* (Dolata, 2013).

[18] It should be noted that during the during the linkage analysis programming, each reference was given a unique identifier; thus should two or more documents in either one of the scientific networks cite the same document, this document would have a number of unique identifiers (equal to the number of documents within the primary document sets that cite that specific reference). However, this duplication was accounted for in LA phase 5.

Ultimately, the two lists referred to above are used in Section 4.3 to identify and highlight the level of integration and overlap between the two sets of documents. In order to perform the LA, the datasets extracted from Scopus were used in a process that included four steps (LA Phases 1 – 4), which are described below.

4.2.2 LA Phase 1: Data pre-processing

This phase primarily entailed the sanitation of the data sets (References (*R*) in the bibliography list. For each reference in the respective data sets, the following operations were performed:

1. i. Normalisation of references (correction heuristic). After the normalisation process, all that remains is the title of the reference, and any additional (nonsense) text that was not removed by the heuristic. This included:
    - a. Conversion of all text (reference strings) to lowercase;
    - b. Converting unicode to ASCII[19];
    - c. Replace all foreign glyphs with the nearest Roman equivalent or remove;
    - d. Remove all author and publication metadata;
    - e. Remove all common abbreviations;
    - f. Remove all punctuation and redundant whitespaces; and
    - g. Remove all URLs, dates and page numbers.
2. ii. Combine all references (R) of an entry (E) with whitespaces (i.e. $R_E^1 = R_1 + R_2 + \cdots$).
3. iii. Repeat process in step 1 and 2 for the second set of references.

Following the normalisation and combining of the references in both data sets (the data sets represents the references from the two scientific networks respectively), is the similarity calculation phase. The aim is to determine how likely a combined *Reference* (*R*) (i.e. the output from steps ii. and iii. above) of an Entry i (i.e. $\mathrm{R_E^i}$) from the technology management set of references is to contain a single reference from the socio-technical transitions of references, and vice versa.

The edit distance algorithm[20] was used during the similarity calculations. This algorithm found the best match for the references in the first set of references within the second set of references, and vice versa. The maximum value for the edit distance would be achieved if one had to insert a completely new reference into the reference list of the entry's references against which the reference is compared. Thus, the value would be equal to the length of the reference string. Consequently, we calculate the similarity coefficient as being $\frac{e}{N}$, where N is the length of the string and *e* is the edit distance of the string.

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[19] ASCII, abbreviated from American Standard Code for Information Interchange, is a character encoding standard. ASCII codes represent text in computers, telecommunications equipment, and other devices. http://www.asciitable.com/.

[20] In computer science, edit distance is a way of quantifying how dissimilar two strings (e.g., words) are to one another by counting the minimum number of operations required to transform one string into the other. (Skiena, 1997. The Algorithm Design Manual, Springer, New York.)

4.2.3 LA Phase 2: Similarity calculation

The similarity calculation phase consisted of two steps. First, a core algorithm was applied to measure the likelihood of an *Entry (E)* to contain a bibliography item, thus *Reference (R),* since the references cannot be directly matched. The second step of LA Phase 2 is the higher-level operation that yields the similarity value (v) that indicates how likely it is that an edit operation has a reference to each reference.

LA Phase 2a: Core algorithm

For the purpose of this study a measure of how likely an *Entry (E)* contains a bibliography item, thus *Reference (R),* was needed. Since the references cannot be directly matched (due to the discrepancies in the format, spelling etc. between references), a modified edit distance algorithm was used as the core algorithm. The edit distance algorithm yields the number of edit operations (insertion, deletion or substitution) necessary to ensure that E contains R. The maximum value of the edit distance is reached when the whole text of R must be inserted into E. And therefore, the similarity value $V = \frac{e}{|R|}$, where e is the number of edit operations.

LA Phase 2b: Higher-level operation

During this phase, the similarity value (v) was calculated. In order to calculate v:

$$\text{Let } E_1 = \text{the first set of entries; and}$$
$$\text{Let } E_2 = \text{the second set of entries.}$$

Then each $e \in E_i$ has a set of references (bibliography entries), R_e. Taking a higher-level view, the objective is then to know for each $e \in E_1$ all $q \in E_2$ that have an overlapping bibliography entry within it. Thus, in set notation, for each $e \in E_1$:

$$Q \ = \{q | (q \in E_2 \ and \ q's \ \ references \ overlap \ with \ e's \ )\}$$

To determine this, each reference Rq was taken from some $q \in E_2$ and compared against the full bibliography text of some $e \in E_1$. This yields a similarity value (v) that indicates how likely e has a reference to Rq.

4.2.4 LA Phase 3: Threshold filtering

This phase filtered out q's based on their similarity values, v's. If v is less than the threshold then q is not included in Q.

To summarise, the process described in LA phases 1 – 3 essentially compares all references (referred to as $R_{TM}1$, $R_{TM}2$, $R_{TM}3$, and so forth in Figure 20) resulting from a document (referred to as 'TM Entry 1' in Figure 20) in the technology management scientific network with the references resulting from all the documents in the socio-technical transitions scientific network (referred to as $R_{STT}1$, $R_{STT}2$, $R_{STT}3$, and so forth in Figure 20) to ultimately establish the similarity between each reference within the technology management network and the references within the socio-technical transition scientific network, and vice versa. The key objective, as stated, is to determine which references are used, and if so, the frequency of use, in both scientific networks concerned. Due to the significant inconsistencies found in the bibliographic data extracted from Scopus, a similarity calculation was used to determine which references are present in the scientific networks, since a direct comparison is not possible as a result of the said inconsistent documentation of references. Comparing the datasets 'as-is' would yield a far lower number of references, as a large number of references are not cited correctly and/or the same.

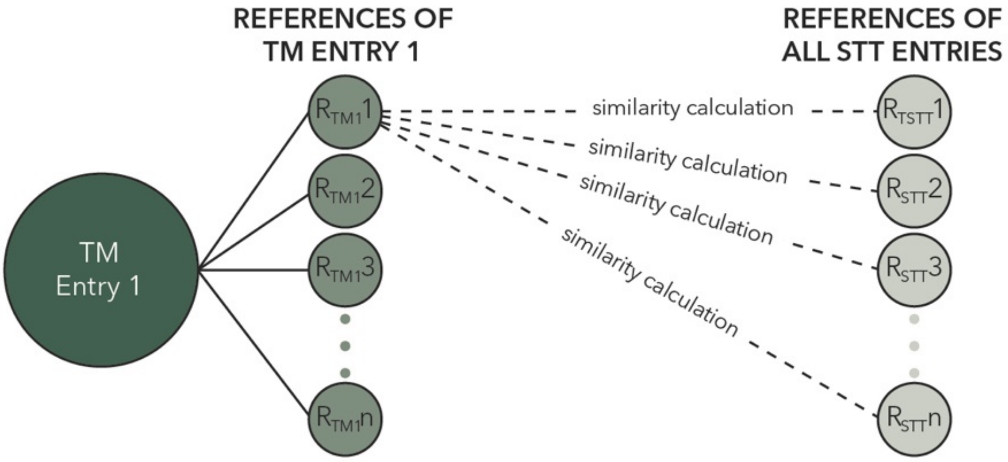

Figure 20. Schematic representation of similarity calculation process

4.2.5 LA Phase 4: Data analysis

The results from LA Phases 1 – 3 yielded an excess of 3,9 billion data entries, namely: the total number of similarity comparisons that were performed when comparing all references from the two scientific networks[21]. An entry being a line item showing the document (*Entry*) from the first set of documents, the document (*Entry*) from the second set of entries (whose references were compared with that of the first set of entries), and the references of the second set that has a similarity to the references of the first set. Similarly, the output from the second set of entries, the document from the first set of entries whose references are, in-turn, being compared with that of the second set of entries, and the references of the first set that has a similarity to the references of the second set. Each reference (in both sets one and two) is given a unique identifier at the start of LA Phase 1. This means that references that are the same will have different unique identifiers. However, the duplication does not influence the final results as care was taken not to include duplicated values. However, the duplication of the references found in each set that evaluated the similarity between the references used in the two document sets was analysed as this indicated the frequency of the reference within the scientific network of that specific *Entry*.

In LA Phase 4 the similarity results, namely the percentage similarity between two references, were evaluated. With the vast inconsistencies between the referencing styles and information included in the close to 130,000 references that were used in this research inquiry, a 75% or more similarity between two references deemed two such references as the same reference. However, there are references with a 75% similarity that, upon further investigation, is not the same reference. In addition, the primary aim of the

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[21] In order to assess the similarity between the references in both datasets, each of the 17,445 STT references are compared with each of the 112,498 TM references, thus (17,445 x 112,498) comparisons resulting in 1,962,527,610 data entries. Similarly, the opposite comparison (i.e. 112,498 TM references compared with 17,445 STT references) result in the same number of data entries; therefore, a total of 3,925,055,220 similarity comparison data entries.

research inquiry is to identify and evaluate the overlap and integration of these two bodies of knowledge, and this will not have a significant impact on the results. Furthermore, in the final set of results (Table 71 in Appendix C) each reference was checked against the raw reference data and corrected if required to ensure the correct number of occurrences are reported.

4.2.6 LA Phase 5: Results

The output from LA phases 1 – 4 were two data sets:

i. A dataset containing all the TM references that are also present in the STT scientific network (thus all TM references that are shown in this dataset has a minimum similarity of 75% with at least one STT reference). This data set also shows the number of times or frequency that each TM reference with a similarity score of at least 75% occurs in the STT scientific network. In addition, the frequency of the occurrence of the TM reference within the TM dataset is also shown.
ii. Similarly, a dataset containing all the STT references that are also present in the TM scientific network (thus all STT references that are shown in this dataset has a minimum similarity of 75% with at least one TM reference). This data set also shows the number of times or frequency that each STT reference with a similarity score of at least 75% occurs in the TM scientific network. In addition, the frequency of the occurrence of the STT reference within the STT dataset is also shown.

The output was subsequently analysed in order to identify the areas (based on the similarity in references used by both the technology management and socio-technical transitions' scientific networks) where (significant) overlap(s) occur. Three different 'overlaps' between the TM references and the STT references were considered:

i. The most prominent references in both data sets[22] (i.e. in the data sets where an overlap has already been identified (the two data sets described above). This included:
    a. The top 50% most prominent STT references that are also a TM reference; and
    b. The top 50% most prominent TM references that are also an STT reference.
ii. References with at least ten instances/occurrences within both data sets.
iii. References with at least an occurrence of 10 in the one dataset, and 5 in the other:
    a. A reference with an occurrence/instance of 10 in the TM dataset and an occurrence/instance of 5 in the STT dataset; and
    b. A reference with an occurrence/instance of 10 in the STT dataset and an occurrence/instance of 5 in the TM dataset.

The three different sets of overlaps set out above provide the titles of references that occur in both the TM and STT datasets with varying number of instances or frequencies that each reference occurs in each scientific network.

From the above results, which essentially entail the articles that cite the same references – thus, the articles from which the references are present in both the TM and STT datasets – a dataset containing the articles

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[22] Refers to the datasets that has already established an overlap (i.e. thus the output datasets described above with an acceptable similarity score as discussed in LA Step 4: Data analysis) between the two scientific datasets concerned.

that draw from the same theoretical foundations (in other words: use the same references) was compiled. This set of articles is subsequently evaluated and discussed in Section 4.3. In addition, this is also used to expand the set of articles that can be used to evaluate the overlap between the technology management and socio-technical transitions bodies of literature, in other words expand on the set of two identified documents in Table 8.

4.3 Linkage analysis: Results and analysis

This section explores the linkages between the socio-technical transitions and technology management bodies of literature, based on the references used by each set of documents (given the data sets extracted as described in Section 4.2), to elucidate the level of integration and overlap that exists between these two bodies of literature, and to what extent these two bodies of literature share intellectual roots.

4.3.1 Linkage analysis results

The results of the various phases of the linkage analysis are outlined below. Table 14 and Table 15 show the references of the 4,740 technology management documents and the 331 socio-technical transitions documents respectively that has a similarity score of 75% and above (refer to Step 2: Linkage analysis in Section 4.2).

4.3.1.1 Data pre-processing outcome

The respective sets of references were normalised (see Section 4.2, LA Phase 1: Data pre-processing for the approach) in order to have two datasets that only show the title of the references. Each document, as well as each reference in each of the two sets, were given unique identifiers (within each set). Essentially, each dataset contains the unique number for the entry, with the corresponding numbers for the references associated with each entry and the title of each reference. The titles are used in the similarity calculation.

4.3.1.2 Similarity calculation outcome

The outcome of the similarity calculation phase is a data set showing the similarity scores. Thus, the similarity score of all references in the technology management set of documents are calculated, enabling the identification of all references associated with the technology management documents (*Entries*) that have a similarity score of 75% or more with references associated with the socio-technical transitions set of documents. As mentioned in Section 4.2, references with a similarity score of 75% or higher are considered to also be included in the set with which it is compared. Similarly, the references associated with the socio-technical set of documents with a similarity score of at least 75%, and thus that are also present in the set of references associated with the technology management set of documents, are identified.

Table 14 and Table 15 show a summary of the results. Here it is important to again note that each reference in each document was given a unique identifier. Thus, if the same reference (*R*) is cited by a number of *Entries* (*E*) the specific reference is counted in each instance where the similarity score is 75% or higher. When Table 8 is considered, 112,498 references are present in the technology management data set, and a large number of these references are cited by more than one of the technology management documents (*Entries*). This is not considered as a concern as both the frequency of documents that overlap as well as the content and/or focus of the references that overlap is of interest here. This is just highlighted in order to note the fact that the number of references that are found to be present in both data sets does not necessarily indicate the number of unique references (the identification of the unique references was dealt with separately).

Table 14. Similarity results yielded from similarity calculations for socio-technical transition (STT) references (R)

STT DOCUMENTS & REFERENCES COMPARED TO TM REFERENCES	100% SIMILARITY	90% - 99,99% SIMILARITY	80% - 89,99% SIMILARITY	75% - 79,99% SIMILARITY
STT references	1,820	1,993	1,719	1,066
Number of occurrences	6,395	6,403	9,580	5,803

Table 15. Similarity results yielded from similarity calculations for technology management (TM) references (R)

TM DOCUMENTS & REFERENCES COMPARED TO STT REFERENCES	100% SIMILARITY	90% - 99,99% SIMILARITY	80% - 89,99% SIMILARITY	75% - 79,99% SIMILARITY
TM references	3,080	2,922	3,393	2,811
Number of occurrences	19,305	7,270	12,446	15,257

Table 16 shows an example of the results yielded by considering which references found within the technology management set of documents that overlaps with references found in the socio-technical transitions set of documents. The example shown in Table 16 essentially means that the article by Geels (2002), '*Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study'*, is cited by five documents in the technology management set of documents, and cited by 122 documents in the socio-technical transitions set of documents. Similarly, the data on the overlap of references cited by the socio-technical set of documents that are also cited by documents in the technology management set are identified.

Table 16. Example of output from the similarity calculations

NORMALISED TITLE OF REFERENCE (NORMALISED DURING STEP I OF LA PHASE 1)	UNIQUE IDENTIFIER OF 'TM REFERENCE'	NUMBER OF DOCUMENTS IN THE STT SET OF DOCUMENTS THAT ALSO CITE THIS REFERENCE
technological transitions as evolutionary reconfiguration processes a multi level perspective and a case study	81092	122
	111781	122
	42219	122
	69636	122

Subsequent to the data gathered from the results of the similarity analysis, a further analysis was done on the results (the two data sets described above as well as in the first part of LA Phase 5), to retrieve a list of references that adheres to the criteria set out in the second part of LA Phase 5, i.e. (i) the most prominent references in both data sets, (ii) references with at least ten instances / occurrences within both data sets, and (iii) references with at least an occurrences of 10 in the one dataset, and 5 in the other. The outcome from this analysis is shown in Table 71 in Appendix C. By applying the set of criteria outlined above, a set of 119 references is yielded. These 119 references appear 3,557 times as a reference used by documents in the technology management set of documents, and 1,538 times as references in the socio-technical transitions set of documents.

As mentioned, the analysis yielded 119 references (Table 71 in Appendix C). Table 17 shows a summary of the different overlaps considered, as well as the corresponding number of articles found in each overlap group, and the number of articles that overlap between these groups (refer to the matrix shown in Table 17 on the right).

Table 17. References overlap 'groups'

NUMBER OF REFERENCES PER GROUP	
OVERLAP 'GROUP'	NUMBER OF REFERENCES
Most prominent STT references	32
Most prominent TM references	87
10 TM references & 10 STT references	15
10 TM references and 5 STT references	30
10 STT references and 5 TM references	21

NUMBER OF REFERENCES OVERLAPPING BETWEEN GROUPS					
OVERLAP 'GROUP'	MOST PROMINENT STT REFERENCES	MOST PROMINENT TM REFERENCES	10 TM REFERENCES & 10 STT REFERENCES	10 TM REFERENCES AND 5 STT REFERENCES	10 STT REFERENCES AND 5 TM REFERENCES
Most prominent STT references	-	7	11	11	17
Most prominent TM references	-	-	9	20	9
10 TM references & 10 STT references	-	-	-	15	15
10 TM references and 5 STT references	-	-	-	-	15
10 STT references and 5 TM references	-	-	-	-	-

4.4 Analysis of overlapping references

In order to identify the areas of integration between the socio-technical transitions and technology management bodies of knowledge, and thus to identify to what degree these two bodies of knowledge overlap and integrate concepts, and to what extent the concepts of the two bodies of knowledge are mutually included in the respective fields, two approaches were taken:

i. Holistic analysis of the resulting overlap from three perspectives:
    a. The resulting overlap (the 119 references highlighted above) are analysed and insights and inference drawn;
    b. A cluster analysis; and
    c. A correspondence analysis is performed on the results from the linkage analysis.
ii. The most significant overlaps in the above-mentioned set of references, that represent the overlap between technology management and socio-technical transitions, are analysed in order to further elucidate the overlap and integration that exists (or lack thereof) between technology management and socio-technical bodies of literature.

4.4.1 Holistic analysis of the resulting overlap

In this section the 119 references identified through the linkage analysis as references that are cited by *Entries* in both technology management and socio-technical transitions bodies of literature, are analysed.

4.4.1.1 Overview of the resulting overlap

The *References* that represent the overlap between the bodies of literature of technology management and socio-technical transitions (Table 71 in Appendix C) represent 0.007% and 0.001% of the references found in the socio-technical transitions and technology management bodies of knowledge respectively – and arguably by any standard a (very) small percentage of the references under consideration. And therefore, the second (quantitative) indication (the first being that only two articles are present in both bodies of literature) of the disconnect that exists between technology management and socio-technical transitions.

When the *References* with the highest number of occurrences in the technology management set are considered (shown in Table 18) it is evident that innovation is a prominent topic. In addition, strategic management and literature dealing with competitive advantage, economics and technological change feature strongly. It should be noted that there is a strong focus on the level of analysis being at firm or organisational level. It is evident that technology management per se does not explicitly feature as a key focus here, but is rather implied through the focus areas, and socio-technical transitions or sustainability transitions are not within this group of key focus areas.

Table 18. Highest number of occurrences in the technology management set

KEY FOCUS	NORMALISED TITLE OF REFERENCE (NORMALISED DURING STEP I OF LA PHASE 1)	# OF TIMES AS TECHNOLOGY MANAGEMENT REFERENCE	# OF TIMES AS SOCIO-TECHNICAL TRANSITIONS REFERENCES
Innovation	diffusion of innovations fre york	145	15
Research methodology	case study research design and methods sage london	129	17
Innovation	absorptive capacity a new perspective on learning and innovation administrative science quarterly	124	2
Innovation	the knowledge creating company how japanese companies create the dynamics of innovation oxfor	124	2
Innovation	the innovator s dilemma harvard business schoo	118	18
Competitive advantage and strategic management	dynamic capabilities and strategic management strategic management	98	4
Competitive advantage	firm resources and sustained competitive advantage	92	2
Economics	an evolutionary theory of economic change harvar	83	26
Research methodology	building theories form case study research acad manag rev	74	10
Economics	the theory of economic development harvar ma	74	6
Innovation	architectural innovation the reconfiguration of existing product technologies and the failure of existing firms administrative science quarterly	64	5
Innovation	mastering the dynamics of innovation boston harvard business school	63	3
Competitive advantage	the competitive advantage of nations macmillan london	62	2
Competitive advantage and strategic management	competitive strategy techniques for analyzing industries and competitors fre york	60	2
Innovation / technological innovation	profiting from technological innovation implications for integration collaboration licensing and public policy research policy	60	1
Technological change	technological discontinuities and organizational environments adm sci q	54	7
Economics	capitalism socialism and democracy new york harper row	52	9
Technological innovation	technological paradigms and technological trajectories research policy	51	22
Strategic management	a resource based view of the firm strategic management	51	2
Organizational science	a dynamic theory of organizational knowledge creation organization science	50	1

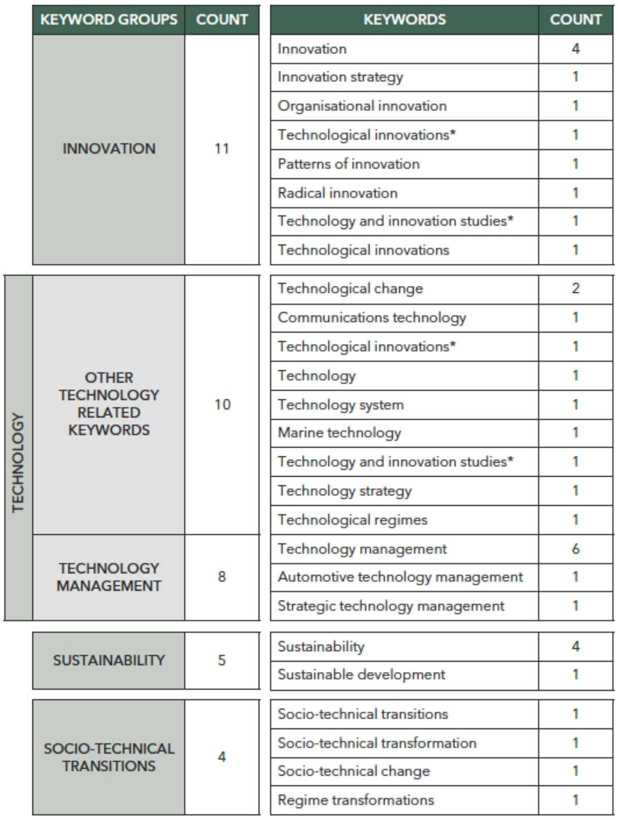
However, when the references with the highest number of occurrences in the socio-technical transitions set that are also present in the technology management set are considered (shown in Table 19), there is a strong presence of documents that focus on transitions to sustainability and/or socio-technical transitions – possibly indicate an area of integration between the two bodies of knowledge under consideration. Also, as mentioned earlier (and as shown in Table 17), seven references fall both within the 'most prominent STT' and the 'most prominent TM' references; the focus of this (very) limited number of references are (equally split between) on economics, innovation, social theory and the social studies of technology, and one article that focuses on research methodologies (see Table 72 in Appendix C).

Table 19. Highest number of occurrences in the socio-technical transitions set

KEY FOCUS	NORMALISED TITLE OF REFERENCE (NORMALISED DURING STEP I OF LA PHASE 1)	# OF TIMES AS TECHNOLOGY MANAGEMENT REFERENCE	# OF TIMES AS SOCIO-TECHNICAL TRANSITIONS REFERENCES
Technological change	technological transitions as evolutionary reconfiguration processes a multi level perspective case study research policy	5	122
Transition to sustainability	system innovation and the transition to sustainability theory evidence and policy cheltenham edward elgar	4	100
Socio-technical transitions	typology of sociotechnical transition pathways research policy	5	99
Transition to sustainability	the governance of sustainable socio technical transitions res policy	4	88
Technological change and environmental sustainability	technological change human choice and climate change resources and technology eds battell	3	86
Technological change	regime shifts to sustainability through processes of niche formation the approach of strategic niche management technology analysis and strategic management	5	77
Innovation	from sectoral systems of innovation to socio technical systems insights about dynamics and change from sociology and institutional theory research policy	6	64
Social studies of technology.	the social construction of technological systems cambridge ma mi	20	55
Transition to sustainability	p innovation studies and sustainability transitions the allure of the multi level perspective and its challenges research policy	1	47
Transition to sustainability	experimenting for sustainable transport the approach of strategic niche management london gbr pp ix spo	2	35
Interlocking technological, institutional and social forces, climate change	understanding carbon lock in energy policy	2	32
Socio-technical transitions	the dynamics of transitions in socio technical systems a multi level analysis of the transition pathway from horse drawn carriages to automobiles technol anal strat manage	1	32
Socio-technical transitions	technological transitions and system innovations a co evolutionary and sociotechnical analysis cheltenham edward elgar	2	31
Transition to sustainability	the multi level perspective on sustainability transitions responses to seven criticisms environ innov soc trans	1	28
Social theory	the constitution of society	24	27
Economics	an evolutionary theory of economic change harvar	83	26
Technological change	networks of power electrification in western society 1880 1930 johns hopkin	7	25
Socio-technical change	of bicycles bakelites and bulbs theory of socio technical change mi ma	6	25
Research methodology	science in action how to follow scientists and engineers through society cambridge ma harvar	13	24
Technological development	shaping technology building society and eds mi ma	10	24

When specifically considering the *Entries* in the technology management body of literature that reference the references that deals with transitions to sustainability (i.e. the articles in the technology body of literature that references the *Reference* in the 'most prominent' overlap group), the 29 occurrences of references focussing on socio-technical transitions from a sustainability perspective or sustainability transitions (as a broad term), yields a corresponding 17 *Entries* in the technology management set of documents (see Table 73 in Appendix C). Thus, there are 17 technology management *Entries* that reference these most prominent '*STT References*' that specifically focus on socio-technical and/or sustainability transitions. Given the objective to identify not only references that overlap, but also to expand the set of two identified documents in Table 14, the two articles that references the most of the '*most prominent STT references'* are in fact the two articles that are present in both bodies of literature and referred to in Table 8, namely the work of Dolata (2013) and Wells & Lin (2015), clearly highlighting again the limited overlap between these two bodies of knowledge.

Further considering the *Entries* associated with the references that deal with transitions to sustainability, namely the articles in the technology management body of literature that references the *References* in the 'most prominent' overlap group (see Table 74 in Appendix C), and by considering the keywords used in these *Entries* (see Table 75 in Appendix C), it is clear that the key concepts that are addressed are in line with the findings when the most frequently used keywords are analysed for both sets of *Entries* in Part A of this investigation (see Chapter 3). Figure 21 shows the most prominent keywords and 'keyword groups' found in these *Entries*. From this, and as highlighted earlier, innovation, technology and sustainability are areas where the technology management and socio-technical transitions bodies of literature overlap. However, here socio-technical transitions are also present as a keyword.



	KEYWORD GROUPS	COUNT	KEYWORDS	COUNT
	INNOVATION	11	Innovation	4
			Innovation strategy	1
			Organisational innovation	1
			Technological innovations*	1
			Patterns of innovation	1
			Radical innovation	1
			Technology and innovation studies*	1
			Technological innovations	1
TECHNOLOGY	OTHER TECHNOLOGY RELATED KEYWORDS	10	Technological change	2
			Communications technology	1
			Technological innovations*	1
			Technology	1
			Technology system	1
			Marine technology	1
			Technology and innovation studies*	1
			Technology strategy	1
			Technological regimes	1
	TECHNOLOGY MANAGEMENT	8	Technology management	6
			Automotive technology management	1
			Strategic technology management	1
	SUSTAINABILITY	5	Sustainability	4
			Sustainable development	1
	SOCIO-TECHNICAL TRANSITIONS	4	Socio-technical transitions	1
			Socio-technical transformation	1
			Socio-technical change	1
			Regime transformations	1

* Keywords in both the 'Technology' and 'Innovation' keyword groups.

Figure 21. Most prominent keywords and 'keyword groups' associated with Entries shown in Table 73

From the above analysis, it can be concluded that an overlap exists at a high level and in terms of broad concepts like innovation, technology and sustainability – which is in line with the findings of Chapter 3 – but, even these overlaps are based on a very small part of the data sets gathered at the start of the linkage analysis. The extent to which one must delve into the datasets to find arguably minuscule overlaps in concepts are vast, and such concepts are then only indicative of overlaps and integration of concept at a high level and in broad terms.

The next section considers the correspondence- and cluster analysis of the 119 *References* considered to represent the overlap between the bodies of literature of technology management and socio-technical transitions (as shown in Table 71 in Appendix C).

4.4.1.2 Correspondence- and cluster analysis

For the correspondence analysis, the standardised residual[23] for each of the *References* (T_1 – T_{119} shown in Table 71 in Appendix C) is calculated and subsequently displayed on a plot showing the varying degree of the strength of the prominence of the *References* to either the technology management domain or the socio-technical transitions domain. The plot is shown in Figure 22. The greater the negative standardised residual, the less prominent the relationship is with a domain, and the greater the positive standardised residual, the more prominent a reference is in a specific domain. This then also means that the closer the standardised residuals are to zero, such *References* have less of a difference in prominence of the *References* in the respective bodies of literature, as well as a relatively significant overlap. Figure 22 shows the *References* in Table 71 in Appendix C given their prominence in either the technology management or socio-technical body of literature based on their unit variance[24]. For example, a reference with a larger occurrence in the technology management body of knowledge will be placed closer to the technology management coordinate value in Figure 22[25]. The closer the coordinates of a *References* (T_1 – T_{119}) are to zero, the more equal the occurrence in both bodies of literature since the standard residual of such *References* are close to zero.

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[23] Standardised residual is calculated by dividing the residual (which is the difference between the observed and predicted value of some variable) by the square root of the residual mean square. This produces scaled residuals that have, approximately, a unit variance.

[24] Variance is a measure of variability defined as the expected value of the square of the random variable around its mean (see also footnote 23 above).

[25] It should be noted that the coordinate value is used as the standardised residual alongside an arbitrary value (that is the same for all References) in order to graphically show the spread of References and that some are more strongly linked to the technology management and some to socio-technical transitions body of literature.

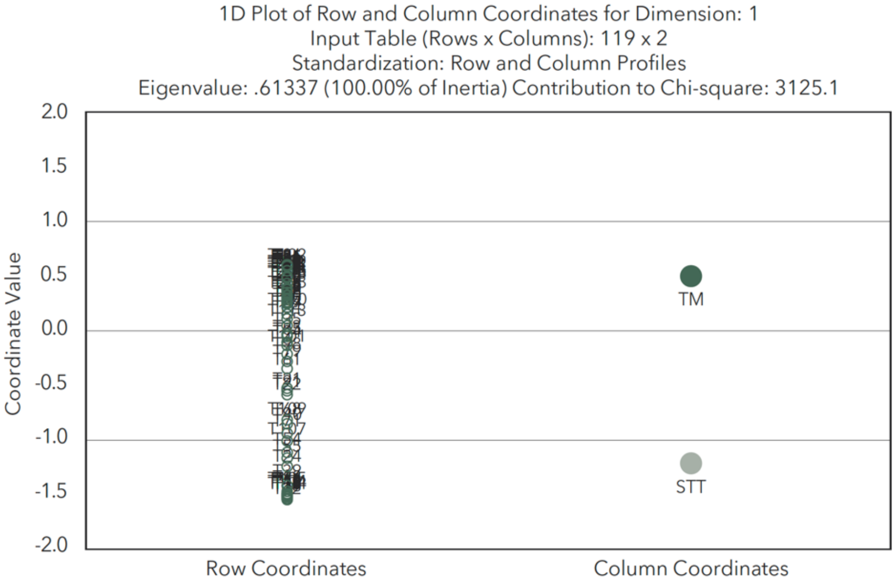

Figure 22. Plot showing the varying degree of the strength of the relationship / prominence of references to either the technology management (TM) domain or the socio-technical transitions (STT) domain

Subsequent to the correspondence analysis, and based on the calculated standardised residuals, a cluster analysis was performed. A cluster analysis aims to group data objects or data points based only on information found in the specific data that describe such data points and the relationship between data points. The goal of cluster analysis is to group data objects together in a cluster that is similar (or related) to one another. The greater the similarity between the data points in a specific group, and the larger the differences between different groups, results in increasingly distinct clusters.

For the purposes of this study, the goal of the cluster analysis was to determine if there is, from a statistical perspective, references that can be grouped together (clustered) in order to draw insights from such clusters regarding the overlap landscape between the technology management and socio-technical bodies of literature (depicted here as the TM or STT domain). Again, as mentioned, the references used by the documents (*Entries*) found in these two bodies of knowledge are considered to evaluate the overlap as only two *Entries* are found in the overlap (refer to Table 8). The correspondence- and cluster analysis provides abstraction from the individual data points presented in Table 71 in Appendix C to the clusters in which those data points reside. In this specific case, when data points (i.e. the references) are grouped in the same cluster, it means that such references have similar standardised residuals, and therefore has a similar prominence in the respective bodies of literature.

Figure 23 shows the Dendrogram that was developed based on the *References* presented Table 71 in Appendix C and the correspondence analysis discussed above. From Figure 23, depending on the selected linkage data, a number of different sets of clusters can be identified. In Figure 23, as depicted by the red line, a linkage distance of 31.581 yields five clusters. The selection of a linkage distance to identify clusters is a subjective decision. When considering the dendrogram in Figure 23, one can see that there are either three (should a linkage distance of between 50 and 60 be taken) or five (should a linkage distance of between 20 and 50 be taken) distinct clusters. The alternative to this will be 9 or 12 clusters if a linkage distance of approximately 11 or 5 respectively is selected. It is argued that, given the results found with the selected linkage distance (31.581), and the five clusters that this yield, provides sufficient insight into the overlap landscape for the purposes of this study.

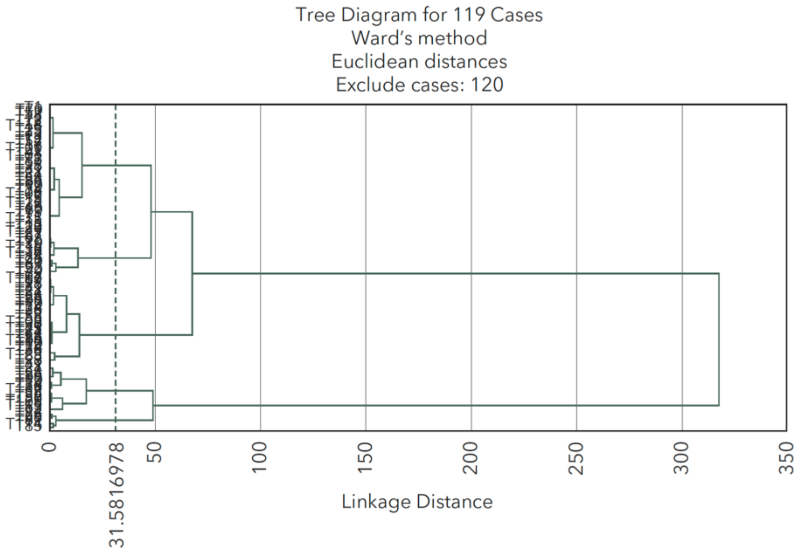

Figure 23. Dendrogram developed based on the references presented in Table 71 in Appendix C and the corresponding correspondence analysis

Figure 24 shows the cluster membership of the five clusters stemming from the dendrogram, clearly indicating the domain within which each cluster (and therefore the references contained in each cluster) is more prominent. Clusters 1, 2 and 5 (and thus also the references associated with these clusters) have a greater prominence in the socio-technical transitions body of literature than in the technology management body of literature (relative to the other clusters a greater positive standardised residuals for socio-technical transitions, and relative to the other clusters a greater negative standardised residuals for technology management), with cluster 2 (with an average standardised residuals of -0,58 and 0,88 for technology management and socio-technical transitions respectively) having the average standardised residuals closest to zero – indicating a relatively high degree of similarity in the prominence of the references in the respective bodies of literature, as well as a relatively significant overlap. Clusters 3 and 4 have a greater prominence in the technology management body of literature than in the socio-technical transitions body of literature, namely positive standardised residuals for technology management, and negative standardised residuals for socio-technical transitions. Figure 25 shows the corresponding clusters on the plot presenting the varying deree of the strength of the relationship/prominence of the *References* ($T_1 – T_{119}$) in the two concerned bodies of knowledge.

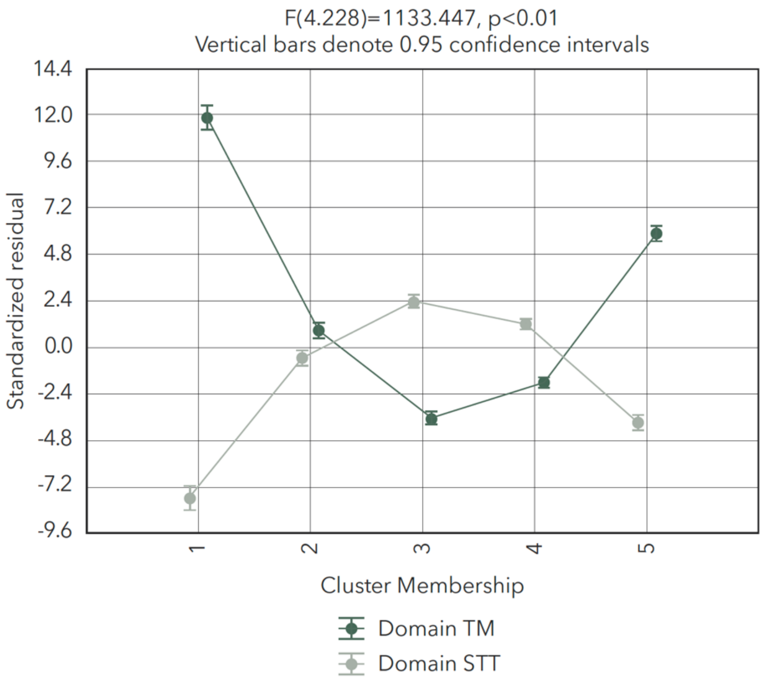

Figure 24. Cluster membership

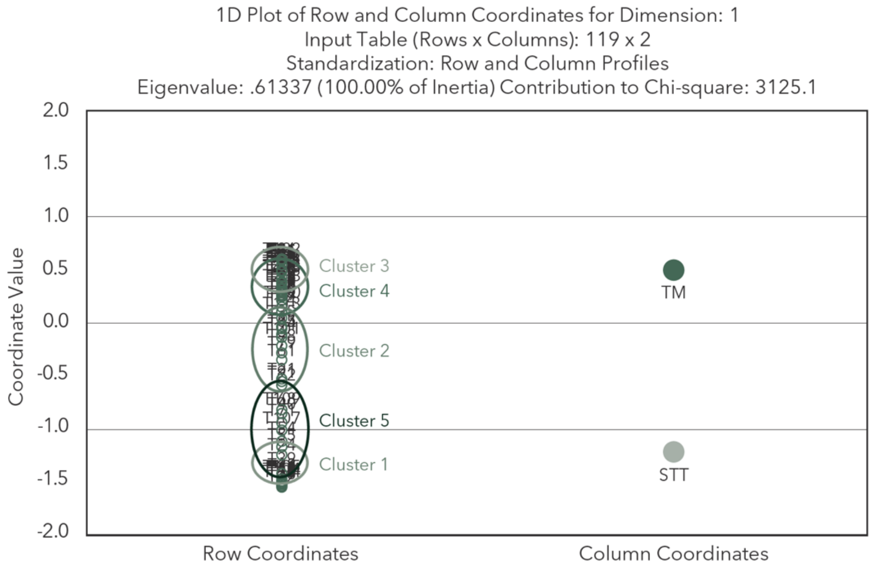

Figure 25: Plot showing the varying degree of the strength of the relationship / prominence of identified clusters to either the technology management (TM) domain or the socio-technical transitions (STT) domain

Table 76 in Appendix C shows the five clusters and the *References* associated with each cluster. The five clusters identified through the correspondence- and cluster analysis described above, are discussed below.

Cluster 1

As discussed above, the references in Cluster 1, compared to the other four clusters, associates the strongest with the STT domain, and therefore the socio-technical transitions body of literature. In other words, these *References*, relative to the other references identified in this overlap between the technology management and socio-technical transitions bodies of literature. The content of the documents (*References*) in Cluster 1 were evaluated, and they consider topics that are explicitly and directly related to conceptual framings of socio-technical transitions and/or sustainability transitions, namely the governance of socio-technical transitions, transition to sustainability theory, and a typology of socio-technical transition pathways.

Cluster 5

Similar to Cluster 1, Cluster 5 also has a stronger association with the socio-technical transitions body of literature than with technology management. However, the *References* are less prominent in the socio-technical transitions literature than the *References* in Cluster 1, and more prominent in the technology management body of literature than the *References* in Cluster 1. When the content of the *References* within Cluster 5 is considered, even though still strongly associated with socio-technical transitions and transition pathways from a conceptual perspective, some more applied and/or case studies based on socio-technical transitions are presented. Another theme that is evident here is the social aspects that have to be considered when technology and the impact of technology is considered.

Cluster 2

Considering the outcome of the correspondence and cluster analysis, Cluster 2 has a slightly stronger association with the socio-technical transitions body of literature than with the technology management body of literature (see Figure 25). As can be expected, the *References* in this cluster are not primarily concerned with socio-technical transitions per se, neither from a conceptual perspective nor from a practical/applied perspective – as is the case with Clusters 1 and 5 – but, the *References* in this cluster are concerned with concepts that are related to socio-technical transitions, i.e. most prominently, economics, technology related topics (i.e. competing technologies, technological paradigms and technology in organisations), innovation, and then also articles dealing with research methodology. And, one article deals with social science. Interestingly, the Brundlandt Report (1987) is also found in Cluster 2.

Cluster 4

The *References* in Cluster 4 have a stronger association with the technology management body of literature than with the socio-technical transitions body of literature (Figure 25). When the 47 *References* in this cluster is considered, themes and topics that are evident include: technology related themes (such as technology acceptance, technology roadmaps and technical change), innovation, economics, organisational theory, strategic management and competitive advantage, social science, and a number of references are concerned with research methodology. However, here there are no clear coherences between the topics addressed by these references like for example is the case with the references in Cluster 1 and Cluster 5 (but to a lesser extent). Both Cluster 2 and Cluster 4 have standardised residuals that are both relatively close to zero for both the technology management and socio-technical transitions bodies of literature, and hence the fact that no clear themes emerge from these clusters is not surprising.

Cluster 3

Cluster 3 is the cluster that has the strongest association with technology management, but not as strong as that of Clusters 1 and 5 with socio-technical transitions. Even though the association with technology management is relatively similar to that of Cluster 4, there is a noticeable difference in the prominence of these references with the socio-technical transitions body of literature compared to that of Cluster 4 (see Figure 25). The topics covered seem slightly more defined in Cluster 3 than in Clusters 4 and 2, with innovation being a theme/topic that emerges quite strongly. Similar to Cluster 4, topics related to strategic management and competitive advantage and organisational theory is also present. A number of *References* address research methodology. It is worthy to note that the focus of the *References* in this cluster is noticeably more geared towards the organisational level as the unit of analysis than clusters with a stronger association with the socio-technical transitions body of literature.

4.4.2 Most significant overlaps (absolute values)

When the 'most significant' overlaps, of the overlaps identified in Section 4.2 under *LA Phase 5: Results*, are considered - this is taken as all overlaps where the number of times that a reference is used / occurs in the technology management set and the number of times that a reference is used / occurs in the socio-technical transitions set are at least 5[26] or higher – it yields 37 *References* (shown in Figure 26). Not surprisingly, of these 37 *References*, 30 are also in either the 'most prominent STT references' (that also has a presence in the technology management body of literature), the most prominent technology management references (that also has a presence in the socio-technical transitions body of literature), or in both. Also, as can be expected given the outcome of the cluster- and correspondence analysis above, all 15 *References* that are in Cluster 2, are also present in the set of *References* shown in Figure 26). Furthermore, if the *Reference* that form part of Clusters 1, 3, 4 and 5 are considered, the distribution in terms of prominence between technology management and socio-technical transitions is relatively equally distributed with 10 *Reference* (Cluster 1 and 5 in Figure 27) being more prominent in the socio-technical transitions body of knowledge and 12 references (Clusters 3 and 4 in Figure 27) being more prominent in the technology management body of knowledge.

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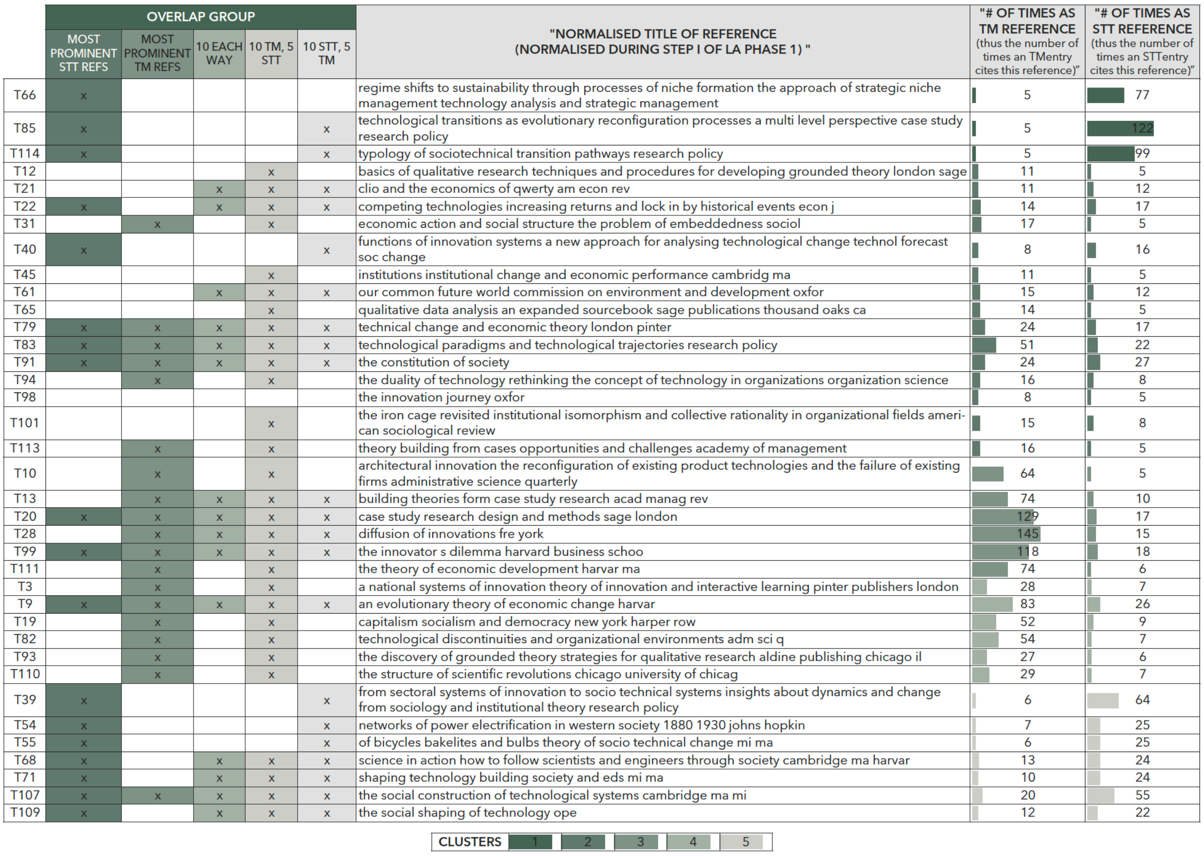
[26] The average overlap across the 119 references in Table 71 in Appendix C are 4.3, thus the most significant overlaps are those that are above average, and thus at least 5.



	OVERLAP GROUP					"NORMALISED TITLE OF REFERENCE (NORMALISED DURING STEP I OF LA PHASE 1) "	"# OF TIMES AS TM REFERENCE (thus the number of times an TMentry cites this reference)"	"# OF TIMES AS STT REFERENCE (thus the number of times an STTentry cites this reference)"
	MOST PROMINENT STT REFS	MOST PROMINENT TM REFS	10 EACH WAY	10 TM, 5 STT	10 STT, 5 TM			
T66	x					regime shifts to sustainability through processes of niche formation the approach of strategic niche management technology analysis and strategic management	5	77
T85	x				x	technological transitions as evolutionary reconfiguration processes a multi level perspective case study research policy	5	122
T114	x				x	typology of sociotechnical transition pathways research policy	5	99
T12				x		basics of qualitative research techniques and procedures for developing grounded theory london sage	11	5
T21			x	x	x	clio and the economics of qwerty am econ rev	11	12
T22	x		x	x	x	competing technologies increasing returns and lock in by historical events econ j	14	17
T31		x		x		economic action and social structure the problem of embeddedness sociol	17	5
T40	x				x	functions of innovation systems a new approach for analysing technological change technol forecast soc change	8	16
T45				x		institutions institutional change and economic performance cambridg ma	11	5
T61			x	x	x	our common future world commission on environment and development oxfor	15	12
T65				x		qualitative data analysis an expanded sourcebook sage publications thousand oaks ca	14	5
T79	x	x	x	x	x	technical change and economic theory london pinter	24	17
T83	x	x	x	x	x	technological paradigms and technological trajectories research policy	51	22
T91	x	x	x	x	x	the constitution of society	24	27
T94		x		x		the duality of technology rethinking the concept of technology in organizations organization science	16	8
T98						the innovation journey oxfor	8	5
T101				x		the iron cage revisited institutional isomorphism and collective rationality in organizational fields american sociological review	15	8
T113		x		x		theory building from cases opportunities and challenges academy of management	16	5
T10		x		x		architectural innovation the reconfiguration of existing product technologies and the failure of existing firms administrative science quarterly	64	5
T13		x	x	x	x	building theories form case study research acad manag rev	74	10
T20	x	x	x	x	x	case study research design and methods sage london	129	17
T28		x	x	x	x	diffusion of innovations fre york	145	15
T99	x	x	x	x	x	the innovator s dilemma harvard business schoo	118	18
T111		x		x		the theory of economic development harvar ma	74	6
T3		x		x		a national systems of innovation theory of innovation and interactive learning pinter publishers london	28	7
T9	x	x	x	x	x	an evolutionary theory of economic change harvar	83	26
T19		x		x		capitalism socialism and democracy new york harper row	52	9
T82		x		x		technological discontinuities and organizational environments adm sci q	54	7
T93		x		x		the discovery of grounded theory strategies for qualitative research aldine publishing chicago il	27	6
T110		x		x		the structure of scientific revolutions chicago university of chicag	29	7
T39	x				x	from sectoral systems of innovation to socio technical systems insights about dynamics and change from sociology and institutional theory research policy	6	64
T54	x				x	networks of power electrification in western society 1880 1930 johns hopkin	7	25
T55	x				x	of bicycles bakelites and bulbs theory of socio technical change mi ma	6	25
T68	x		x	x	x	science in action how to follow scientists and engineers through society cambridge ma harvar	13	24
T71	x		x	x	x	shaping technology building society and eds mi ma	10	24
T107	x	x	x	x	x	the social construction of technological systems cambridge ma mi	20	55
T109	x		x	x	x	the social shaping of technology ope	12	22

CLUSTERS 1 2 3 4 5

Figure 26. Most significant reference overlaps an clusters

Also as can be expected, especially given the insignificant overlap between the two concerned bodies of knowledge when considering the small number of documents (two) found in the combined search (refer to Table 8), the overlap considered in Figure 26 is not indicative of any specific dimensions across which these bodies of knowledge share intellectual roots; some of these references are sources that discuss research methodologies and/or seminal papers and are therefore expected to be present in these (and other trans-/multidisciplinary) fields, not due to the content relating to either socio-technical transitions or technology management, but rather due to the foundational concepts discussed in such documents, and could be considered to have a high likelihood to be present in most multi- and trans-disciplinary bodies of knowledge that considers management sciences, engineering, technology and social sciences. However, these 37 documents are further analysed to identify relevant overlaps and infer the intellectual roots shared between the technology management and socio-technical transitions bodies of literature. The authors and year of publication of the references under consideration here are shown in Figure 27 and discussed below.

FOCUS AREA	AUTHOR(S)	PUBLICATION DATE	CLUSTER		NORMALISED TITLE OF REFERENCE (Normalised during step i of LA Phase 1)	# OF TIMES AS TM REFERENCE (thus the number of times an TMentry cites this reference)	# OF TIMES AS STT REFERENCE (thus the number of times an STTentry cites this reference)
T	Kemp, R., Schot, J., Hoogma, R.	1998	1	T66	regime shifts to sustainability through processes of niche formation the approach of strategic niche management technology analysis and strategic manag	5	77
T	Geels, F.W.	2002	1	T85	technological transitions as evolutionary reconfiguration processes a multi level perspective case study research policy	5	122
STC	Geels, F.W., Schot, J.	2007	1	T114	typology of sociotechnical transition pathways research policy	5	99
RM	Strauss, A., Corbin, J.M.	1998	2	T12	basics of qualitative research techniques and procedures for developing grounded theory london sage	11	5
E	David, P.A.	1985	2	T21	clio and the economics of qwerty am econ rev	11	12
T	Artur, W.	1989	2	T22	competing technologies increasing returns and lock in by historical events econ j	14	17
E	Granovetter, M.	1985	2	T31	economic action and social structure the problem of embeddedness sociol	17	5
I	Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M.	2007	2	T40	functions of innovation systems a new approach for analysing technological change technol forecast soc change	8	16
E	North, D.C.	1990	2	T45	institutions institutional change and economic performance cambridg ma	11	5
B	Brundtland, G.	1987	2	T61	our common future world commission on environment and development oxfor	15	12
RM	Miles, M.B., Huberman, A.M.	1994	2	T65	qualitative data analysis an expanded sourcebook sage publications thousand oaks ca	14	5
E	Dosi, G., Freeman, C., Elson, R.N., Silverberg, G., Soete, L.	1988	2	T79	technical change and economic theory london pinter	24	17
T	Dosi, G.	1982	2	T83	technological paradigms and technological trajectories research policy	51	22
S	Giddens, A.	1984	2	T91	the constitution of society	24	27
T	Orlikowski, W.J.	1992	2	T94	the duality of technology rethinking the concept of technology in organizations organization science	16	8
I	Van De Ven, A.H., Polley, D.E., Garud, R., Venkataraman, S.	1999	2	T98	the innovation journey oxfor	12	5
S	DiMaggio, P.J., Powell, W.	1983	2	T101	the iron cage revisited institutional isomorphism and collective rationality in organizational fields american sociological review	15	8
RM	Eisenhardt, K.M., Graebner, M.E.	2007	2	T113	theory building from cases opportunities and challenges academy of management	16	5
I	Henderson, R., Clark, K.B.	1990	3	T10	architectural innovation the reconfiguration of existing product technologies and the failure of existing firms administrative science quarterly	64	5
RM	Eisenhardt, K.	1989	3	T13	building theories form case study research acad manag rev	74	10
RM	Yin, R.K.	2003	3	T20	case study research design and methods sage london	129	17
I	Rogers, E.M.	1995	3	T28	diffusion of innovations fre york	145	15
I	Christensen, C.M.	1997	3	T99	the innovator s dilemma harvard business schoo	118	18
E	Schumpeter, J.A.	1961	3	T111	the theory of economic development harvar ma	74	6
E	Nelson, R.R., Winter, S.G.	1982	4	T9	an evolutionary theory of economic change harvar	83	26
E	Schumpeter, J.A.	1942	4	T19	capitalism socialism and democracy new york harper row	52	9
I	Lundvall, B.A.	1992	4	T3	a national systems of innovation theory of innovation and interactive learning pinter publishers london	28	7
T	Anderson, P., Tushman, M.	1990	4	T82	technological discontinuities and organizational environments adm sci q	54	7
RM	Glaser, B.G., Strauss, A.L.	1967	4	T93	the discovery of grounded theory strategies for qualitative research aldine publishing chicago il	27	6
RM	Kuhn, T.P.	1962	4	T110	the structure of scientific revolutions chicago university of chicag	29	7
I	Geels, F.W.	2004	5	T39	from sectoral systems of innovation to socio technical systems insights about dynamics and change from sociology and institutional theory research policy	6	64
T	Hughes, T.P.	1983	5	T54	networks of power electrification in western society 1880 1930 johns hopkin	7	25
STC	Bijker, W.E.	1995	5	T55	of bicycles bakelites and bulbs theory of socio technical change mi ma	6	25
RM	Latour, B.	1987	5	T68	science in action how to follow scientists and engineers through society cambridge ma harvar	13	24
T	Bijker, W.E., J. Law	1992	5	T71	shaping technology building society and eds mi ma	10	24
T	Bijker, W.E., Hughes, T.P., Pinch, T.	1987	5	T107	the social construction of technological systems cambridge ma mi	20	55
T	Mackenzie, D., Wacjman, J.	1999	5	T109	the social shaping of technology ope	12	22

Figure 27. Key focus areas per cluster of the references in the most significant overlaps (absolute values)

When considering the references shown in Figure 27, deemed the most significant overlaps in terms of the references found in the TM and STT bodies of knowledge respectively, eight of these references are concerned with the **science of research and/or research methodologies** (denoted with 'RM' in Figure 27) – this is the work of Strauss & Corbin (1998), Eisenhardt (1989), Yin (2002), Miles & Huberman (1994), Latour (1978), Glaser & Strauss (1967), Kuhn (1962) and Eisenhardt & Graenber (2007). These eight references could be considered indicative of an overlap in terms of research methodologies and/or approaches but are not indicative of the dimensions across which these bodies of knowledge share intellectual roots.

Of the remaining 29 references (thus excluding the references that are concerned with the science of research and/or research methodologies), seven focus on **economics, economic development and economic theory** (denoted with 'E' in Figure 27) – this is the work of David (1985), Granovetter (1985), Dosi *et al*. (1988), Schumpeter (1942), Schumpeter (1961), Nelson & Winter (1982), and North (1990), seven focus on **innovation and innovation studies** (denoted with 'I' in Figure 8) - the work of Henderson & Clark (1990), Rogers (1995), Lundvall (1992), Christensen (1997), Geels (2004), Hekkert *et al*. (2007), and Van de Ven *et al*. (1999)), ten focus on **technological related themes such as technology adoption, technological change, social studies of technology and technological development** (denoted with 'T' in Figure 27) - the work of Artur (1989), Hughes (1983), Dosi (1982), Mackenzie & Wacjman (1999), Kemp *et al*. (1998), Bijker & Law (1992), Anderson & Tushman (1990), Geels (2002), Orlikowski (1992), Bjiker *et al*. (1987), two focus on social studies (denoted with 'S' in Figure 27) - the work of Giddens (1984) and DiMaggio & Powell (1983)), and then the Brundtland report (1987) (denoted with 'B' in Figure 27) is also part of this set of references, and two documents (the work of Bijker (1995) and Geels (2007) focus on socio-technical change (denoted with 'STS' in Figure 27). However, Bjiker (1995) does not consider **socio-technical change** from a sustainability perspective, but rather describes where technologies come from and how societies deal with them. The work by Geels (2007) considers various transition pathways development along 'technological trajectories', however also not with a specific focus on sustainability. It is also interesting to note that two of the mentioned 29 articles form part of the 'STT Entries' (i.e. the 311 socio-technical transition articles referred to in Table 8): the work of Hekkert *et al*. (2007) and the work of Geels (2007). None of the 29 articles under consideration here is also found in the 'TM Entries' (the 4,740 technology management articles referred to in Table 8).

4.5 Discussion

The linkage analysis highlights the most prominent areas of overlap between the technology management and socio-technical transitions' bodies of literature based on the *References* that the documents (*Entries*) in these bodies of literature cite. The linkage analysis yielded 119 *References* (out of a possible 17,445 socio-technical transitions *References* and 112,498 technology management *References*) that are present in both bodies of literature, thus representing the overlap with regards to the documents cited by the respective bodies of literature. As stated, the most significant and/or the most prominent overlaps are identified (refer to *LA Phase 5: Results* in Section 4.2.1); it is argued that the criteria used to identify any significant or prominent overlaps are justified given that it allows for all overlaps of five or more to be included in the set, as well as any overlap that are smaller than five but that are in the top half of references in either one of the bodies of literature. This means that 0,007% of the socio-technical transitions references are also technology management references, and 0,001% of the technology management references are also socio-technical transitions references – as mentioned, the second quantitative indication that there exists a disconnect between these two bodies of literature.

Areas of focus that emerge when the references with the highest number of occurrences in the respective bodies of literature, as well as the references that fall both within the '*most prominent STT*' and the '*most prominent TM*' references are considered (refer to Table 18 and Table 19), are innovation, strategic management and competitive advantage, economics, technological change, socio-technical transitions, and social studies. This expanded set of articles that was established and the keyword analysis of this set of articles again highlights that the areas of (limited) overlap is strongly geared towards innovation and technology related concepts; interestingly only here (at this significantly detailed level of analysis) does technology management and socio-technical transitions feature.

The correspondence- and cluster analyses highlight similar findings, which is that areas of overlap exists in terms of:

i. science of research and/or research methodologies;
ii. economics, economic development and economic theory;
iii. innovation and innovation studies;
iv. technological related themes such as technology adoption, technological change, social studies of technology and technological development;
v. strategic management and competitive advantage;
vi. social studies; and
vii. socio-technical change.

It is interesting to note the trend that as one progresses through the clusters from those with the most prominence in socio-technical transitions to those with a stronger prominence in technology management, it is clear how the references increasingly deal with a unit and level of analysis that is at the level of organisations in Cluster 3 as opposed to at the macro level of society or the economy in Clusters 1 and 5.

An interesting observation is that there is one technology management concept that emerges, even though in the broader scope of things could be considered still a limited emerging theme considered in both bodies of literature, namely: technology roadmapping. Technology roadmapping is present three times in Cluster 3, and two times in Cluster 4. Even though not indicative of a significant overlap of conceptual framings, this is noted as an emerging research area when considering technology management and socio-technical transitions together.

Taking a step back and considering the total number of references found in the two datasets, namely 17,445 and 112,498 for the socio-technical transitions and technology management datasets respectively (refer to Table 8), the overlap discussed above (of 29 references) is arguably negligible. Even though insights are gained from considering these overlaps, it remains seemingly insignificant.

4.6 Conclusion: Chapter 4

From the various analyses performed and documented in this investigation (both Part A (Chapter 3) and Part B in this chapter), one may conclude that the level of integration between the fields of technology management and that of socio-technical transitions is diminutive. The overlaps are highlighted throughout this study, and that are summarised in Section 4.5, are primarily in terms of key concepts that are present in both bodies of literature, but arguably only at an aggregate level. There does not exist overlaps in terms of conceptual framings fundamental to either technology management or socio-technical transitions that emerge as a clear overlap between these two areas of research. It may further be argued that the overlaps highlighted in these documents used in this study are partly as a result of the nature of the two bodies of literature concerned, in that they are inter-, trans- and multidisciplinary.

Ultimately, from the research and analysis conducted and discussed throughout this chapter, and the multiple perspectives from which the overlap and integration between technology management and socio-technical transitions has been considered, it is concluded that the fields of technology management and socio-technical transitions have not been integrated at a conceptual or theoretical level.

Even though there is clear evidence that the fields of technology management and socio-technical transition are not integrated from a conceptual or theoretical perspective, it is evident that they do share intellectual roots across a number of dimensions as highlighted throughout this chapter and summarised in Section 4.5. However, the unit and level of analysis from which these key dimensions are used in the respective fields largely differ; the unit and level of analysis that is at the level of organisations in Cluster 3, as opposed to at the macro level of society or the economy in Clusters 1 and 5.

It is thus concluded that the integration of socio-technical transitions approaches, concepts, frameworks and aspects with that of technology management theories and practices, and vice versa, are not adequately addressed in literature. Given the role of technology, and the management thereof, to address the grand challenges, more research efforts are required across these bodies of knowledge to enable a just transition towards sustainability. The process to uncover and develop a premise for the integration of technology management and the concept of socio-technical transitions commences in the following chapter (Chapter 5) through the alignment between technology management and socio-technical transitions.

Chapter 5.

Towards an integration strategy: Alignment between technology management and socio-technical transitions

Given the rationale and need highlighted in Chapters 1 and 2 for research efforts that consider the management of technology within the context of socio-technical transitions, and the disconnection that exists between these two fields of research, this chapter – building on the research and findings discussed in Chapter 2 – begins the process of unearthing the foundational steps for developing a premise for the integration of technology management and the concept of socio-technical transitions.

5.1 Introduction: Towards an integration strategy

The integration of technology management and the concepts of socio-technical transitions is not an end in itself, but rather the value that such an integration may add to the problem-solving context when sustainability transitions are considered. It is argued that the integration of technology management and socio-technical transitions can be effectively oriented towards (i) an improved understanding of the capability required to encourage, facilitate, enable, and/or move along sustainability transitions, and (ii) the increased mobilisation and contextualisation of different kinds of information in tandem to elicit the criteria around which technology management strategies in the context of sustainability transitions can be identified, evaluated, and developed.

5.1.1 Methodology

In this section, the phases of the approach followed to develop the integration strategy, which rests on the need to support both technology management and socio-technical transitions frameworks and approaches from an analytical and methodological point of view, within the context of sustainability, are laid out. Here the objective is to conceptualise a meta-perspective[27], that will allow for an understanding of where the integration between technology management and socio-technical transitions fits into a larger scheme. It does so by means of a three-pronged approach, including: (i) alignment, (ii) bridging, and (iii) iteration – an approach used by Turnheim *et al*. (2015) to bridge analytical challenges between various approaches that

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[27] A meta-perspective allows theorists and research workers to understand where their work fits into a larger scheme.

aim to evaluate sustainability transition pathways. The approach developed by Turnheim *et al*. (2015), which is used in this chapter in order ultimately to elucidate an integration strategy, is founded on the idea that, by connecting the insights from the different approaches and perspectives (i.e., socio-technical transitions and technology management), one may reach an increasingly coherent understanding, and subsequently articulate (emerging) approaches and concepts – as in the case of this specific research effort. The development of an integration strategy thus involves identifying, developing and building active links between technology management and socio-technical transitions based on data, information and elucidations in a shared stream of analysis that is appropriate, necessary and sufficient to inform the development of a concept that transcends, and integrates technology management and socio-technical transitions.

5.1.1.1 Alignment

Turnheim *et al*. (2015) define 'alignment' as identifying the *"the joint elements around which an integrated 'meta-perspective' ... can be articulated..."*. Here the particular elements, variables, concepts, ideas and/or approaches on which an integrated 'meta-perspective' can be based and articulated are identified. The foundations of socio-technical transitions and technology management, the challenges faced by the respective fields (within the context of the need to transition towards increasingly sustainable systems), and the findings from the bibliometric and linkage analysis (discussed in Chapters 3 and 4) are evaluated in order to identify and define the elements around which an integrated meta-perspective can be articulated. This will inform the objective to establish and elaborate on a common understanding and rationality about the transcending phenomenon/a.

5.1.1.2 Bridging

The common understanding and coherence established with regard to the overall phenomenon in the alignment phase, justifies the need for shared, common and bi-directional interaction to occur (Turnheim *et al*., 2015); in this research effort, this common understanding and coherence fall within the context of aiming to contribute towards sustainability by developing a concept or construct that transcends technology management and socio-technical transitions approaches and frameworks, while also allowing for integration between technology management and the concept of sustainability transitions. The objective is to establish shared concepts, i.e., boundary objects[28] (Turnheim *et al*., 2015); this involves identifying and developing links between concepts and around contact points, concepts, shared value-adding activities, possible similar framings of challenges, and, most importantly, the shared and common contribution that technology management and socio-technical transition perspectives can make to further our quest to move towards sustainability.

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[28] The boundary objects theory comprises the standardisation of interfaces between different social worlds – as described in the original paper by (Star and Griesemer, 1989). Due to the variety of actors – each with different interests, commitment and perceptions of the world, it is a given that social reality has different interpretations for each group of actors. The idea of boundary objects connects these actors – like language does – by providing objects that contain elements from each actor's 'world'. That does not mean that the understanding is the same, but the common interface for communication between actors is.

5.1.1.3 Iteration

Finally, as is the case with the development of (almost) all conceptual, complex (or at least highly complicated) concepts and approaches, the development process is iterative in nature. Here, the research strategy of aligning and bridging between largely unconnected scientific networks, and therefore also largely separate analytical approaches, and iterations of such interactions, facilitates the development of an integration strategy.

Through the two iterative processes of alignment and bridging, a set of guiding principles is developed by aligning problem frames and considering the new and alternative insights that are gained by considering technology management from a socio-technical transitions perspective, and vice versa. The discussion of such insights forms the basis from which the subsequent bridging is directed.

5.2 Aligning problem frames

In this section, we build on the overview of technology management and socio-technical transitions presented in Chapter 2, the bibliometric and linkage analyses presented in Chapters 3 and 4, as well as the challenges faced by the respective bodies of literature in the face of sustainability challenges, in order to identify and highlight the joint elements around which an integrated meta-perspective could be articulated. Ultimately, the aim is to formulate a set of guiding principles and questions that efforts to transcend and integrate technology management and socio-technical transition should attend to.

Technology management concepts, approaches and theories are primarily concerned with the planning, directing, control and coordination of the development and implementation of technological capabilities (Centidamar, Phaal and Probert, 2010). Moreover, theories concerned with socio-technical transitions approaches and frameworks are primarily concerned with analytical structures that consider large-scale socio-technical system changes, and that aim to capture, identify and analyse the dynamic complexity within such multi-dimensional systemic change processes. This is highly relevant when considering the alignment between technology management and socio-technical transitions with the aim of contributing towards the larger global aim of realising a sustainable future. As mentioned in Chapter 1, the aim of this research inquiry is to develop a premise for the integration between technology management and socio-technical transitions that that brings the theories together, or that at least describes how the theories that relate to technology management and socio-technical transitions relate to one another, whilst maintaining the vividness and distinctions of the respective disciplines. Alignment theory (Chorn, 1998) provides a premise for such integration; alignment theory is a meta-theory that aims to preserve the power of the individual and distinct views of the respective theories and/or frameworks (Dym and Hutson, 2012). Alignment essentially refers to the appropriateness of the various elements (Chorn, 1998). Therefore, the alignment of problem frames is geared towards creating abstraction from the challenges faced by these two scientific networks, to address their difference in focus, in order to inform the development and definition of key concepts that transcend the bodies of knowledge, as a unifying aspect that needs to be addressed for sustainability transitions.

Sections 5.2.1 and 5.2.2 below respectively consider technology management from a socio-technical transitions perspective and socio-technical transitions from a technology management perspective. The objective here is to identify a set of dimensions according to which considering technology management from a socio-technical transitions perspective, and vice versa, could support the development of a meta-perspective.

5.2.1 Technology management from a socio-technical transitions perspective

Technology management, as well as the process of developing technological innovations, is interdisciplinary in nature, and throughout the literature researchers and technology management professionals and scholars are urged to integrate various perspectives in a coherent manner for the effective management of technology. In addition, it is argued that this amalgamation of concepts will play an important role in addressing the challenges facing technology management.

Technology management primarily is focused within the regime level, when the nested hierarchy (Geels, 2012) is considered. However, incorporating a multi-level perspective into the concept of technology management could enhance technology management to support the interplay between the existing regime, on the one hand, and emerging and/or alternative technological innovations, on the other hand. In addition, taking this perspective will also then place the management of technologies within the existing regime in context with landscape pressures and emerging technologies (niches). Due to the fact that socio-technical transitions have an unquestionable orientation towards sustainability, this perspective will support technology management in contributing towards sustainable development. The task thus still remains to link the concept and theories of a nested hierarchy and multi-level perspective effectively with those of specific technology management objectives. Technology management scholars, such as Cetindamar, Phaal and Probert (2010), for instance, provide an invaluable account of activities, tools and techniques for managing technology. However, the challenge remains to identify existing, or develop new frameworks, concepts, tools and techniques that will ensure that landscape and niche pressures are accounted for in technology management, and thus also to contribute toward a socio-technical system's capability to transition to a more sustainable future system state. This research inquiry, however, will not attempt to develop such tools, but to develop, firstly, an integrated meta-perspective that takes into account technology management and socio-technical transitions, and secondly (ultimately) develop a framework that provides an approach to highlight the role of technology management within the context of sustainability transitions.

In order to adequately address the challenges facing new types of technological innovation, or technologies that facilitate increasingly sustainable production and consumption patterns, concepts from strategic niche management (SNM) seem to offer applicable concepts. As mentioned throughout the previous chapters, the characteristics of new types of innovations, especially those that are directed at societal and environmental issues, are often different from 'traditional' innovations. And, it is here that incorporating the concepts of SNM, by focussing on the dynamics around the early adoption and diffusion stages of technological innovations into the management of technology, might prove valuable for the management of such technologies. However, when considering a successful or resilient sustainability transition, it means that a new or alternative regime has been/has to be institutionalised, and thus that all the transition phases, i.e., pre-development, acceleration and stabilisation (Rotmans, Kemp and Van Asselt, 2001), have been 'completed' and that the new (more sustainable) regime is now the dominant regime. Furthermore, the dynamics between actors, institutions, technology, etc. across transition phases and pathways differ, clearly highlighting the need to consider the management of technologies – both the new or alternative technological innovations (which are associated with the niche level of the multi-level perspective) as well as those technologies that are incumbent (and thus associated with the regime level of the multi-level perspective) across transition phases, and not only in the early stages of a transition.

The environment within which we live, and within which we conduct business, is undoubtedly becoming increasingly complex. One of the key complexities is the increased number of role players in the life cycle of technologies, especially in the early stages of innovation. Taking an innovation systems approach to understanding the increased complexity, and more specifically the increased number of actors involved, could hold potential for the management of technology. The innovation systems approach takes a broader view than just technological change, thus possibly creating avenues for technology management to go beyond the ordering of the current system. An additional advantage of this approach is that it also compares the system or technology under consideration with the dominant technology within the existing regime. This approach could thus enhance technology management (and vice versa) by providing an approach to deconstruct the innovation system within which a technology exists, highlighting barriers to technology development and adoption, which clearly resonates with the objectives of managing technology.

When traditional transitions are considered, it is clear that the management of the technology that brought about these (traditional) transitions played a significant role in these episodes. However, sustainability transition, in order to ensure a sustainable future, requires technology management to facilitate the development of strategies that will facilitate such a shift towards sustainability – highlighting the need for alternative considerations than only the commercial and technological aspects. However, there is a lack of strategic approaches to deal with technologies that are developed with the aim of supporting sustainability transitions, especially when considering the tailored approach required, given the different technology management approaches for: (i) the various phases and pathways of sustainability transitions, (ii) combined technology management strategies that considers not only the niches that are deemed to contribute towards and facilitate increasingly sustainable systems, but also the management of existing or incumbent regime technologies to minimise the risk of system-level collapse (Binder, Mühlemeier and Wyss, 2017; Schilling, Wyss and Binder, 2018). This reiterates the importance and value of linking the management of technology with the theories and concepts of how socio-technical transitions are brought about.

It is clear that we need technology management to support the process of transitioning to more sustainable ways of production and consumption and doing business in general. This then calls for technology management to support the management of technologies aimed at societal and environmental challenges and supporting the development of strategies and business models that meet the needs of contemporary organisations. However, it is important also to note the role that technology management has to play in the transitioning of systems - not only to manage and support the elements that facilitate transitions, but to, through technology management, contribute towards facilitating transitions. We see this as possibly a concept where technology management is strategically linked to, or incorporates, activities that enable transitions. Although technology management develops technological capabilities, we foresee that it also has a role to play in the development and exploitation of the ability of organisations and systems, to transition these towards a more sustainable future. And this is where valuable insights can be borrowed from socio-technical transitions.

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Geels (2012) argues that approaching sustainable development from a socio-technical perspective allows for a broader view than the most prominent alternative approaches. And it is this broader view that could facilitate the process of addressing the challenges faced by technology management in order ultimately to contribute towards addressing the societal, economic and environmental challenges we face as a global society. The socio-technical approach to transitioning towards sustainable development highlights the co-evolutionary nature of, and interrelatedness between, industry, technology, culture, markets, policy, and society – and it is the amalgamation of such an interrelated way of approaching contemporary challenges with technology management principles, concepts and theories, that we foresee possessing great value.

Given the consideration of technology management from the perspective of socio-technical transitions, the undeniable role that technology plays in the quest for sustainability, and the discussion of the challenges that the management of technology face, the dimensions along which it is argued that the theories, concepts, frameworks and approaches that underpin the socio-technical transitions literature could enrich technology management, and thus support discussions on how the integration of technology management and socio-technical transitions concepts could add value, are as follows: Technology management should ideally be enhanced in order to:

i. Go beyond the ordering of the current system – the requirement here is that integration will have to transcend technology management and the concepts associated with socio-technical transitions, and that the integration will have to be sensitive to, and allow for bridging of, the differences in focus; this highlights the need for alternative considerations than merely the commercial and technological aspects.

ii. Address the challenges facing technological innovation that are deemed able to contribute towards the sustainability of socio-technical systems, and this includes the management and commercialisation of such technological innovations;

iii. Support technology management actors in understanding how to manage technology in environments with increasing complexity, and more specifically within the context of sustainability transitions;

iv. Support the development of strategic goals, where strategic goals refer to the safeguarding of both societies (current and future generations) and the environment (in addition to ensuring that an organisation is competitive and profitable), and incorporating this into organisational strategies – this highlights the requirement of an integrated framework to elucidate specific objectives towards which technology management should be steered; and

v. To support and facilitate sustainable development, and therefore transitions – the requirement here is thus to consider the impact of the management of technology on the capability of a socio-technical system to transitions, as well as the requirements set by a socio-technical transition on the management of technology(ies).

5.2.2 Socio-technical transitions from a technology management perspective

This section interprets the challenges that the socio-technical transitions approaches and frameworks face to be ones that could potentially be addressed, or at least discussed, based on the way that technology management frameworks structure the elements that support the development of technological capabilities. Rather than attempting a fundamental reconceptualisation of approaches to study socio-technical transitions in order to elucidate possible areas for integration, insights are drawn from the field of technology management given that the aim is to, ultimately, provide for a premise for the integration between these two fields.

It is argued that there are a number of concepts that offer lessons on how the different elements of technology management are structured and integrated could enhance our understanding of socio-technical transitions. Firstly, given the undisputed complexity of socio-technical systems, and thus also those of socio-technical transitions, it is evident that the contexts and pathways of transformation will vary from one socio-technical system to another. Nevertheless, a set of core rationales, however small this set may be at first, should be identified that could provide a common, universally accepted basis from which socio-technical transitions are understood and subsequently governed. Any approach or framework developed (in the case of this research inquiry, thus with a focus on integrating technology management and socio-technical transitions frameworks, approaches, etc.) needs to be sufficiently general so that it is applicable across a wide variety of contexts, whilst also being specific, robust and unambiguous enough to be useful and purposeful without requiring a deep understanding of the underlying theoretical assumptions. This would require an identification of the differences and similarities across a number of dimensions (the work produced by Coenen and Díaz López (2010), amongst others, could serve as a starting point), and subsequently a definition of the foundational activities that would support the analysis, development, fostering and governance of socio-technical systems within the context of sustainability. Such core activities should preferably be common across socio-technical systems and contexts. The differences between the perspectives and conceptual basis of the existing bodies of socio-technical transition literature could resist a problem-free synthesis of these core technology management activities that could contribute towards sustainability transitions, which is deemed possible, at least to an extent. This thus necessitates that any proposed framework also establishes an appropriate level and unit of analysis for an integration of the fields.

The need for any activities that are identified as potentially contributing towards the analysis, development, fostering and/or government of socio-technical systems within the context of sustainability to be linked to, and supported by, practical tools and techniques, is highlighted. The primary aim should remain to address the questions about the concepts, practicalities and methodologies that would result in the ever-elusive promise of sustainable development, as implied by socio-technical transition governance and management, and how these desired future states are to be achieved. Such tools should support transition managers, activists and policymakers to overcome confusion when concerned with socio-technical transitions. These tools and techniques should provide direction when dealing with both the barriers and the enabling factors when concerned with incumbent technologies and practices. Such tools should thus be applicable not only to operational activities but should reach across all levels of organisation – and in the event of socio-technical systems and more specifically sustainability transitions, across transition pathways and phases too.

It is clear that defining a set of core activities, at an appropriate level of analysis, and subsequently the activities that could develop and exploit such activities, will make it possible to contribute towards standardisation and consensus building across the various socio-technical perspectives. In addition, it is envisaged that the quest for increased crossover and integration between socio-technical transition perspectives, approaches and frameworks will be advanced at the activities level, as well as the tools and techniques level given the approach proposed above. If these foundational similarities can be explicated, they hold the promise for cross-pollination between socio-technical transition perspectives, as well as with the concept of technology management.

Another proposition, taken from technology management, is that a set of supporting activities is identified, and linked with specific transition activities, and transition tools and techniques. The granularity, and the dissemination of the elements that constitute a transition, and subsequently the linking of different perspectives, fields of knowledge and supporting activities across these elements are envisaged to contribute to the accumulation of a consistent stock of knowledge about socio-technical transitions. A key objective will be to ensure that resources are effectively linked to transition requirements to contribute towards establishing resilient transition management competencies. Here, given that the focus is on technology management and sustainability transitions, resource allocation is implied, given the technology management capacities required, rather than explicitly stating what specific resources are required.

When transitions literature, the above synthetisation, and the challenges faced by this body of literature are considered, the proposition is that the dimensions, which should be considered in an integration strategy, include:

i. Allowing for consensus building across socio-technical perspectives, ultimately implying simplification and standardisation – here the requirement for an integration strategy and subsequent framework is that it should be applicable to a range of contexts;
ii. Improving the application selection process and reducing the confusion between frameworks and approaches – the requirement here links with the requirement above, in that the framework should ideally not bring about the challenge of application selection, but that it should ideally allow for insights across a broad spectrum of contexts;
iii. Addressing the barriers that hinder the accumulation of a consistent knowledge stock for socio-technical transitions;
iv. Enabling and/or fostering collaboration, integration and cross-over between the various socio-technical transition perspectives, frameworks and approaches, as well as other (supporting) frameworks and activities; and
v. Assisting with the process of operationalising and institutionalising the concepts of socio-technical transitions, i.e., how do we offer some practical guidelines to support the transitioning of socio-technical systems – this is envisaged to be one of the key motivations driving the development of the integrated framework.

5.2.3 Guiding principles and questions

Having explored and discussed the key epistemic and methodological grounds of socio-technical transitions and technology management, as well as having highlighted the challenges and views from the respective bodies of literature that could assist in addressing such challenges, at least in part, in this section the element(s) around which a 'meta-perspective' is proposed are discussed. In addition, they way that a premise for integrating technology management and socio-technical transitions may contribute to moving towards sustainability and how this may be articulated through the insights gained from the parallel analysis of technology management and socio-technical transitions, with the proposition that the 'integration' or 'bridging' of such concepts offers value within the context of sustainability, is discussed.

From the five dimensions that are respectively articulated for both technology management (Section 5.2.1) and socio-technical transitions (Section 5.2.2), a set of guiding principles is proposed that will form the basis upon which an integrated meta-perspective (i.e., the integration strategy) between socio-technical transitions and technology management is developed. Thus, any concept, construct and/or framework that aims to provide a helpful premise for integration between technology management and socio-technical transitions should:

i. Go beyond the ordering of either technology management or socio-technical transitions (thus looking outside the current scopes of these two scientific networks in order to find 'common ground'). This implies that such an attempt will call for an alternative unit and/or level of analysis that allows for integration;
ii. Facilitate in dealing with complexity; this entails that an objective should be to support the development of goals and objectives across system levels (strategic and operational), as well as the alignment of such goals and objectives that are potentially defined at different levels and from different perspectives of a system and across different transition phases;
iii. Support the development of strategic, tactical and operational goals that will enable/facilitate (i) the transitioning of socio-technical systems, and (ii) the increased sustainability of socio-technical system from the perspective of technology management;
iv. Contribute towards the operationalising and institutionalising of the concept of transitions;
v. Support the idea of a set of core rationales and/or activities – this guiding principle is linked with guiding principle (iii) in that an objective should be to keep the framework as parsimonious and generic as possible; and
vi. Develop and exploit (the required) capabilities within a socio-technical system that will support transitioning towards increasingly sustainable futures.

Thus, an integration strategy between socio-technical transitions and technology management should support the understanding of the role of technology in transitioning towards sustainability, and it should enable effective means to integrate the concepts of technology management with those of socio-technical transitions. And, ultimately, the integration strategy needs to contribute towards the fostering, enabling and bringing about of sustainable transitions. Consequently, against the backdrop of technology management and socio-technical transitions, it is proposed that the identification of the required capabilities and subsequent development and exploitation of such capabilities, which will support transitioning towards a (sustainable) future state (accounting for transition progress through transition phases, as well as across transition pathways), should be explored. It is not a specific transition, a socio-technical system or a technology deemed fit to contribute towards sustainability that becomes the unit of analysis, but rather the capabilities required to transition and/or to facilitate the progression of the transition. Given that the focus is on the integration of technology management, "transition technology management" could thus be envisaged as the (i) identification, (ii) development, and (ii) exploitation of the technology management capabilities required at a given point (or period) of a system's transition towards a future (more sustainable) system state.

Technology management within the context of socio-technical transitions has to be seen as a punctuated equilibrium, meaning that, as the particular socio-technical system evolves, and more specifically, the transition progresses (either towards the desired state or away from it), a need for a different set of, and/or different constellation of transition technology management capabilities will arise. Expressed as such, technology management within the context of socio-technical transitions is imagined to incorporate a set of practices/activities to execute and coordinate the tasks required to foster transitions, or more specifically, contribute towards transition progression.

The aim is not to impose some fixed, predetermined view of socio-technical transitions, sustainable future states and goals, or desirable paths to sustainability; but rather to contribute towards the transition debates, by introducing complementary views on the way to mobilise socio-technical transitions through the development of technology management capabilities. This concept acknowledges the fact that socio-technical transitions are necessarily more complex than the initial stages where a particular vision of sustainability is negotiated (Smith and Stirling, 2008), and the perception that a 'one-model-fits-all', as if all transition activities will exist within one socio-technical transition, will not be entertained. It is certain that socio-technical systems will have to focus on particular transition activities, given their specific contexts as well as goals and objectives, and more importantly that technology management activities and depending on, amongst other factors, the change in transition progress. Technology management activities here are envisaged to potentially comprise a significant number of activities, when a number of different socio-technical systems and transition phases – especially given the number of elements present in such socio-technical systems - are considered. However, it is argued that it might be possible to identify a set of processes and/or routines that addresses the fundamental and common processes that are critical to socio-technical transition progress, and that the identification, development and exploitation of the (required) technology management capabilities will contribute towards (i) an improved understanding of sustainability transitions, more specifically insights into the role of technology management in such transitions, and (ii) to gain an improved understanding of the relationship between transitions and technology management, specifically given the co-evolutionary nature of sustainability transition.

Any concept that transcends technology management and socio-technical transitions, within the context of socio-technical transitions, and the role and management of technology within such transitions, is thus conceived as the development and exploitation of the capability of a system to transition. Such a concept should be purposefully oriented towards improving our understanding of decision-making that will develop and exploit the capability of a socio-technical system to transition, and for the transition to progress and hence not fail.

Two key questions that must be addressed when further conceptualising the abovementioned concept, are proposed below. These questions, along with the set of guiding principles, form the basis from which operational links between technology management and socio-technical transitions will be explored and elaborated on in the bridging phase in order to develop an integration strategy. The questions that should be addressed in order to develop an integration strategy include:

i. What are the appropriate perspectives and/or units of analysis that will allow for linkages to be established between sustainability transitions and technology management?
ii. How does one identify the technology management considerations required that will contribute towards sustainability transitions?

It is proposed that transition technology management, therefore, identifies the technology management considerations, which enable responses to sustainability opportunities (and challenges), and which demand a socio-technical system to transition. This implies that differentiation and alterations to products, services and technologies occur. Transition technology management addresses the effective identification, selection, development, exploitation and protection of transition capabilities (product, process, resources and infrastructure), which are needed to improve a socio-technical system's capability to transition. The goal of transition management is thus to facilitate the synergy and collaboration between elements that bring about the capability of a socio-technical system to transition.

5.3 Conclusion: Chapter 5

In this chapter, the importance and opportunities associated with integrating the perspectives of technology management and socio-technical are highlighted. and the rationale for an integration strategy that identifies and defines the interface between technology management and socio-technical transitions is further evidenced. The concluding argument is that integration and translation across these fields will lead to qualitative contributions in the theoretical and methodological approaches of both fields, and that an increasingly pluralistic understanding and framing of how technology could, or should, be managed within the context of socio-technical transitions is necessary. In Chapter 6, a strategy – in the form of a set of requirements - for the integration between technology management and socio-technical transitions is presented.

Chapter 6.

An integration strategy: Bridging between technology management and socio-technical transitions

This chapter sets out a proposal for an integration strategy that acts as a bridge between the concepts of technology management and socio-technical transitions. This integration strategy is formulated in the form of a set of requirement specifications. It concludes the background research and the synthesis of the literature to support the development of a premise for integration between the concepts of technology management and sustainability transitions. The 'bridging' step of the methodology introduced in Chapter 5 is conducted in this chapter. Its objective is to use the insights gained from the alignment step, which is presented in Chapter 5, to enable the formulation of an integration strategy that transcends technology management and socio-technical transitions. The goal here is thus to articulate the conceptual notions from which to develop a premise for integration between the concepts of technology management and sustainability transitions. In this chapter, a semi-systematic review of literature is initially done to identify constructs, frameworks and concepts that may be used to elaborate on the guiding principles and questions derived in Chapter 5, the guiding questions and principles are subsequently elaborated on, and finally a set of requirement specifications is presented.

6.1 Concepts, constructs, frameworks and approaches to support the development of an integration strategy

In order to support, and elaborate on, the guiding principles and questions, a semi-systematic literature analysis was conducted. In presenting their analysis of literature review methodologies, Snyder (2019) highlights the fact that semi-systematic reviews of literature seek to identify literature that could be potentially relevant for the research at hand. The guiding principles and questions (presented in Section 5.2.3) guided our review of the literature in order to identify constructs that are (i) relevant to our particular research, and that may (ii) support the development of a premise for the integration between technology management and socio-technical transitions. It should be noted that, for the sake of brevity, only the literature deemed relevant and conducive to the development of the abovementioned premise is presented in this chapter, even though our review stretched beyond these bodies of literature.

Section 6.1.1 starts with an overview of transition characteristics and the implications of such characteristics for any proposed integration strategy. Next, further concepts identified in the literature, that are deemed appropriate and necessary to address and elaborate on the respective guiding principles and guiding questions, are discussed in Section 6.1.2.

6.1.1 Transition characteristics and the implications for an integration strategy

In this section, the transition characteristics (as stated in the literature) are explored and the implications of such characteristics for an integration strategy are inferred.

The following characteristics were identified, which are considered to allow for the distinctness of sustainability transitions – as provided by a group of 29 scholars in the field of transitions (amongst them some of the most prominent in this field, i.e., Jonathan Köhler, Frank Geels, and Jochen Markard) in a recent publication that considers the state of the art and future directions of sustainability transitions research (Köhler *et al.*, 2019):

i. Multi-dimensionality and co-evolution;
ii. Multi-actor processes;
iii. Stability and change;
iv. Long-term process;
v. Open-endedness;
vi. Values, contestation and disagreement; and
vii. Normative directionality.

The following sections provide a summarised account of these characteristics, and elaborate on their implications for developing an integration strategy between technology management and socio-technical transitions. Given the aim of addressing the disconnection between sustainability transitions and the management of technology, and given that at this point in the research the focus is on establishing a strategy for integration, the implications of the characteristics are considered from the perspective of implications for such an integration strategy.

Multi-dimensionality and co-evolution	*"Socio-technical systems consist of multiple elements: technologies, markets, user practices, cultural meanings, infrastructures, policies, industry structures, and supply and distribution chains. Transitions are therefore co-evolutionary processes, involving changes in a range of elements and dimensions. Transitions are not linear processes, but entail multiple, interdependent developments"* (Köhler *et al.*, 2019:2).

Implications of the multi-dimensionality and co-evolutionary characteristic of transitions for an integration strategy

The multi-level perspective (Geels, 2004), which informs much of the socio-technical transitions literature and concepts, regards transitions as the interaction between three levels: landscape, regime and niche. When specifically considering technology management in the context of sustainability transitions, the regime represents incumbent technologies, actors and institutions. Niches reflect emerging and less developed configurations of technological innovations that could potentially become established as a new (more sustainable) regime. Given this multi-level perspective, an integration strategy should account for the role of technology management across both regime and niche levels, as this is where the technology that has to be managed, is primarily at play. When considering transition progress and the phased approach to transitions (Rotmans, Kemp and Van Asselt, 2001), an integration strategy is thus envisaged to consider technology management that supports the factors/drivers that facilitate and support transition progress (i) at the niche level, and (ii) at the regime level. This dual consideration is then applicable across the different transition phases, as the factors/drivers that facilitate/support transition progress across transitional phases differ (Frantzeskaki and de Haan, 2009; Kivimaa *et al.*, 2019; Schilling, Wyss and Binder, 2018).

When considering technology management, and as mentioned in Chapter 5, incorporating a multi-level perspective could enhance the management of technology to be able to, in turn, support the (effective[29]) interplay between the existing regime and technological innovations. This essentially means also putting the management of technology in relation to the requirements at regime level, and in relation to the requirements at niche level that will contribute towards a successful transition.

Multi-actor process	*"Transitions are enacted by a range of actors and social groups from academia, politics, industry, civil society and households. These actors and groups have their own resources, capabilities, beliefs, strategies, and interests. Transitions involve many kinds of agency (e.g. sense-making, strategic calculation, learning, making investments, conflict, power struggles, creating alliances), which makes them very complicated processes that cannot be comprehensively addressed by single theories or disciplines"* (Köhler *et al.*, 2019:2).

Implications of the multi-actor process for an integration strategy

When considering innovation systems, a distinction is made in the literature between primary and secondary actors. Actors who are directly involved in performing innovation activities are primary actors, whereas secondary actors affect the behaviour of, or interaction between, primary actors (Coenen and Díaz López, 2010; Liu and White, 2001). However, even though it is envisaged that an integration strategy will consider both primary and secondary actors, the primary focus will be on the required capacities and/or capabilities required to support the transformational processes rather than specifically considering the actors who will perform such functions. Kivimaa *et al.* (2018) and Kivimaa *et al.* (2019), amongst other scholars, investigated intermediaries in transition processes (i.e., actors connecting other actors in transition processes), and even though intermediaries are not regarded as a necessary element in the development of an integration strategy, the intermediary functions identified by Kivimaa *et al.* (2019) and the intermediary typology developed by Kivimaa *et al.* (2018), specifically the stated goals of the intermediaries, proved to be useful in order to further refine the transitions goals and/or targets across the various transition phases.

Stability and change	*"A core issue in transition research is the relation between stability and change. Because of its interest in system change, transitions research aims to understand the multi-dimensional interactions between impulses for radical change and the forces of stability and path dependence. Transition research mobilizes insights from*

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[29] The effective interplay between the existing regime and niche-level activities are considered to such that will contribute towards transition progress.

different disciplines and theories to understand this dialectic relationship between stability and change" (Köhler *et al.*, 2019:2).

Implications of stability and change for an integration strategy

The implications for the integration strategy here are considered to be fairly obvious: Firstly, transitions are observed as an interplay between (i) change driven by innovations, by landscape developments, and by internal changes in incumbent systems (forces of change), and (ii) the stability (incumbent nature) of the regime (resistance against transformational change) – whilst also bearing in mind that transitions in fact depend on the ability of a regime to be destabilised (Köhler *et al.*, 2019). Secondly, the notion that transition resilience is dependent on transition progress (thus change), stability (which are depicted as the stability of the transition pathway and the system resilience), and adaptability (the extent to which the transition process can be adapted) (Schilling, Wyss and Binder, 2018) have to be taken into account. With regard to the management of technology, the way that technology may (or should) be manged to support either change or stability (or both) should be understood. Given the multi-level characteristics of transitions, the integration strategy should then take into account transition progress, stability and adaptability across multi-levels and across the various transition phases.

Long-term process

"Transitions are long-term processes that may take decades to unfold. One reason is that radical 'green' innovations and practices often take a long time to develop from their early emergence in small application niches to widespread diffusion. Another reason is that it takes time to destabilize and 'unlock' existing systems and overcome resistance from incumbent actors. To make research tractable, transitions can be divided into different phases, e.g. predevelopment, take-off, acceleration, and stabilization" (Köhler *et al.*, 2019:3).

Implications of transitions as a long-term process for an integration strategy

Given that transition progress is conceptualised as the dialectic between drivers for system change and resistance against system change, and the fact that sustainability transitions are considered long-term processes due to the interaction between the niche developments (drivers) and the incumbent regime (resistance), it is clear that transition progress should be considered across the different phases for at least three reasons:

i. To allow for a more nuanced view on the co-evolution present within transitions;
ii. To account for the different constellations of transition progress along a transition pathway; and
iii. To make research into transitions manageable.

Open-endedness and uncertainty

"In all domains, there are multiple promising innovations and initiatives and it is impossible to predict which of these will prevail. Since there are multiple transition pathways (Geels and Schot, 2007; Rosenbloom, 2017), the future is open-ended. Uncertainty also stems from the non-linear character of innovation processes (which may experience failures, hype-disappointment cycles or accelerated price/performance improvements), political processes (which may experience setbacks, reversals or accelerations) and socio-cultural processes (which may

experience changes in public agendas and sense of urgency)" (Köhler *et al.*, 2019:3).

Implications of the open-endedness and uncertainty of transitions for an integration strategy

The characteristics of sustainability transactions such as open-endedness and uncertainty will inevitably create boundaries and limitations to any methodological approach (Walrave and Raven, 2016). However, it is argued that, by integrating the concepts of adaptability (Schilling, Wyss and Binder, 2018) into the integration strategy, it allows for a nuanced view of transitions that incorporates open-endedness and uncertainty, at least to an extent. Even though there might be many promising innovations and initiatives whose success is 'impossible' to predict (Köhler *et al.*, 2019), understanding the forces that drive or resist transitional change, and then considering the action (be this from a technology management perspective or not), which is required to support the transition progress, could allow for analytical and methodological simplification in order to interpret the transition at a given period in time.

Values, contestation, and disagreement	*"The notion of sustainability is, of course, highly contested, so different actors and social groups also tend to disagree about the most desirable innovations and transition pathways for sustainability transitions. Since sustainability transitions may threaten the economic positions and business models of some of the largest and most powerful industries (e.g. oil, automotive, electric utilities, agro-food), such incumbents are likely to protect their vested interests and contest the need, for and speed of, transitions"* (Köhler *et al.*, 2019:3).

Implications of values, contestation and disagreement for an integration strategy

The way in which transition progress is conceptualised and adopted in this research inquiry, i.e., as the tension between the drivers for system change and the resistance against it, accounts for the contestation and disagreement characteristic of sustainability transitions. In addition, a key consideration in the transitions literature – which also links to the 'long-term process' characteristic of sustainability transitions – is the patterns of decline and destabilisation of incumbent regimes. It is argued that an integration strategy will explicitly have to incorporate the destabilisation, decline and phase-out of incumbent regimes. However, as mentioned when the 'multi-actor' characteristic of sustainability transitions was discussed above, the specific actors will not be integral to the integration strategy but will be kept in mind at certain junctions in the integration strategy.

Normative directionality	*"Since sustainability is a public good, private actors (e.g. firms, consumers) have limited incentives to address it owing to free-rider problems and prisoner's dilemmas. This means that public policy must play a central role in shaping the directionality of transitions through environmental regulations, standards, taxes, subsidies, and innovation policies. This necessitates normative statements about what transitions seek to achieve"* (Köhler *et al.*, 2019:3).

Implications for an integration strategy:

The integration strategy, and thus any subsequent concept that aims to transcend and/or bridge technology management and socio-technical transitions should thus contribute to establishing normative directionality. This is also aligned to GP2 – GP5 (see Table 29 and Table 30). However, the aim of this research inquiry is not to identify and highlight the incentives of sustainability for private actors, but rather to highlight the requirements and therefore opportunities for businesses, for example, in terms of including social and environmental value creation alongside the 'traditional' understanding of value creation. Nonetheless, this will most likely not directly result in the creation of normative directionality, but rather – as is the case for the other transition characteristics too – merely contribute towards an increased understanding of ways to deal with these challenges.

6.1.2 Theoretical background for the integration strategy

The multi-phase concept (pre-development, take-off, acceleration, and stabilisation – see Figure 28), the multi-level concept (landscape, regime, niche – see Figure 29), and the multi-change concept (i.e., during transitions new structures emerge, while existing structures are broken down) provide for three analytical perspectives that are used throughout the literature to recognise and explain transition patterns (Brugge and Rotmans, 2007). Therefore, these concepts will also be used herein to elucidate the link between technology management and sustainability transitions in order to investigate the role of technology management in the context of sustainability transitions. In addition to these overarching concepts, and in line with the elaborations of the guiding questions and the guiding principles discussed at the start of this chapter, the concepts discussed throughout this Section 6.1.2 include transition phases, transition resilience, forces driving and resisting transitional change, transition and transformational failures and points of interventions in the multi-level structure of socio-technical systems.

6.1.2.1 Transition phases

Transitions can be delineated into phases, with each phase having different dynamics of transitional change. This in turn allows for different processes to be identified in each of the transitions phases (Frantzeskaki and de Haan, 2009). The interplay of the functional subsystems (i.e., regime, niche, niche-regime and landscape) is different from one phase to the other – as is the case with the interaction between different subsystems relating to transition pathways. At the conceptual level, transitions can be depicted as having four different transition phases (Rotmans, Kemp and Van Asselt, 2001): (i) a predevelopment phase, where change builds up, as well as where tensions between the regime and landscape developments can start to be observed; (ii) a take-off phase between the pre-development phase and the acceleration phase that represents a tipping point in system change; (iii) a breakthrough or acceleration phase, where a new or alternative regime is produced that changes the functioning of the socio-technical system; and (iv) a stabilisation phase, where the self-organising dynamics of the newly produced regime institutionalise the new order and functioning of the socio-technical system, thus leading to a new dynamical equilibrium. In each phase, functioning is either empowered or depowered, increasingly resulting in more and more actors adhering to the new functioning (Frantzeskaki and de Haan, 2009). Furthermore, transition scholars (i.e., Grin et al., 2010; Köhler et al., 2019) are clear on the fact that the required interventions to support transition progress may change, depending on the transition phase, and that they are thus an important consideration for the integration strategy and any subsequent concept(s) that may be developed. Figure 28 shows the various transition phases as change in the system over time. In the subsequent sections, the four phases summarised above are elaborated on further.

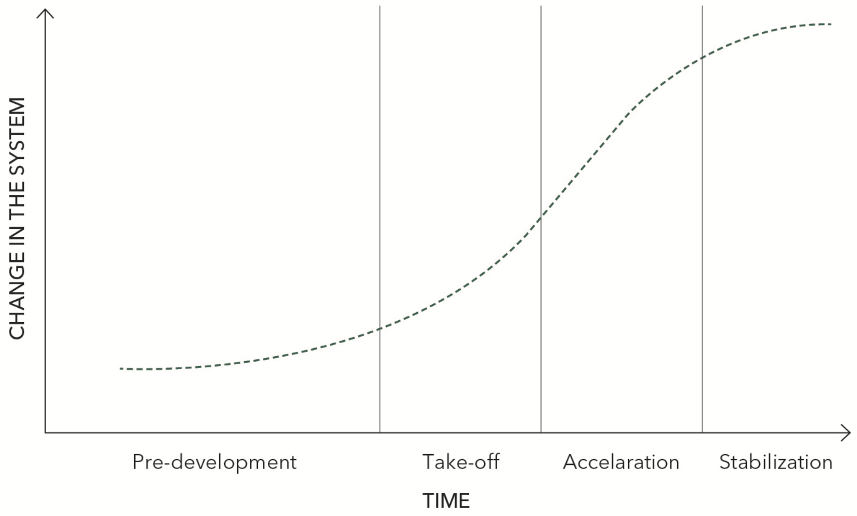

Figure 28. Transition phases shown as change in the system over time (adapted from Rotmans, Kemp and Van Asselt, 2001)

Phase 1: Pre-development

In the pre-development phase, a socio-technical regime is characterised by dynamic equilibrium, and thus, even though landscape pressures are present, very little change is visible within the regime. Van der Brugge and Rotmans (2007) state that, during this phase, co-evolutionary regime dynamics increase regime interdependencies and, as a result, the regime organisation approaches criticality. The resilience of the system decreases, and the system structure becomes increasingly vulnerable. The changes, though limited, create stress within the regime and on the regime structure, and thus results in actors within the regime putting efforts and resources into improving existing technologies and employing strategic efforts to caution against new developments that (might) threaten the regime (Rotmans, Kemp and Van Asselt, 2001). Challenges are perceived as singular technological problems, and the solutions that are provided do not solve the challenges on a more fundamental level; the (fundamental) challenges that the system faces are consequently not addressed. This path-dependent way of managing the challenges within the system initially relies on efficiency improvements and incremental changes, but in due time the system approaches criticality, which essentially means that the system's thresholds are being reached (Van der Brugge and Rotmans, 2007).

In the pre-development phase, innovations that can potentially challenge the incumbent (unsustainable) technologies in the regime are still isolated and fragmented, improperly embedded and not yet sufficiently developed to challenge the existing regime (Van der Brugge and Rotmans, 2007). Even though the regime is in a dynamic equilibrium state, innovations emerge in peripheral niches (Geels, 2018) due to a great deal of experimentation happening at the individual level (Dewulf *et al.*, 2009). The novelties that surface in this transition phase emerge in the context of developments on landscape and regime levels. Landscape pressures are present, and even though the regime is still in dynamic equilibrium, innovations and novelties are produced. However, at this stage of the transition, there is not yet a dominant design and various different niches might be competing with one another. During this phase, actors typically improvise, experiment with designs, and try to align heterogeneous elements in co-construction processes. Niches are also supported, as actors hope that these innovations will be incorporated into the regime over time, or even eventually replace the regime. This uptake of niches into the regime and/or the replacement of technologies in the regime with new or alternative technologies are challenging, as the existing regime is rooted in many ways (e.g. institutionally, organisationally, economically, culturally). Furthermore, niches with the potential to fulfil the societal functions that are currently fulfilled by the regime are often misaligned with the existing regime and may struggle to break through (Geels, 2006).

Often, in this early period of a transition, the current (unsustainable) regime acts as an inhibiting factor (Rotmans, Kemp and Van Asselt, 2001). The success of a transition process in the pre-development phase depends on whether the relation between the transition drivers and the resistance against the (required) changes in the system develops in a way that enables system change (Schilling, Wyss and Binder, 2018).

Phase 2: Take-off (triggering change and build-up of new regime)

In the take-off phase, the structure of the incumbent system starts to change due to: (i) the emergence of innovations (that were/are being developed in niches), and (ii) the destabilisation of the existing regime (Van der Brugge and Rotmans, 2007). Thus, the regime grows 'critical', and the innovations and novelties that are being developed start to perturb or shock the incumbent system, triggering large-scale change. As the system becomes progressively 'critical', serious challenges and system inadequacies affect all critical system domains due to the high interconnectivity of socio-technical systems. What is important here, is that change has to be triggered, thus actors have to recognise the inherent problems of the current system and to provide for strategies that will address such fundamental problems (Van der Brugge and Rotmans, 2007).

In this phase, innovations stabilise and enter small market niches (Geels, 2018) – also referred to as niche-regimes (Frantzeskaki and de Haan, 2009). The community(ies) that engage in the market niches, articulate new rules, and the emerging technology develops a path of its own. As users increasingly interact with alternative or new technologies, and as these technologies are incorporated into user practices, users build up experience with such technologies and gradually explore new functionalities (Geels, 2006). Here, access to resources is critical for networks to develop. A key indicator of success in this phase is whether or not there is an innovation network that is able to become self-sustaining. Van der Brugge and Rotmans (2007) emphasise that the build-up of the new regime is critical in this phase. In order for innovations to 'break through' (which happens in the acceleration phase of a transition), regime structures must open up windows of opportunity that allow the innovation(s) to enter the system. Success, or the 'path forward', which will result in the transition progressing from the take-off phase, given the dynamics at the regime and niche levels, as well as the interaction between the niche and regime levels, depends on the ability of the niche innovation(s) to stabilise (i.e., their 'survival fitness), as well as on the co-evolutionary developments in the regime. This essentially means that a dominant innovation emerges that is reinforced by smaller innovation networks, and this dominant design is enabled to accelerate and diffuse.

Van der Brugge and Rotmans (2007) state that there are two ways in which a transition will no longer be considered to be progressing, and this can occur under the following two conditions: Firstly, when competing innovation networks continue to co-exists, it is referred to as lock-in (see Figure 32). Or, secondly, when there is a (more or less) chaotic world in which innovation networks are all insufficient in becoming self-sustaining, and when they continue to compete for the same resources, there is thus no suitable substitute to replace the existing (destabilising) regime – this is referred to as system breakdown (also see Figure 32). A more detailed account of transition and transformational failures is presented in Section 6.1.2.4.

Loorbach (2004) introduced the idea of 'multi-level governance', which sees the management of transitions as the interactions between processes at (i) the strategic level, (ii) the tactical level, and (iii) the operational level. Elements at the strategic level include problem structuring, envisioning and long-term goals. At the tactical level, agenda-building, negotiations and networking are considered. Lastly, the operational level comprises projects, innovations, experiments and implementation. Van der Brugge and Rotmans (2007) argue that, as long as 'gaps' exists between the strategic and operational levels – in other words, as long as the strategic intent is not translated into operational objectives – the transition will remain in the take-off phase. Changes that are performed well and that are conducive to transitional progress at the institutional level have significant reinforcing power. However, if not well-aligned with the transition objectives, institutional changes can either slow down the transition or block the progression in the desired or required direction.

Phase 3: Acceleration (cascading effects)

During the acceleration phase, niches enter the mainstream market and begin to compete with the incumbent regime (Schot, Kanger and Verbong, 2016). Here structural transformation of the system takes place. The acceleration phase is demarcated as the event when the selection rules for policy and implementation change according to the requirements of the new or alternative emerging regime – indicating that the selection power is transferring from the existing regime to the emerging regime. In this phase, the existing regime undergoes a process of re-configuration that potentially demands significantly different modes of operation, cooperation and regulation. In this phase, it is important to note that the transition is still in the transformation process between the two regime attractors, and the decisions that are being made here have and will have a significant impact on the direction of the transition (Van der Brugge and Rotmans, 2007).

During the acceleration phase, new technologies break through, are widely diffused and are in competition with the existing incumbent regime. The factors that drive transformational change here are two-fold (and complementary): firstly, there are internal drivers in the niche that may relate to price and/or performance improvements, increasing returns, virtuous cycles of processes within the niches, and/or actors that support the new technologies and drive the diffusion thereof. And secondly, there are factors external to the niche, i.e., at landscape and regime level. These may be ongoing tensions in the regime, such as challenges that cannot be met with existing technologies (for example, technical bottlenecks (Hughes, 1987), weakening returns of existing technologies (Freeman and Perez, 1988), etc. Changes in markets, user preferences and cultural changes in the existing regime may also drive the transition. Furthermore, changes such as changes in policies, regulations, etc. may create favourable environments for new/alternative technologies (Geels, 2018). All of these processes create (additional) windows of opportunity for the emerging regime to grow and increase its power. A key notion here is that in order for (successful) transitions to come about, niche-internal processes have to align with ongoing processes and tensions in the existing regime and landscape developments. This highlights the fact that the existing regime does not only allow for barriers for the emerging niche-regime to overcome, but may also provide opportunities for such emerging niche-regimes in that they could fulfil the requirements and address the tensions and landscape pressures that the existing regime potentially cannot (Geels, 2018).

Thus, in the acceleration phase, visible structural changes take place as a result of an accumulation of economic, cultural, institutional and ecological changes (Ehnert et al., 2018). These are often due to the effects of large-scale applications of new or alternative technologies – highlighting the need to control the possible (unintended) consequences of the large-scale application of such new or alternative technologies.

Phase 4: Stabilisation

In the stabilisation phase, the speed of the system change decreases and a new dynamic equilibrium is reached, when the new technology replaces the old regime. However, changes in the socio-technical regime may still occur as mis-alignment might still exists between the new technology and socio-economic dimensions (Geels, 2006).

Although the MLP and the transition phases are interconnected, this link is mostly made only implicitly in the literature (Kivimaa *et al.*, 2019). However, throughout the literature, incorporating a phased approach to transitions highlights the importance of the timing of interventions that aim to steer such transitions (Kivimaa *et al.*, 2019; Safarzyńska, Frenken and Van Den Bergh, 2012). This means that the required (technology management) activities in each phase will vary. It should be noted that by taking niche development as the start of a transition (as is the case with MLP (see Figure 29) and as demarcated by the notion of transition phases (Rotmans, Kemp and Van Asselt, 2001), other transition pathways (i.e., such as when transformational change originates from the regime level) are not taken into account (Kivimaa *et al.*, 2019). Recently scholars have increasingly highlighted the importance of the destabilising, decline and phase-out of existing systems and regimes (Roberts, 2017; Kungl and Geels, 2018; Köhler *et al.*, 2019). However, concepts like the MLP and the phased view of transitions underplay the process of destabilisation (Kivimaa *et al.*, 2019; Turnheim and Geels, 2012). Nonetheless, the destabilisation, decline and phase-out of incumbent (unsustainable) systems are, almost without fail, considered a key requirement for successful transitions. In this research inquiry, destabilisation is taken into account in our conceptualisation of transition phases, as proposed by Kivimaa *et al.* (2019), to occur concurrently with, or before or after, niche-specific processes of exploration (pre-development and take-off phases) and embedding (acceleration and stabilisation phases).

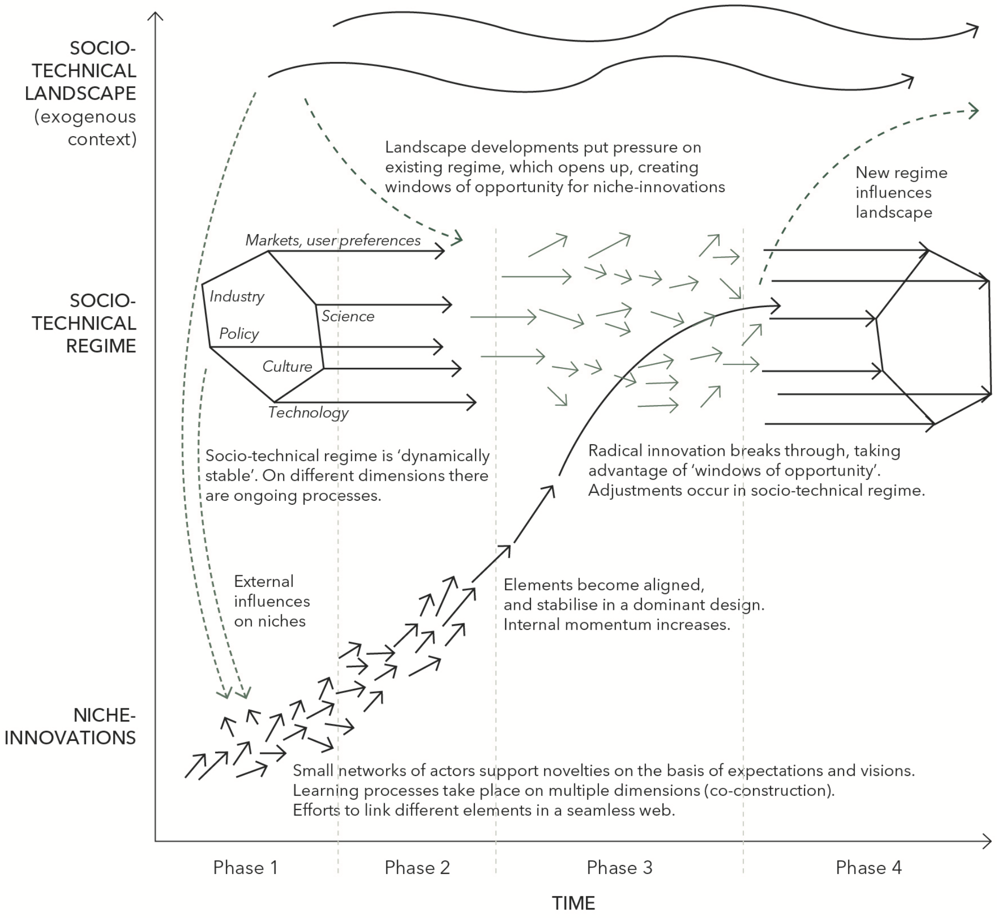

Figure 29: Multi-level perspective and transition phases (adapted from Geels & Schot, 2007; Geels, 2018)

It should be noted that the various transitions phases are demarcated slightly differently by different transition scholars. However, that is not perceived to be a challenge when considering the aim of this research inquiry, namely, to develop a concept that allows for differentiation between phases, but that is applicable across all phases.

6.1.2.2 Transition resilience

Resilience is defined as "*the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress"*[30]. Within the context of socio-technical systems, resilience is described as *"the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks"* (Walker *et al.*, 2004). Binder *et al.* (2017), upon investigating the resilience of a system in transition, concluded that, in order for a transition to be successful, a system has to maintain its functionality. This is essentially in-line with transition and transformational failures in that transitions cannot progress if the system breaks down. Schilling *et al.*

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[30] https://www.merriam-webster.com/dictionary/resilience

(2018) developed the resilience of sustainability transitions (RST) concept and proposed (i) transition progress, (ii) stability, and (iii) adaptability as three dimensions that, when the overall transition process itself is regarded as a procedural entity, are essential for the success (and thus the resilience) of goal-oriented sustainability transitions. This concept is particularly useful in the context of this study, in that it specifically focusses on sustainability transitions. It moreover provides a premise for analytical dimensions along which the dynamic development of transitions (and more specifically transition phases) may be analysed. It further provides sufficient grounds to use in conjunction with the dynamic concepts of socio-technical transitions, such as the MLP, and transition phases and transition failures to unpack the relationship between the requirements for a resilient transition in order to derive the required interventions. Also, given the focus of this research inquiry, such research interventions will specifically be defined from a technology management perspective.

Furthermore, what makes this approach particularly relevant to the aim of this research inquiry (i.e., to provide a premise for the integration between technology management and socio-technical transitions) is that, besides the evident contributions of the RST concept to conceptualise sustainability transitions as resilient processes, Schilling et al. (2018:19) state that *"Subsequent management activities could aim at creating a resilient sustainability transition process resulting from the proper balance between transition drivers (e.g., supporting innovation), transition process stability (e.g., fostering commitment to the sustainability goals among system actors), and adaptability (e.g., facilitating continuous monitoring, reflection, and discussion of the sustainability transition process)".* Itis here that the proposition aligns with that of this study – although the management activities will be, as mentioned above, considered from a technology management perspective. The three dimensions integrated within the RST concept, i.e., progress, stability and adaptability are discussed in the sections below.

6.1.2.2.1 Progress as an RST concept dimension

Transition progress depends on the impact of the actions of actors in a system that results in changes in the structures and functions that define the current state of the system (Grin, Rotmans and Schot, 2010; Schilling, Wyss and Binder, 2018). The most fundamental characteristic of a sustainability transition is the degree to which the system transforms within a period of time; and this change in the system is dependent on two aspects (Schilling, Wyss and Binder, 2018):

i. Drivers for system change: these could be, for instance, an innovation that results in system state changes, and thus also affects the transition progress; transition drivers could vary in terms of their direction of influence, in that they could either contribute positively towards the sustainability transitions and towards a desired future state, or contribute negatively, away from sustainability and away from a desired future state; and
ii. Resistance against system change: resistance is the counterpart of drivers of system change, either slowing down transformational change or preventing it entirely.

6.1.2.2.2 Stability as an RST concept dimension

The second dimension addressed within the RST concept is 'stability'; this is related to the capacity of the system's actors to (i) deal with uncertainty; (ii) react to unforeseen events; and (iii) recover from shocks while maintaining the sustainability transition process. Stability consists of two sub-dimensions: (i) stability of the sustainability transition pathway, and (ii) system resilience. Transitions mostly occur in uncertain and unpredictable environments (Grin, Rotmans and Schot, 2010), and systems under transition are exposed to unpredictable events and risks that could have the potential to cause changes in the direction of the transition (i.e., away from the original sustainability goals), or even threaten the transition process in its entirety (Schilling, Wyss and Binder, 2018). This could then be linked to the transition and transformational failures discussed in Section 6.1.2.4. The sections below look at issues relating to the stability of the sustainability transition process and system resilience.

The overall stability of the transition process is affected by (i) the stability of the envisioned system state with the corresponding sustainability goals, and (ii) the stability of the transition pathway that is supposed to lead to the envisioned state. The stability of the envisioned (more sustainable) state is influenced by factors such as the following (Späth and Rohracher, 2010; Hecher *et al.*, 2016):

i. the specificity of the sustainability goals;
ii. the clarity and outreach with which sustainability goals are communicated towards actors in the system;
iii. the perceived advantages of the envisioned system state compared to the current state; and
iv. the general acceptance of the vision – i.e. given that sustainability is the guiding narrative for sustainability transitions, role players and stakeholders in the system have to agree on what sustainability is within the context of the system under (or in need of a) transition.

Along with the stability of the sustainability goals (i.e., the future state) and the pathway (i.e., how to realise the future state) discussed above, the stability of the system under transition also forms part of the 'stability equation', and is referred to as 'system resilience' (Schilling, Wyss and Binder, 2018). Essentially, this refers to the fact that a system has to maintain functionality throughout a transition, and not to collapse. Therefore, when transitions are considered, the basic structures and functions of the system that will protect against system collapse should be identified (Binder, Mühlemeier and Wyss, 2017). However, systems in transitions do go through (necessary) periods of instability, as the incumbent regime has to be destabilised to create windows of opportunity. Such events, which are necessary for the progression of transitions, also bring with them flaws and tensions in the system (Köhler *et al.*, 2019), and this tension and/or interplay between stability and change is central to approaches like the MLP (Geels, 2002).

6.1.2.2.3 Adaptability as an RST concept dimension

Adaptability, i.e., "*the extent to which the transition process can be adapted, if necessary*" (Schilling, Wyss and Binder, 2018:13), is the third dimension of the RST concept, and is also considered from two analytical perspectives: (i) the adaptive capacity of a system, and (ii) lock-in.

The adaptive capacity of system actors can be determined by considering the extent to which actors are capable of identifying, evaluating, and subsequently making decisions on changes to transition goals and pathways in the event of a change in boundary conditions (i.e., market developments, changes in political priorities, technological innovations, changing societal norms and/or values) (Schilling, Wyss and Binder, 2018).

Secondly, the extent to which lock-ins (i.e., extreme stability) exist should be considered. Lock-ins result in narrow and inflexible conceptions of the transition process, and limit the extent to which necessary adaptations can be made (Schilling, Wyss and Binder, 2018).

Table 20 shows the analytical perspective and the relevance of each of the dimensions' analytical perspectives to sustainability transitions.

Table 20. Analytical perspective and relevance to sustainability transitions of progress, stability and adaptability (based on Schilling, Wyss and Binder (2018)

RST DIMENSION	ANALYTICAL PERSPECTIVE	RELEVANCE FOR SUSTAINABILITY TRANSITIONS
Transition progress	Drivers for system change	Transition drivers affect the system state by changing its structure of functionality.
	Resistance against system change	Resistance is the counterpart of transition drivers. Resistance can negatively affect the sustainability transition progress by slowing it down or even preventing it.
Stability	Stability of the sustainability transition process	The stability of the transition process relates to how a system deals with uncertainty and recovers from unexpected shocks without losing its original sustainability goals as well as the envisioned transition pathway.
	System resilience	Resilience relates to the stability of the system that is experiencing the transition; the system has to maintain its functionality throughout the transition process in order for the transition to be successful. A high level of system resilience during a transition reduces the risk of system-level collapse.
Adaptability	Adaptive capacity	The adaptive capacity of system actors determines whether they are capable of identifying, critically reflecting, discussing and consensually deciding upon adaptations of the sustainability transition progress (goals or transition pathway), if boundary conditions change.
	Lock-in	Lock-ins are an extreme form of stability that can cause a very narrow and rigid conception of the transition process and prevent necessary adaptations.

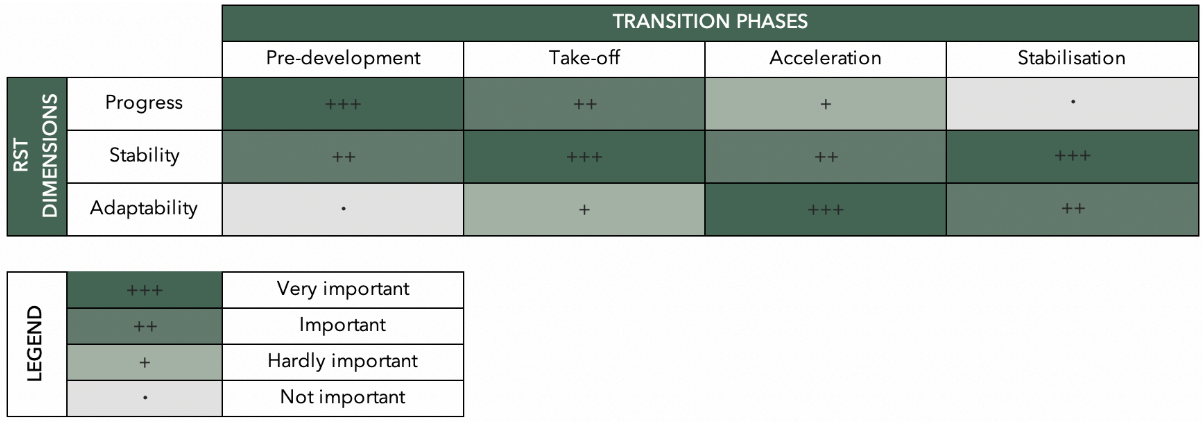
6.1.2.2.4 Progress, stability and adaptability across transition phases

The importance of progress, stability and adaptability differ across the different transition phases, given the different dynamic interactions and interrelationships between the different actors and levels. Schilling *et al.* (2018) conclude that, during the pre-development phase of a transition, particular attention should be paid to the dimension of transition progress (refer to Table 21), as the conditions for success during the pre-development phase depend on the relation between the drivers for system change and the resistance against system change; this relationship should develop in such a way that transformational change is enabled. The key here is to then exploit the drivers that contribute towards moving the system towards a set (sustainability) goal, while managing manage resistance against such system change. Progress in the take-off phase is important, but less so than stability, as the chance of system or transition failure in the take-off phase is greater due to the increasing tension and destabilisation of the existing regime. It should be noted that the relation of the importance of the dimensions is in relation to the dimensions in the same phase rather than in relation to the same dimension in another phase. For example, it is not that progress is more important in the pre-development phase than in the take-off phase, but rather that, in the take-off phase, special attention should be given to stability (over progress), as the risks here for the system to fail are greater than for the transition to fail, etc.

In Table 21, the relative importance and prominence of the dimensions in relation to each other for each of the four transitions phases are denoted with '+++', '++', '+', and ' ▪ ' for 'very important', 'important', 'hardly important' and 'not important', respectively.

During the pre-development phase, attention focuses on those aspects that will protect against stability goals being abandoned; if stability aspects are not accounted for, it becomes easy to abandon sustainability goals and visions (Schilling, Wyss and Binder, 2018). Stability is therefore an important (++) factor to consider during pre-development, but not more so than progress (refer to Table 21). Adaptability is not an important dimension during the pre-development phase, simply because the transition is only beginning; as the trajectory has not been determined in this phase, there is thus no need to consider changing the transition's trajectory. During take-off, stability is very important (+++), as the old system structures still exist and thus allow for alternatives to the sustainability transition (i.e., solutions to the disruption experienced by the incumbent system); moreover, since the regime structures have not yet changed, the transition is particularly vulnerable to unforeseen events (Schilling, Wyss and Binder, 2018). However, during the acceleration phase, even though stability is still important (++), more focus falls on the adaptability of the transition processes. Thereafter, during the stabilisation phase of a transition, stability becomes more important (++) again, as it contributes towards the development of a stable system state. During the stabilisation phase, it is of key importance to fade out transition processes (and thus not to focus on progress) and on building system resilience in order to facilitate the stabilisation of the system to (ultimately) end the transition process (Schilling, Wyss and Binder, 2018).

Table 21: Importance of RST dimensions across transition phases (based on Schilling et al., 2018)



		TRANSITION PHASES			
		Pre-development	Take-off	Acceleration	Stabilisation
RST DIMENSIONS	Progress	+++	++	+	·
	Stability	++	+++	++	+++
	Adaptability	·	+	+++	++

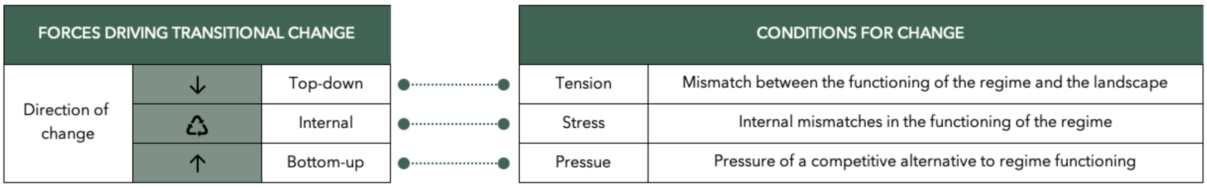
LEGEND		
	+++	Very important
	++	Important
	+	Hardly important
	·	Not important

6.1.2.3 Forces driving and resisting transitional change

Socio-technical transitions require the existing regime to change (transition/transform) to a new or alternative (more sustainable) system state; regime change is a function of two processes (Smith, Stirling and Berkhout, 2005): (i) changing selection pressures on a regime, and (ii) the coordination and management of available resources (internal and external to the regime) to adapt the regime and its functioning to the landscape developments and pressures. Within the framework of the pillar theory of transitions (De Haan, 2010; Frantzeskaki and de Haan, 2009), such drivers of transitional change are referred to as 'conditions for change’. Three conditions of change are recognised: (i) tensions with the landscape (i.e., a mismatch between the functioning of the regime and the landscape developments), (ii) stress within a constellation (internal mismatches within the regime), and (iii) pressure from constellations (mismatch with emerging and/or new niche innovations, functioning and/or technology). For transitions to occur, tension, stress and pressure are necessary – however, these are not necessarily sufficient conditions to bring about transitional change (De Haan, 2010; Frantzeskaki and de Haan, 2009). De Haan’s (2010) conceptualisation of conditions for transitional change is applicable and appropriate to sustainability transitions, as is evident in the use of these conditions for transitional change in subsequent published works, which consider transitions within the context of sustainability and sustainability transitions (i.e., Frantzeskaki and de Haan, 2009; Loorbach and Wijsman, 2013; Van Den Bergh, Truffer and Kallis, 2011).

As mentioned, conditions for change are the “*necessary but not necessarily sufficient conditions*” (Frantzeskaki and de Haan, 2009:596) that drive change in socio-technical systems. Therefore, the forces that ‘set the stage’ for these conditions need to be identified in order to gain insights into the dynamics of transitions. Forces are defined as “*a descriptive variable of the system state during a transition”* (Frantzeskaki and de Haan, 2009:596), and can either contribute towards transitional change, or in fact inhibit it. Forces that that ‘set the stage’ for conditions for change provide insight into transition dynamics. These forces of change, however, can be either stimulating or inhibiting (Frantzeskaki and de Haan, 2009), which is in line with transition progress being dependent on the dialectic between drivers of system change and resistance to system change (Schilling, Wyss and Binder, 2018).

Socio-technical systems that experience the conditions of change, may either resist it, or accommodate it, thus the system can change as a result of such conditions, or (either actively or passively) resist change, as a result of experiencing conditions of change. The changes that occur in a system are captured in patterns of change, while the resistance exerted by a system is captured in patterns of resistance (Frantzeskaki and de Haan, 2009). Figure 30 shows the relationship between forces driving transitional change and conditions for change. Essentially, the direction of change (i.e., top-down, internal or bottom-up) indicate the conditions for change experienced by the socio-technical system.



FORCES DRIVING TRANSITIONAL CHANGE			CONDITIONS FOR CHANGE	
Direction of change	↓	Top-down	Tension	Mismatch between the functioning of the regime and the landscape
	♺	Internal	Stress	Internal mismatches in the functioning of the regime
	↑	Bottom-up	Pressue	Pressure of a competitive alternative to regime functioning

Figure 30: Relationship between conditions for change ad forces driving transitional change (based on Frantzeskaki and De Haan, 2009)

Forces for transitional change are clustered together by Frantzeskaki and De Haan (2009) into three clusters, based on the influence of the force on the interaction and interplay of various actors during the transition, and their ambivalence in possibly either hindering or enabling the transition. These clusters are: (i) formation forces, (ii) support forces, and (iii) triggers or triggering forces. Forces for transitional change can thus be characterised by (i) the direction of change (i.e., top-down, internal, or bottom-up), and whether they are (ii) formation forces, supportive forces or triggers (based on the clustering criteria stated above). Figure 31 shows the forces driving transitional change (keeping in mind that these forces are ambivalent), the direction associated with the forces (i.e., top down, internal or bottom-up), as well as the clusters of the forces (i.e., formation forces, supportive forces and triggers or triggering forces).

Formation forces relate to the potential for societal innovation and include: (i) the presence of a niche, (ii) the presence of a new demand, and (iii) the presence of a new functioning. Support(ive) forces are forces that strengthen or weaken present transitional trends, and include: (i) standardisation of practices, (ii) provision of resources, and (iii) the exercise of power (over the system by external or internal centres of influence). Triggers or triggering forces perturb or shock the system; they include: (i) systemic failures, (ii) crises, and (iii) exogenous events (Frantzeskaki and de Haan, 2009). When socio-technical systems experience these conditions of change (i.e., tension, stress and/or pressure), they may either adapt to the system change, accommodate the system change, or resist it.

	DIRECTION OF CHANGE			CLUSTERING OF FORCES INFLUENCING TRANSITIONS		
Forces driving transitional change (…influence the transitional development of societal systems)	Top-down	Internal	Bottom-up	Formation forces	Support(ive) forces	Triggers or triggering forces
Crises, exogenous events	↓					T
Standardisation of practices/routines	↓				S	
Provision of resources	↓				S	
Exercise of power (over the system by external or internal centres of influence)	↓				S	
Imposition of a new functioning	↓					
Systemic failures		♺				T
Self regulation of the system		♺				S
Presence of a niche			↑	F		
Presence of a new demand			↑	F		
Presence of a new functioning	↓		↑	F		

Figure 31: Forces driving transitional change (authors own formulation based on Frantzeskaki and de Haan (2009)

6.1.2.4 Transition and transformational failures

Progress is defined as *"a forward or onward movement (to an objective or to a goal)*"[31]. Transition is defined as *"a movement, development or evolution from one form, state or style to another"*[32]. However, within the context of sustainability transitions, system transformation raises the question of how to monitor and evaluate continuing transitional progress (as a transition that no longer progresses, but stops and thus fails), as well as the resilience of such a transition over time (Binder, Mühlemeier and Wyss, 2017). The success of a transition is multi-faceted, and only in the recent literature (Panetti *et al.*, 2018) have the mechanisms that enable and drive transitions been explicitly addressed. However, in order to understand what is meant by a resilient and/or a successful transition, we consider here the scenarios that explain 'failed transitions'. Failed transitions, and the conditions under which such failures occur, are described in the literature by a number of scholars (De Haan, 2010; Van der Brugge and Rotmans, 2007). Figure 32 shows a schematic representation of the different transition failures.

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[31] https://www.merriam-webster.com/dictionary/progress
[32] https://www.merriam-webster.com/dictionary/transition

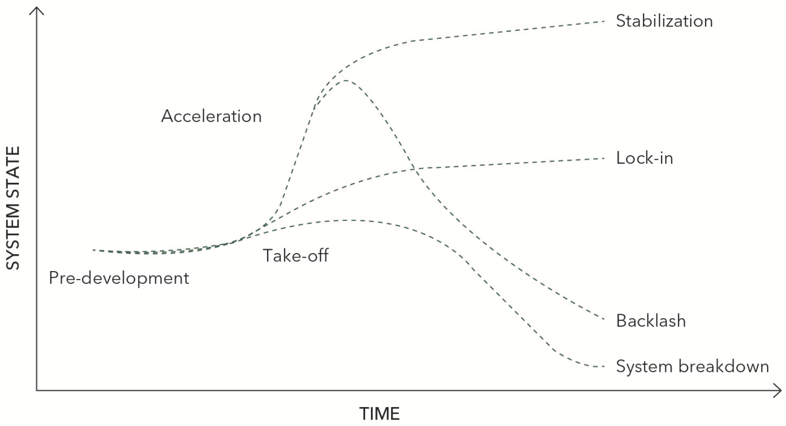

Figure 32. Possible system pathways (adapted from Van der Brugge and Rotmans, 2007)

Transition failures

Transition failures are linked to whether or not a transition manages to progress from one transitional phase to the next. Van der Brugge and Rotmans (2007) classify three transition failures, which relate to transitions that do not reach the stabilisation phase, in other words, a new or alternative (and more sustainable) system state; the transition failures include (i) lock-in, (ii) system break-down, and (iii) backlash. Table 22 outlines the description of the respective transition failures, as well as the key mechanisms that lead to the occurrence of these.

Table 22: Transition failures (based on Van der Brugge and Rotmans, 2007)

TRANSITION FAILURE	DESCRIPTION
Lock-in	Van der Brugge and Rotmans (2007) describe this as a transition path where an innovation does gain influence in the societal system, but fails to completely replace the regime co-existing with it in a locked-in state. Lock-in occurs when the incumbent (unsustainable) regime remains to co-exist alongside competing innovations, or when competing innovations co-exist but none of these innovation networks are powerful enough to stabilise as the new regime, thus creating a lock-in of innovations.
System breakdown	A system breakdown refers to the event where there are no innovation networks available that become self-sufficient, and all innovation networks continue to compete for the same resources; this results in no viable alternative being available. Alongside this, a regime is destabilising, meaning that it can no longer fulfil the societal functions. However, because no alternative is available, the system breaks down.
Backlash	When niches that initially gained power and popularity, and thus progressed to the 'take-off' phase, subsequently fail to become the mainstream practice to meet societal needs, the system experiences backlash. This can happen if, for example, the demand for a certain functioning increases quickly, but the niche is unable to cope with such drastic increases in demand and/or changes in demand, and thus fails. In another scenario, some novel functioning could be initially adopted by many, until unexpected challenges arise and the niche is no longer adopted by users as a mainstream practice; in this case too, backlash can occur.

Failures in the context of transformational change

When primarily focussing on innovation performance, conventional markets and system failure arguments (such as infrastructure failures, institutional failures, interaction of network failures, and capabilities failures) (Klein Woolthuis, Lankhuizen and Gilsing, 2005) are useful and valid. However, Weber and Rohracher (2012) argue that, when transformative change of socio-technical systems, and thus the long-term and fundamental character of the transition process in question, is studied, alternative instances of failure must also be considered. Weber and Rohracher (2012) further argue that, because conventional market and system failure arguments do not allow for policies that induce processes of transformational change, and because these are limited to addressing structural shortcomings in innovation systems, as well as not providing adequate justice to the arguments from the MLP, four "transformational failures" can be proposed: (i) directionality failure, (ii) demand articulation failure, (iii) policy coordination failure, and (iv) reflexivity failure. These failures are specifically focused on the failures that affect the transitional progress of a socio-technical system. Raven and Walrave (2018:3) argue that a "*sophisticated understanding of the policy challenges around a problem framing that is concerned with how transitions in entire socio-technical system towards sustainability come about, and the kind of 'failures' that may hinder such transitions*" is necessary. Also, Foxon and Pearson (2008) stated that, in order for us to move towards increasingly sustainable future states, and therefore more sustainable socio-technical systems, innovation and sustainable policy objectives have to be reconciled – clearly highlighting the need for alignment between the challenges and enablers of transitions with those of innovations.

Recent research efforts have focused on overcoming such transformational failures (Raven and Walrave, 2018). This research proved to be particularly useful in the context of this study, as it proposes overcoming such transformational failures by either addressing the incumbent system or through performance improvements of the emerging innovations, thereby strengthening the ability of such innovations to challenge (and ideally replace) the incumbent system. The four transformational system failures defined by Weber and Rohracher (2012) are elaborated on in Table 23, Table 24, Table 25 and Table 26 respectively.

Table 23: Directionality failures

DIRECTIONALITY FAILURE		
Description	Examples of overcoming these failures	Examples of key mechanism that lead to the occurrence of the failure
Directionality failure refers to the observation that, in the context of societal challenges, a need to consider the direction of innovation in such a way that the innovation contributes towards societal challenges exist (Raven and Walrave, 2018). Directionality failures are associated with the danger that one is locked into particular solutions that are not optimal from a long-term perspective (Kemp, Loorbach and Rotmans, 2007).	Overcoming directionality failures requires that guiding orientations are translated and that intermediation of guiding orientations occurs: i.e., requirements external to the innovation system need to be absorbed, such requirements need to be interpreted and negotiated in order to provide direction for the different relevant actors (Raven and Walrave, 2018).	Examples of key mechanisms leading to directionality failures include: the lack of a shared vision regarding the goal and direction of the transformation process; the inability of collective coordination of actors that are involved in the shaping of systemic change; a lack of sufficient regulations and/or standards to provide guidance for the direction of the systemic change; and insufficient targeted funding for R&D, projects, and infrastructure to facilitate the development of acceptable development paths (Weber and Rohracher, 2012).

Table 24: Demand articulation failures

DEMAND ARTICULATION FAILURE		
Description	Examples of overcoming these failures	Examples of key mechanism that lead to the occurrence of the failure
Demand articulation failures refer to the observation that, in the context of societal challenges, markets for new technologies may not (yet) exist, and may result in a lack of articulation of what such markets may require, or what user preferences are – this results in a lack of being able to anticipate user needs (Weber and Rohracher, 2012).	Interventions to address demand articulation failure include: (i) the support of learning processes that involve producers and users (e.g., strategic niche management), (ii) greater attention to new and hitherto neglected forms of innovation, (iii) integrating consumers and producers in innovation processes (iv) creating and being aware of new possibilities, (v) innovation-oriented procurement mechanisms, and (vi) policy support to facilitate building up the competencies of potential users to articulate their needs and demands (Weber and Rohracher, 2012).	Examples of key mechanisms leading to demand articulation failures include: insufficient opportunities for anticipating and learning about user needs; a lack of orientation and stimulating signals from public demand; and a lack of demand-articulating competencies (Weber and Rohracher, 2012).

Table 25: Policy coordination failures

POLICY COORDINATION FAILURE		
Description	Examples of overcoming these failures	Examples of key mechanism that lead to the occurrence of the failure
Policy coordination failures refer to the observation that, in the context within which grand societal challenges exist, policies and institutions may need to transform in order to respond to the challenges and to support the development of innovations to address such challenges (Raven and Walrave, 2018).	To overcome policy coordination failures, it is important to ensure coherence between the activities at national, regional, sectoral and technological institutions levels. Furthermore, the harmonisation of, for example, R&D funding and the regulatory environment is important (Weber and Rohracher, 2012).	Examples of key mechanisms leading to policy coordination failures include: a lack of cross-level policy coordination; a lack of horizontal coordination between research, technology and innovation policies on the one hand and sectoral policies; incoherence between public policies and private institutions; a lack of temporal coordination that may result in misalignment between the timing of interventions and different system actors (Weber and Rohracher, 2012).

Table 26: Reflexivity failures

REFLEXIVITY FAILURE		
Description	Examples of overcoming these failures	Examples of key mechanism that lead to the occurrence of the failure
Reflexivity failures refer to the observation that, in the context of grand societal challenges, there is a need to monitor the development of technological innovation systems continuously, with regard to such systems' contribution towards broader transformation goals, as well as the development of adaptation strategies (Raven and Walrave, 2018).	Examples of overcoming reflexivity failures include the provision of platforms for interaction as well as opportunities for experimentation, monitoring and learning among different actors and platforms; learning by actors by reflecting on the conditions for change and engage in the transformation of the very systems in which they operate, is particularly valuable (Weber and Rohracher, 2012).	Examples of key mechanisms leading to reflexivity failures include: insufficient monitoring, anticipation and inclusion of actors in processes of self-governance, lack of distributed reflexive arrangements to connect different sectors in order to provide opportunities for experimentation and learning, and insufficient adaptive policies that allows for policy options to be kept open in order to deal with uncertainty (Weber and Rohracher, 2012).

6.1.2.5 Interaction among technology(ies)

The interactions between technologies are a relevant feature in the literature. However, the interactions between technologies are often described in terms of competition between technologies. Pistorius and Utterback (1997), for instance, described three major modes of interactions between technologies, namely: pure competition, symbiosis, and predator-prey. However, these modes of interactions are primarily concerned with competition between technologies. Sandén and Hillman (2011) state that, until 2011, the literature on technology interaction focussed on competition, and that the characteristics of each of these modes of interactions between technologies differ. Interactions between technologies go beyond 'competition', however. Researchers have thus expanded on the view that interactions between technologies are merely competition-oriented by offering more detailed and nuanced descriptions of technology interactions. However, the interactions between technologies are grounded in the fact that technologies contribute towards a specific technology's growth rate (amongst other factors), by either positively or negatively influencing the technology's growth rate (Pistorius and Utterback, 1997).

Technologies consist of a hierarchy of value chains, which include upstream supply chains and down-stream application chains (Sandén and Hillman, 2011). The mode of interaction between technologies is then defined in terms of the elements in different parts of the value chains that are shared among technologies; six modes of interaction are defined by Sandén and Hillman (2011) (see Table 27). Six interaction modes between technologies are defined, including: competition, symbiosis, neutralism, parasitism, amensalism and commensalism.

Table 27: Six modes of interaction between technology (Sandén and Hillman, 2011)

MODE OF INTERACTION	DESCRIPTION
Competition	Technologies compete with each other for markets and resources. Competition could be for markets, as well as for resources. Inhibition of technologies occurs when a short supply of resources or markets exists.
Symbiosis	Interaction between technologies is favourable for all technologies involved in the concerned interaction. Complementary products of technologies are mutually dependent in an application.
Neutralism	Neutralism occurs when technologies deliver different services and use different resources, or when a common resource is a non-exclusive good. Thus technologies do not affect each other.
Parasitism (and predation)	Parasitism occurs when an emerging technology enters the market space that was developed by an established technology, or when an emerging technology makes use of the upstream supply chains that were developed by the established technology. Parasitism thus occurs when an emerging technology benefits from the existence of the established technology, while the established technology is inhibited.
Amensalism	Amensalism refers to a situation where an emerging technology is inhibited (structurally locked out). When the emerging technology does not fit into the environment or the system created or developed around an established technology, then the emerging technology is inhibited, while the established technology is unaffected.
Commensalism	When one technology benefits from a resource that is developed by another technology, but the technology that developed the resource is not affected, we have a situation of commensalism.

The literature highlights the importance of understanding the modes of interaction between technologies for purposes such as policy development and managing technologies and innovations. Porter (1985) emphasised that a technology extends beyond the technologies directly associated with a product, thus highlighting the importance of understanding the relationship between different technologies. Musango and Brent (2011) investigated the role that the interdependence of technologies plays with regard to the implementation of large-scale socio-technical changes; they argued that socio-technical systems cannot be analysed in terms of a single technology, but should be considered in terms of the interactions and relationships between coexisting technological, institutional, and social change.

6.1.2.6 Points of intervention

Efforts focussing on the comparison and integration of MLP, TIS, TM and SNM (Markard and Truffer, 2008; Meelen and Farla, 2013; Panetti *et al.*, 2018) provide valuable insight across these theoretical concepts to support the unpacking of the dynamics around the interaction and co-evolution of the various 'technology related' considerations. One area that proved to be particularly valuable in the context of this study, and that was elucidated by scholars who considered these most prominent approaches to studying transitions in parallel, is the identification and verification of the points of intervention that have to be considered. These include (Meelen and Farla, 2013):

i. Landscape-TIS interaction;
ii. Regime-TIS interaction;
iii. TIS-TIS interaction;
iv. TIS internal; and
v. Niches.

Bergek et al. (2015) also considers the TIS-TIS interaction, but adds to this the interaction between a focal TIS and relevant sectors, TIS development in geographical context structures, and interaction between a TIS and the political context. In addition to the elucidation of the points where interventions for the support of system transformation are necessary, policy goals and examples of policy instruments and/or guidelines are integrated into an integrated framework for sustainable innovation policy (Meelen and Farla, 2013).

Table 28: Policy goals for the different points of intervention (based on Meelen and Farla, 2013)

POINTS OF INTERVENTION		
	Landscape-TIS interaction	Policy goals
		Goal-oriented modulation (Kemp, Loorbach, and Rotmans 2007) using landscape developments Use regime weaknesses and internal regime contradictions (Kemp and Grin 2009) Provide guidance of the search Reflexivity (monitoring and evaluation)
		Examples of policy instruments and/or guidelines
		Develop long-term visions and long-term policy goals (in transition arena) (Rotmans, Kemp and Van Asselt, 2001) Development rounds to reflect on thepast and future of the goals and activities Set short-term and long-term policy goals, technology targets and express positive expectations (Bergek, Hekkert and Jacobsson, 2008) Include entrepreneurs in innovation policy-making (Hekkert, 2010)
	Regime-TIS interaction	Policy goals
		Weaken existing regime Prepare regime for new technology Create broad societal support for a technology Use resources from aligned regimes (Hillman et al., 2011) Create legitimacy for new technology
		Examples of policy instruments / guidelines
		Policies to put pressure on regime (Kemp and Grin 2009; Hekkert 2010) Minimal consumption quotas (Hekkert et al. 2007) Adapt regulations/institutions: change 'rule of the game' (Van Alphen et al. 2010) Open and interactive communication with stakeholders about the technology (Van Alphen, Hekkert and Turkenburg, 2009)
	TIS-TIS interaction	Policy goals
		Use positive externalities between TISs (Bergek, Hekkert and Jacobsson, 2008)
		Examples of policy instruments / guidelines
		Identification and support of complementary TISs

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POINTS OF INTERVENTION	TIS internal	Policy goals
		Knowledge development Knowledge diffusion Create (TIS-internal) networks to support the transmission and retention of knowledge (Musiolik, Markard and Hekkert, 2012) Create institutions Development of positive externalities (Bergek et al., 2010)
		Examples of policy instruments / guidelines
		Financing and facilitating R&D (Negro, Hekkert and Smits, 2008) Stimulate cross-linking platforms (Smits, Kuhlmann and Teubal, 2010) Co-ordinate intellectual property rights (Van Alphen et al., 2010) Issue best practices (Van Alphen et al., 2010) Training activities (Hudson, Winskel and Allen, 2011)
	Niches	Policy goals
		Enrol actors/entrepreneurs; build a constituency (Kemp, Schot, and Hoogma 1998) Knowledge development Higher order learning Create alignment (technology-user/ technology-institutions/ producer-technology, etc.)
		Examples of policy instruments / guidelines
		Mobilise resources for experiments Choose technologies and experiments with criteria from SNM (Kemp, Schot, and Hoogma 1998) Commercial-scale demonstrations (Van Alphen et al. 2010) Public-private partnerships (Van Alphen et al. 2010) Favourable tax regimes (Hekkert et al. 2007) (Temporarily) adapt regulations and institutions in niche: regulatory flexibility (Van Alphen et al. 2010)

6.2 Elaborating on the guiding questions and principles

As mentioned previously, the final step of the background research and synthesising is to develop an integration strategy. To do this, the guiding principles and guiding questions (posed in Section 5.2.3) are elaborated on through key concepts, which support these.

The guiding questions relate to identifying the appropriate level, unit and/or perspective of analysis in developing an integration strategy between technology management and sustainability transitions. And further, to determine what preliminary characteristics concerning transitions one would require in order to infer if, and if so, which technology management considerations are required to contribute towards the transitioning of a socio-technical system. These two guiding questions were considered in parallel, as the one informs the other, and they were thus considered in an iterative manner with the insights gained from the preceding sections. The guiding principles are elaborated on below; more specifically, the given elaborations provide the foundational concepts from which the integration strategy may be developed. Table 29 shows the elaborations of the guiding question, and the identified and proposed concepts that will support in addressing the guiding principles towards the objective of establishing an integration strategy.

Table 29: Elaboration on guiding questions

GUIDING QUESTION 1 (GQ1)	
What are the appropriate perspectives and/or units of analysis that will allow for linkages to be established between sustainability transitions and technology management?	Theoretical constructs
Brent and Pretorius (2008) argued that the 'environment' component of the technology management framework developed by Phaal et al. (2006) (shown in Figure 8) should be expanded on in order to allow for a sustainable development perspective to be incorporated into technology management. Brent and Pretorius (2008) further argue that technology management has an internal-to-external perspective, and in order for sustainability perspectives to be incorporated, technology management should consider external-to-internal perspectives; thus, in the case of this study, it should allow for the integration of sustainability transition concepts. Furthermore, and in line with the GP1 (see Table 30), Brent and Pretorius (2008) show that the system under consideration should extend beyond the firm level when aiming to incorporate sustainable development concepts into technology management. Given that sustainability challenges our traditional understanding of value creation (value creation, of course, being a central element to business models), a broader perspective is required. Given the nature of technology management (i.e., the planning, directing control and coordination of the development and implementation of technological capabilities [Cetindamar *et al*., 2010]), as well as the aim of this research inquiry – which provides a premise for the integration of technology management and the concept of socio-technical transitions – it is deemed appropriate to consider an integration strategy (i) from the perspective of transition progress, and (ii) from the perspective of transition capability (i.e., to what extent a socio-technical transition is capable of transitioning). It is argued that considering the transition progress and transition capability – both of which are deemed key requirements for successful transitions – inferences can be made about the role of technology management in contributing towards (i) transition progress, and (ii) transition capability. Transition progress is well defined in the literature, and the concept of transition resilience (Schilling, Wyss and Binder, 2018) is argued to serve as an appropriate proxy for transition capability. The premise, also in line with the multi-phase approach to transitions, will thus call for an approach that requires horizontal and vertical integration – horizontal meaning across phases, and vertical meaning within each phase – between transition progress, transition capability and the management of technology. Thus, the development of 'linkages' across different levels of analysis, we argue, is necessary to effectively allow for a premise for the integration between technology management and socio-technical transitions.	Transition progress Transition resilience Points of intervention

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GUIDING QUESTION 2 (GQ2)	
How does one identify the technology management considerations required that will contribute towards sustainability transitions?	Theoretical constructs
Turnheim *et al.* (2015) highlight the fact that a practical approach to study, analyse and govern sustainability transitions requires knowledge of (i) the current state of transitions processes by assessing the current state of the transition, and (ii) an analysis of the adjustments that will be needed to achieve transition targets. This thus requires knowledge of the transition state, as well as of the goals and targets set for the transition, in order to infer and/or develop interventions that have the potential to (i) contribute towards transition progress and capability, and (ii) overcome any barriers or resistance to transitional change (without compromising the resilience of the transition). The concept of transition progress requires one to not only consider the progression of transitions, but also failure to progress. Van der Brugge and Rotmans (2006) conceptualised 'transition failures', and Weber and Rohracher (2012) suggested that four 'transformational failures' should be considered; scholars argue that taking into account such failures creates an enriched perspective of the enabling (supporting) and limiting (resisting) factors of transitional change. Hara *et al.* (2012) state that it is essential to enable strong coupling between top-down visions and goals, and bottom-up emergence of novelty – this highlights that the direction of forces or drivers of transitional change has to be addressed. In addition, given the focus of technology management, it is envisaged that an integration strategy should consider the role of technology management from the perspective of the emerging novelties (i.e., technologies that are deemed feasible to support and enable a sustainable regime), but also to then expand the perspective to other levels, i.e., the regime. This then implies that there then will be 'two technology management sets' that have to be considered – and most importantly, this must be done in parallel and not individually, as the interaction between the developments and regime and niche levels has to be taken into account concurrently. Furthermore, in order to provide for an integration strategy between technology management and sustainability transitions, it is thus argued that the drivers and forces of change at play, the resistance against change and any potential risks (i.e., potential transition failures) should be considered. In addition, transition goals should then be considered, as these will assist in developing the transition requirements (i.e., the required processes in order for transitions to progress as well as to remain resilient). In addition to the drivers and forces of change, the points of intervention (Meelen and Farla, 2013) and the policy goals, instruments, guidelines and recommendations (which are linked to the 'transition goals' mentioned above) provided by transition scholars (Hekkert, Suurs, Negro, Kuhlmann and Smits, 2007; Hillman, Nilsson, Rickne and Magnusson, 2011; Kemp, Loorbach and Rotmans, 2007; and others) also allowed for points of integration to be identified between these concepts that are linked to sustainability transitions and technology management.	Factors and/or forces driving transitional change Factors and/or forces resisting transitional change Transition failures and transformational failures Transition phases

From the elaboration of the two guiding questions (GQ1 & GQ2), the guiding principles (GP1 – GP6) are elaborated on in Table 30 below. Here the focus is on (i) supporting and substantiating the guiding questions, and (ii) further strengthening the development of an integration strategy between technology management and sustainability transitions, and more specifically, elucidating possible points of integration.

Table 30: Elaboration on guiding principles

	GUIDING PRINCIPLES (GP)
GP1	Go beyond the ordering of either technology management or socio-technical transitions (thus looking outside of the current scopes of these two scientific networks in order to find 'common ground'); such an attempt will call for alternative perspectives and/or units of analysis that allow for the premise for integration.
	The creation of an avenue (as mentioned under GQ2), and by using the concepts of transition progress and transition capability in combination with system performance elements is argued to allow for common ground to be created between sustainability transitions and technology management.

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GP2	Facilitate in dealing with complexity, which entails that an objective should be to support the development of goals and objectives across system levels as well as to align such goals and objectives that are potentially defined at different levels and perspectives of a system and across different transition phases.
	The concepts identified from the literature and summarised in Table 29 allow for the systematic process of unpacking transition processes across transition phases and across the multiple levels of a societal system, in order to elucidate the 'current scenario' – i.e., the factors contributing towards the transition towards sustainability or the factors and forces that resist transformational system change towards sustainability. Such a multi-faceted analysis and multiple perspectives then enable goals and objectives to be set that are aligned to the specific system level and perspective, while also fostering an understanding of the interrelatedness between the different elements in a system.
GP3	Support the development of strategic, tactical and operational goals that will enable and facilitate the transitioning of socio-technical systems and increase the sustainability of socio-technical system from the perspective of technology management.
	Here, the concepts of drivers for and against transitional change can be used to develop (i) goals and objectives (especially given a specific transition phase), and (ii) intervention strategies that focus on (a) exploiting the drivers that contribute towards moving towards a more sustainable future system state, and (b) managing resistance to system change. The 'avenue' between sustainability transitions and technology management, as described under the elaboration of GQ2, will serve as the foundation from which a premise for the integration of technology management and socio-technical transitions may further be inferred.
GP4	Contribute towards the operationalising and institutionalising of the concept of transitions.
	This principle is implied by the search for an integration strategy between technology management and sustainability transitions. As mentioned throughout Chapter 2, and as highlighted in the challenges facing the concepts, frameworks and approaches dealing with socio-technical transitions, a key challenge is the lack of operationalisation of concepts. It is argued that, by integrating and linking operational concepts (such as technology management that are focused on less aggregated levels of societal functions) with those of transitions that are focussed at an increased level of aggregation, the operationalisation and institutionalisation of actions that contribute towards sustainability transitions may be supported.
GP5	Support the idea of a set of core rationales and/or activities – this guiding principle is linked with guiding principle (iii) in that an objective should be to keep the framework as parsimonious and generic as possible.
	Here, the objective is to keep the framework as parsimonious and generic as possible, and therefore the integration strategy is not limited to a technology-specific innovation system. The identification of a 'core set of rationales' will assist in (i) allowing for generalisation, and (ii) facilitating simplicity without compromising complexity (GP2) – in fact it is argued that GP2 and GP5 are complementary, rather than contradictory.
GP6	Develop and exploit the required capabilities within a socio-technical system that will support transitioning towards an increasingly sustainable future.
	GP6 is strongly related to GP3, in that it is evident that a number of elements and factors influence a socio-technical system's capability to transition. Furthermore, this highlights the need to link management practices, such as the management of technology, to such requirements. It should be noted that the specific focus of this research is on the management of technology within the context of socio-technical transitions, although within this research it is clearly acknowledged that there are numerous other management practices that, together with technology management, may contribute towards the transitioning process of socio-technical systems towards increasing levels of sustainability.

Transition studies focus on the evaluation and analysis of apparently coincidental and arbitrary events and changes that take place, what the fundamental origins and drivers of such events and changes are, and to what extent they can be anticipated and dealt with in a more strategic and systemic way (Grin, Rotmans and Schot, 2010; Loorbach, 2014). The envisaged premise for the integration of technology management and socio-technical transitions, based on the integration possibilities between technology management and sustainability transition, will aim to contribute towards this overarching focus.

The four frameworks that have achieved prominence in transition studies, and that are considered central to the theoretical framing of socio-technical transitions, include: (i) transition management, (ii) strategic niche management, (iii) multi-level perspective, and (iv) technological innovation systems (TIS) (Markard, Raven and Truffer, 2012), these frameworks share a key objective: to evaluate and gain insight into and understanding of the progress of transition dynamics. In addition, the recent literature still highlights the increasing importance of understanding and explaining the different progressions of transitions across different contexts (Köhler *et al.*, 2019). Here we argue that adopting a broad, shared problem framing and formulation around transition progress can act as a starting point for dialogue between technology management and sustainability transitions. Transition can be conceptualised as the as the gradual continuous process of change, where the structure of a socio-technical system undergoes transformation (Rotmans, Kemp and Van Asselt, 2001), specifically towards a more sustainable future state when sustainability transitions are considered. Transition progress is then conceptualised as the dialectic between transitional drivers for system change and resistance against system change (Frantzeskaki and de Haan, 2009; Schilling, Wyss and Binder, 2018). Schilling et al. (2018) further highlights the importance of considering the different constellations that transition progress might take, and that this is key to inferring whether and how a system transforms towards sustainability. Therefore, a transition that no longer progresses (i.e., increasingly changes towards sustainability), fails.

The elaboration of the guiding principles and questions outlined above informs the development of an integration strategy in the form of a set of requirement specifications, which is discussed in Section 6.3.

6.3 A strategy for integration: Requirement specifications

Integration refers to a means of ‘bridging’ the largely separate approaches of technology management and sustainability transitions at both a conceptual level, and at a more operational level. Integration strategies that are concerned with the co-evolution of social and technological innovation processes in the context of sustainability transitions range from once-off methodological enhancements to increasingly recursive amalgamations, based on iterative interactions and collaborative linkages (Turnheim *et al.*, 2015). The integrative effort proposed herein will aim to go beyond a once-off enhancement, and rather look to ‘translating’ insights from the literature into requirements that will support the development of a premise for the integration of technology management and the concept of socio-technical transitions. The integration strategy is posed as a set of requirement specifications, as discussed in Section 6.3.1.

Given the aim of the research, the insights gained from the literature, the set of requirement specifications outlined below, as well as an evaluation of various research products such as typologies, conceptual frameworks, models (i.e., theoretical models, conceptual models, mathematical and/or statistical models), toolkits, strategies, blueprints, logic models and roadmaps it is concluded that a ‘conceptual framework’ is an appropriate research product through which a premise for the integration of technology management and the concept of socio-technical systems may be conceptualised (see also 1.5.2). As mentioned in Section 1.5.1, practical utility is considered important within this research study, and the operationalisation of the conceptual framework is therefore also considered.

6.3.1 Requirement specification for the framework design

To support the development of a premise for the integration of technology management and the concept of socio-technical transitions, a number of requirements are proposed. The guiding questions and principles that emerged from the parallel and comparative investigation of technology management and socio-technical transitions literature (Chapter 5 and the preceding sections of Chapter 6) are translated into a set of requirements that the developed framework has to adhere to. Van Aken *et al*. (2006) distinguished among five requirement types, including:

i. ***Functional requirements (FR):*** The functional requirements are the core of the requirement specification, and outline the performance demands on the framework, that is, the functionality the framework is designed to provide for;
ii. ***User requirements (UR):*** The user requirements refer to the requirements that are set from the perspective of the user. These ideally should explain the constraints as well as how the framework will or should be used;
iii. ***Design restrictions (DR):*** This refers to the requirements pertaining to the preferred solution space, and specifically the limits and exclusions of the design;
iv. ***Attention points (AP):*** Attention points are requirements that are relevant to the development of the framework – and that should be noted as desirable; these are not requirements that have to be met, nor are they design restrictions, but they should be considered nonetheless; and
v. ***Boundary conditions (BC):*** These refer to requirements and rules that have to be met unconditionally and that may not be altered, e.g. legislation, ethical habits and code of conduct.

The requirements for the premise for the integration of technology management and the concept of socio-technical transitions that aim to support the understanding of how technology(ies) should be managed in order to support sustainability transitions are outlined below.

6.3.2 Functional requirements

The functional requirements support the key functionality that the framework should provide for. The set of functional requirements is divided into three groups: (i) overarching functional requirements that transcend all functional requirements, (ii) conceptual functional requirements, and (iii) operational functional requirements. The conceptual functional requirements, as the name suggests, should be addressed by the conceptual framework, while the operational functional requirements should be addressed by the guidelines that outline the operationalisation of the framework (see Chapter 8). Table 31 shows the functional requirements. The functional requirements include overarching requirements that transcend the conceptual and operational functional requirements, i.e., FR1 – FR5. In addition to these more detailed functional requirements, the framework should also support the overall research aim. Furthermore, it should be noted that, even though a distinction is made between conceptual and operational functional requirements, there is an overlap between these two sets; this distinction is made, as it is argued that the framework has to be translated into a 'methodology' (i.e., the operationalisation of the framework) to provide, for example, decision support.

It is acknowledged that not all requirements might be applicable to all users. However, the framework – as highlighted with FR 5 – aims to facilitate the understanding that (i) sustainability, and specifically

(ii) transition capability, depends activities that transcend the incumbent regime and the niche. This then calls for a cross-actor understanding of the contributing systems and actors, as well as the actions required to realise system performance and sustainability goals.

Table 31. Functional requirements

REQUIREMENT NUMBER	REQUIREMENT
Overarching functional requirements	
FR1	The framework should contribute towards understanding, identifying and/or analysing of technology management considerations within the context of sustainability transitions.
FR2	The framework should incorporate the socio-technical nature of systems that fulfil societal functions.
FR3	The framework should contribute towards an understanding of the capability of a socio-technical system to transition from the perspective of the management of technology.
FR4	The framework should be used to consider sustainability from a systems perspective, and it should not employ a one-dimensional or narrowly defined view of sustainability.
FR5	The framework should facilitate cross-actor understanding of the contributions and requirements from the incumbent regime and emerging or alternative niche respectively.
Conceptual functional requirements	
FR6	The framework should consider both the incumbent regime and the emerging or alternative niche, as both influence the (un)sustainability of a system as well as the capability to transition. The framework should therefore encompass: i. the incumbent regime; and ii. the emerging or alternative niche.
FR7	The framework should allow for contextual specificity in terms of: i. the environment within which a socio-technical system exists; and ii. the transitions phase within which the system is located.
FR8	The framework should support the cross-actor understanding of: i. The contributions towards the (un)sustainability of the socio-technical system of: a. The incumbent regime; and b. The emerging or alternative niche. ii. The required contribution(s) towards sustainability of: a. The incumbent regime; and b. The emerging or alternative niche. iii. The contributions towards the capability of a socio-technical system to transition from: a. The incumbent regime; and b. The emerging or alternative niche. iv. The required contribution(s) towards transition capability of: a. The incumbent regime; and b. The emerging or alternative niche.
Operational functional requirements	
FR9	The framework should provide decision support in transition management pertaining to the management of technology within the context of a sustainability transition.
FR10	The framework should guide transition goals and objectives to be aligned with technology management goals and objectives of both incumbent and emerging or alternative technologies.
FR11	The framework should support and/or enable the development process of technology management considerations, to facilitate transitional change from a technology management perspective.

6.3.3 User requirements

It is acknowledged that the users of the developed framework can most likely be divided into two broad groups: users will either consider the framework from a technology management perspective, or from a transition perspective. Ideally, and this is one of the key arguments of this research, a joint perspective should be taken. However, the framework is intended to guide both transition analysts[33] and technology managers[34] who regard the role of technology (and the management thereof) as contributing towards the sustainability of socio-technical transitions. Table 32 shows the user requirements.

Table 32. User requirements

REQUIREMENT NUMBER	REQUIREMENT
UR1	The framework should be practicable.
UR2	The framework should be considered a management aid, both from a technology management perspective, as well as from a sustainability transition perspective.
UR3	The framework should provide clear definitions and explanations to cater for a broad range of levels of experience in the technology management and/or transitions disciplines.
UR4	The framework should be sufficiently general to be applicable in a wide variety of contexts, while simultaneously being specific enough to be useful without a thorough and deep understanding of the theoretical bases.

6.3.4 Design restrictions

The design restrictions outline the requirements pertaining to the desired solution space. Here the scope, limitations, and exclusions are considered (see Table 33).

Table 33. Design restrictions

REQUIREMENT NUMBER	REQUIREMENT
DR1	The conceptual framework and the operationalisation thereof are not meant to include an exhaustive set of tools and methods to elucidate the technology management requirements or transition capabilities in each transitional phase at any of the possible levels of analysis, but they should be comprehensive enough to provide guidance on the requirements set out in Section 6.3.2.
DR2	The framework is intended for a systems level analysis, but may be applicable to analysis at a lower level of analysis.
DR3	The framework is not a policy or regulatory guide, and thus input required for such items should be obtained from subject matter experts. However, the framework is intended to support the development of systems level interventions to facilitate sustainability transitions and therefore can also contribute towards policy and regulatory development processes.
DR4	The framework does not guarantee improved transition capability or transitional change due to a multitude of factors that influence such an outcome. However, it does aim to provide principles and guidelines that will contribute towards the capability of a socio-technical system to transition and for a transition to be resilient from a technology management perspective.

6.3.5 Attention points

Attention points aim to highlight and allow for framework requirements that are relevant for the development of the framework and that should be taken note of; however, they are not requirements that should be strictly

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[33] 'Transition analysts' is purposefully used as a broad term to indicate the wide-range of parties that are interested transitions, i.e., academics, policy analysts and developers, regulatory authorities, etc.

[34] Similarly, the term 'technology managers' is also purposefully intended to be a broad description of parties interested in the management of technology within the context of (i) fulfilling societal functions from (ii) a sustainability transitions or sustainable development perspective.

adhered to by the framework, nor do attention points constrain the development of the framework as in the case of the design restrictions outlined in Section 6.3.5. The attention points are shown in Table 34.

Table 34. Attention points

REQUIREMENT NUMBER	REQUIREMENT
AP1	The framework should be seen as a reflection of early onset practice within two ever-evolving fields.
AP2	Due to the nature of the framework, a number of opportunities for integration with other complementary management approaches and frameworks are envisioned. However, it falls outside the scope of this research study to explicitly address such opportunities or to provide and/or develop such management approaches or frameworks.
AP3	It should be noted that, even though the integration strategy and developed framework provide for the integration of transition concepts with those of technology management at a conceptual level, and the integration or linking of technology management concepts with that of sustainability transition concepts at an increasingly operational level, the framework is developed from the perspective of sustainability transitions. Thus, it is primarily focused on informing the role of technology management within the context of sustainability transitions, and not on informing the role of transitions concepts in technology management.
AP4	The developed framework is a high-level framework that supports the understanding of key aspects of technology management within the context of sustainability transitions. As a result, this framework may also be seen as an emerging and potentially integrative approach to understanding newer, sustainability-oriented sources of competitive advantage to organisations.

6.3.6 Boundary conditions

Boundary conditions have to be met unconditionally in order for the framework to work. These requirements are included, as they prescribe reasonably assumed boundaries for the application of the framework; the boundary conditions listed below are not derived from the preceding chapters, but are adapted from the work of Van Aken *et al*. (2006) and Kennon (2017). The boundary conditions are outlined in Table 35.

Table 35. Boundary conditions

REQUIREMENT NUMBER	REQUIREMENT
BC1	The framework should be used in an ethical way. It is assumed that the framework will be applied so that it adheres to governance and other relevant governing bodies that might exist within environment of the socio-technical system under consideration.
BC2	The framework should not be used to exploit stakeholders negatively, and risks and opportunities should be highlighted across the system under consideration.
BC3	The framework should promote value for all parties, thus assuming that a common goal and vision of what is meant by sustainability of the socio-technical system has been established.

6.4 Conclusion: Chapter 6

The integration strategy, and thus also the framework that will be developed from this integration strategy, highlights and supports the following two themes:

i. Establishing and maintaining linkages between technological resources (both incumbent and alternative or emerging technologies) is of vital importance, but represents continuing challenges (from both an analytical and practical perspective); this requires the effective conceptualisation of the management of technology within the context of sustainability transitions, with a specific focus on the dialogue and understanding that needs to established between incumbent and alternative or emerging technologies; and

ii. Ensuring that technological resources are effectively linked to transition requirements (which is the focus of the framework proposed in the following chapter).

The integration strategy proposed in this chapter is primarily intended to act as a vehicle for bridging as it is argued to be interpretively flexible enough for the mobilisation of different kinds of information offered by the various approaches to be incorporated into the strategy, yet specific enough to enable systematic analysis and cumulative knowledge development. On a more practical level, the integration strategy facilitates the capturing of the rich multiplicity of sustainability transitions, and selectively identifies and evaluates opportunities to elucidate the role that technology management can play in structuring and moderating the dynamics of transitions. Although not explicitly an objective addressed in this study, it is argued that this approach has the potential to link near-term decisions to longer-term transition objectives of sustainability transitions more effectively.

Chapter 7.

A dynamic framing of the management of technology in socio-technical transitions: The integrated technology management-oriented sustainability transitions framework

At the beginning of this chapter, the purpose of the framework, the framework development approach and the construct guidance for the development of the framework are discussed. The developed framework, of which the development is guided by the set of requirement specifications outlined in Chapter 6, is subsequently presented. The operationalisation of the framework is presented in Chapter 8. It should be noted that the framework presented in Chapter 7, and the methodology presented in Chapter 8 are the final research products that already incorporates the feedback and refinements that emerged from the evaluation process discussed in Chapter 9.

7.1 Introduction: The purpose of the integrated framework

The purpose of the proposed framework is to provide a premise for the integration of technology management and the concept of sustainability transitions, and subsequently to provide the basis and guiding principles for a robust analysis to identify and define technology management considerations within the context of sustainability transitions. Thus, the framework aims to support our understanding of how technology(ies) should be managed in order to facilitate sustainability transitions. The framework does not offer a guidebook or blueprint on how to govern such processes, but rather conceptually frames the co-evolution of a transition and technology management considerations across different sub-systems over the course of a transition.

The developed framework seeks to be sufficiently general to be applicable in a wide variety of contexts, while simultaneously being specific enough to be useful without a thorough and deep understanding of the theoretical basis. Ultimately, the framework aims to contribute towards addressing two interrelated challenges that have been highlighted throughout the literature that is concerned with socio-technical systems and transitions (Genus and Coles, 2007; Papachristos, 2014; Smith, Voß and Grin, 2010): (i) to generate an improved understanding of transitions in order to inform and/or develop interventions to support and facilitate sustainability transitions, and (ii) to advance and refine the theories, frameworks and approaches for such analyses.

7.2 Framework development approach

The development of the framework is guided by the theory building process outlined in Section 1.5.2 as well as the simplified systems engineering approach shown in Figure 33. Kasser, John and Weng (2008) argue that systems engineering applies to all sorts of systems and provides a general, yet rigorous, approach to guide the development of systems that function in an integrated nature. Other researchers (i.e., Ungerer, 2015, and Kennon, 2017) who, similar to this research study, aimed to develop conceptualisations of complex phenomena, also employed the systems engineering approach in a simplified manner. Like a typical systems engineering process, the framework development approach involved the identification of a set of requirement specifications from the literature that then have to be fulfilled by a conceptualisation that constitutes the theoretical construct before the proposed conceptualisation is evaluated. In this research study, given the stated importance of practical utility (as discussed in Section 1.5), the conceptualisation is also operationalised (see Chapter 8) in order to ensure the practical utility of the developed theoretical conceptualisations. The iterative nature of the research is illustrated in Figure 33, which shows that the evaluation of the developed framework and methodology resulted in refinements made to the framework and methodology.

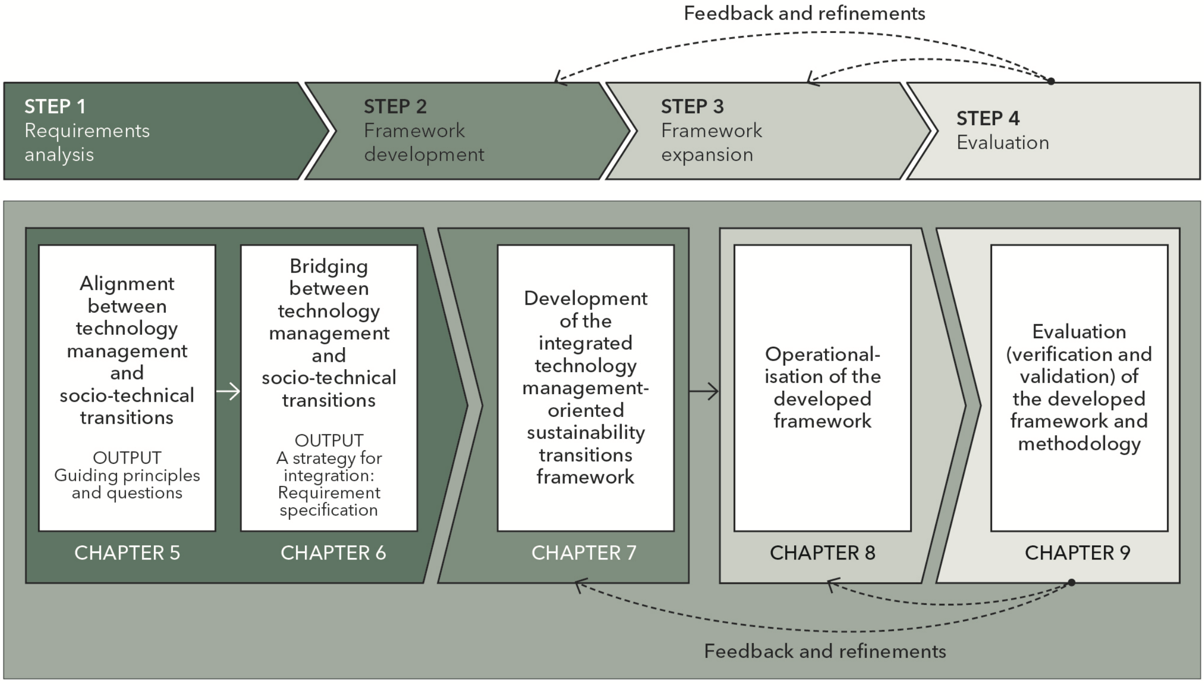

Figure 33. Simplified systems engineering approach used for the development of the conceptual framework and subsequent operationalisation (adapted from Ungerer (2015) and Kennon (2017), and aligned with the framework and methodology development approach employed in this study)

7.3 Construct guidance for the development of the framework design

The implication of the research aim is (i) to contribute towards an understanding of the capability of a socio-technical system to transition, (ii) the objective of which is to transition towards sustainability, and (iii) the scope of the contribution to a system's capability to transition is from the perspective of technology, and more specifically the management thereof. These constructs are elaborated on by considering the context and scope within which the proposed framework is set, and how sustainability is perceived and defined within this study.

7.3.1 Context and scope: System state and technology

This research inquiry is concerned with a socio-technical system that is deemed unsustainable, primarily because the (dominant) technology or set of technologies embedded in the regime, that fulfil societal functions and/or needs, are unsustainable. Thus, when the four-fould typology shown in Figure 13 (on page 36) is considered, the scope of this research extends to socio-technical change where external resources are required. In addition, given the nature of sustainability transitions, scenarios of high coordination (or a degree of coordination) are desirable, especially given the urgency of such transitions. It is envisaged that the framework may also be applicable to emergent transformations, but those are not the focus of this study.

Essentially, and as depicted in Figure 34, the system states that are reflected on in this study include (i) sustainable, (ii) unsustainable, and (iii) a pathway of transition (depicted by lines AB, AC, AD, CD and BD) – which together represent a system under transition from one regime to another. The system's state is categorised based on whether or not landscape developments and pressures are present. An unsustainable system state thus implies that the modes of production and consumption are not sustainable, in one way or another. It should be noted that landscape developments only exert pressure if they are perceived and acted on by actors in the system (Geels and Schot, 2007). The technologies being considered, as mentioned above, include an incumbent technology that fulfils a societal function, and an emerging or alternative[35] technology – a technology or set of technologies that is could have the potential to fulfil the societal functions that the incumbent technology or set of technologies is/are fulfilling. The emerging or alternative technology is deemed 'sustainable', and can thus address the tension between the current regime and the landscape developments. In addition to the four transformations discussed in Section 2.2.5, Geels and Schot (2007) also mention a 'reproduction process' in which there is no external landscape pressure, resulting in the socio-technical regime being dynamically stable and able to reproduce itself; i.e., state B in Figure 34. Table 36 gives an overview of the various transitions pathways shown in Figure 34 and how these relate to the typologies offered by Geels and Schot (2007) and Berkhout, Smith and Stirling (2004) (discussed in Section 2.2.5). This further highlights the scope and intended context of the proposed conceptual framework presented in this chapter.

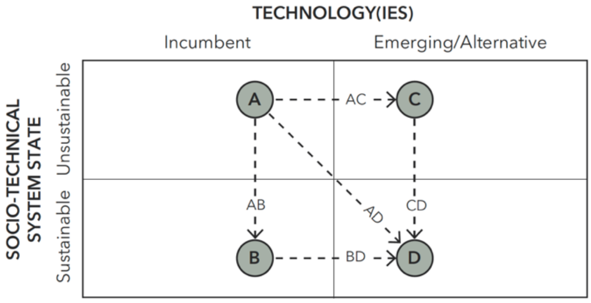

Figure 34. Schematic representation of possible transition pathways[36]

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[35] The reference to 'emerging' or 'alternative' suggests that, when the transition phases are considered, technologies that are developed in niches will in earlier transition phases not be sufficiently developed or aligned to be deemed an actual alternative to the incumbent technology. However, in later transition phases, when technologies gain momentum and the required infrastructure, networks, etc. they may be deemed as 'alternatives' to the incumbent technology.

[36] It should be noted that there are alternative pathways that are not indicated in Figure 34 (as with most (all) frameworks, models and/or schematic representation of real word scenarios, this figure too is a simplification). However, the purpose of Figure 34 is not to provide an exhaustive representation of all possible transition pathways, but rather highlight the particular pathways that are considered in this researh inquiry.

Table 36. Description of transition paths AB, AC, AD, BD and CD shown in Figure 34.

TRANSITION PATH	DESCRIPTION
AB	In this transition, typically sustainable alternative technologies are not (yet) available or landscape pressures (i.e., sustainability challenges) can be addressed and/or overcome with changes to existing or incumbent technologies. This would of course only be possible if the technology is not inherently unsustainable. However, if unsustainability is linked to social issues, and not inherently brought about by technical aspects, transition AB is possible to achieve a sustainable system state. Also, and if they are then aligned to what Geels and Schot (2007) termed 'transformation' and 'reconfiguration' pathways, this often includes the adoption of symbiotic niche innovations into the regime configuration – however, the basic architecture of the regime remains the same, i.e., a transformation pathway. Pathway AB is also aligned with the 'reorientation of trajectories' and 'endogenous renewal' transition contexts and tranformation processes, as depicted by Berkhout, Smith and Stirling (2004) and outlined in Section 2.2.5.
AC, BD	Transitions can take place by replacing an incumbent technology with an alternative technology that does not result in a change of the system state. Tranditional transitions[37] are examples of technological transitions that did not necessarily result in sustainable socio-technical system states. This pathway is aligned with 'emergent' or 'purposive' transformations in that resources external to the regime are required to address the tension in the regime. In the case of BD, for example, a system is sustainable, and thus there is no tension in the regime due to landscape pressures, although innovations that offer new or alternative advantages replace the incumbent technology(ies).
AD	This transition path is aligned with the 'de-alignemnt and realignment' and 'technological substitution' pathways, as defined by Geels and Schot (2007), in that landscape pressures occur at a time when alternative technologies are suffiencitly developed, or at a time when such alternatives are not (yet) sufficiently developed. Also, pathway AD is aligned with the 'purposive transition' and 'emergent transformation', as defined by Berkhout *et al.* (2004) in that external resources – i.e., emerging or alternative technology(ies) - are required to address landscape pressures and therefore the unsustainability of the system under consideration. The key difference between path AD and paths AC and BD is that the key objective is to move from an unsustainable system state to a sustainable system state.
CD	Transition path CD is similar to transition path AB, where a socio-technical system adopts an alternative technology and reconfigures or transforms in order to reach a sustainable future state.

Given that the transition context and transformation processes depicted by transition path AD are the key focus area of this study and for the developed framework, the key characteristics of the socio-technical system in focus are reiterated:

i. A socio-technical system is deemed unsustainable due to developments at landscape level (i.e., landscape pressures); such pressures are perceived by regime actors and create tension in the regime;
ii. The unsustainability of the socio-technical system manifests in societal challenges (e.g., climate change), but these are brought about by the nature of the technology that fulfills societal functions (i.e., fossil fuel based electricity generation);
iii. Incumbent regimes are not able to transform or reconfigure to achieve a sustainable system state, as the nature of the technology is what resulted and is resulting in the unsustainable system state; as alternative and more sustainable technology(ies) is/are fundamental to achieving a sustainable system state, a new socio-technical configuration has to be established; and
iv. Alternative technologies may or may not be sufficiently developed.

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[37] An example is the American transition from horse-drawn carriages to automobiles (Geels, 2005).

Essentially, in order to achieve a system state that is deemed 'sustainable', the societal need that is being met by the incumbent technology – and enabled by the current socio-technical configuration – has to be met by an alternative technology that does not result in an unsustainable system state.

7.3.2 Sustainability and a sustainable system state

The question of what is considered a 'sustainable' system state, or when such a state is reached, needs to be examined. The objective of transition management is to steer processes of transformation towards a predefined 'goal' or vision. Quite obviously, the predefined goal associated with sustainability transitions is sustainability. However, sustainability means different things to different people, and involves context-dependent evolutionary processes with emergent properties (Turnheim *et al.*, 2015).

Technology only adds value when embedded in social structures; De Haan and Rogers (2019) state, for instance, that 'solutions' (to meet societal needs) come in 'package deals', meaning that the networks, organisations, policies, and institutions required to make one solution successful, may not be what is required to make another solution work. This may be due to technical, institutional, ideological incompatibilities, cultures, and so forth. Such packages are referred to as constellations. And, for the purpose of this study, primarily due to the study partly being focused on the management of technology within such constellations, which seek to fulfil societal needs, such constellations are referred to as 'technology domains'. '***Technology domains***' is the term used to refer to the technology as well as the (innovation) system(s) within which such a technology exists. Thus, it includes the networks, organisations, policies, institutions, etc. that are present, or which are required to support the success of such a technology in fulfilling societal functions.

Within the context and scope outlined in Section 7.3.1, it is evident that technology domains contribute towards the (un)sustainability of a socio-technical system, since both regimes (i.e., incumbent technology domain) and niches (i.e., emerging/alternative technology domain) form part of the socio-technical system. Technology domains then, to one extent or another, contribute towards: (i) fulfilling societal functions, and (ii) the socio-technical systems' performance. It should be noted that a contribution may be negligible; for example, at the start of a transition, in the pre-development phase, technologies or infant technology domains might not yet contribute towards fulfilling societal functions and/or their contribution to the (un)sustainability of the socio-technical system may be negligible. Many environmental challenges, such as climate change, resource depletion, and loss of biodiversity comprise grand societal challenges that continue to be the primary motivation for research on sustainability transitions (Köhler *et al.*, 2019). However, it is important to take all system performance elements into account, since a technology domain may contribute positively to one or more system performance elements, but negatively to (an)other elements(s). This is primarily due to the possibility that emerging/alternative technology(ies) may not offer the same (often economic) benefits as incumbent technology(ies), and thus the contribution towards (other) system performance elements other than the initial element may be negatively affected.

The outlook is thus that: (i) both incumbent and emerging/alternative technology domains contribute – either positively or negatively – towards the (un)sustainability of a socio-technical system; (ii) the state of the sustainability of the socio-technical system may be misaligned with system performance targets or desired levels of system performance/sustainability; and (iii) any such (perceived) misalignments can (should ideally) be translated into requirements – i.e., the required contribution from the respective technology domains to move towards the sustainability goals, and ultimately to realise such goals.

For the transition path contemplated in this study, and as outlined in Section 7.3.1, the emerging technology can address the unsustainability of the socio-technical regime that results from the incumbent technology domain, should the dependence gravitas of the socio-technical system be of such a nature that the desired or required level of sustainability is achieved. Typically, this would mean that the societal functions are then primarily fulfilled by the (sustainable) alternative.

It is also important to note the positioning of (a) socio-technical transition(s) within the larger sustainability context – specifically to further clarify the scope and context for which this framework is intended. Transition scholars are, in addition to conducting detailed analyses of socio-technical systems, 'zooming' out to look at transitions from an increasingly encompassing perspective, which includes interactions between multiple socio-technical systems, such as electricity, transport, agriculture, etc. in order to understand how multiple regime shifts can contribute towards the quest for sustainability (Köhler *et al.*, 2019; Papachristos, Sofianos and Adamides, 2013). The investigation into how multiple regime shifts can impact societies is referred to as 'deep transitions' (Schot, 2016). The framework that is developed in this study when investigating 'deep transitions', is limited to a single socio-technical system. However, the developed framework is still embedded in the concept of 'nested hierarchies' – and the two key reasons why this is important are: (i) it underlines the notion that systems contribute towards higher-order systems, and that the level at which sustainability is ultimately defined (and determined) is important; and (ii) it alludes to the notion that not all systems are equally capable of contributing towards system performance/sustainability across all the system performance elements. Finally, it is important to acknowledge that what is considered sustainable may be subject to interpretation, and that it might change over time (Garud, Gehman and Karnoe, 2010). This highlights the contextual specificity of sustainability, as well as the importance of defining sustainability for the context under consideration, and to understand the extent to which a system is in fact capable of being sustainable under the temporal boundaries of the analysis.

7.3.3 Transition capability and resilience

The capability of a socio-technical system to transition from one (unsustainable) system state to another (sustainable) system state depends on a number of measures. A theoretical concept that outlines the dimensions affecting the success of sustainability transitions was developed by Schilling *et al.* (2018). Earlier work considered the resilience of systems in transitions, and concluded that, in order for a transition to be successful, the function of the socio-technical system has to be maintained (Binder *et al.*, 2017). Furthermore, the resilience of sustainability transitions is considered the sum of the factors that determine the dynamics of a sustainability transition process, and the 'level' of resilience thus determines whether or not the socio-technical system is "*capable of successfully going through a sustainability transition process and eventually reaching a higher state of sustainability*" (Schilling, Wyss and Binder, 2018: 5). The three key dimensions, defined by Schilling *et al.* (2018), that determine the resilience of a transition, and therefore the dimensions according to which the capability of a system to transition can be analysed, are: (i) progress, (ii) stability, and (iii) adaptability. Refer to Section 6.1.2.2 for a more detailed discussion of these concepts relating to the resilience of sustainability.

As mentioned in Section 6.1.2.2, a key factor on which a transition relies is the ability of a socio-technical system to maintain functionality (Binder *et al.*, 2017). Such functionality is the ability and/or capacity of the socio-technical system/configuration to fulfil societal functions (Geels, 2002). However, and as stated throughout the literature (Geels, 2005; Geels and Schot, 2007; Verbong and Geels, 2007), "*socio-technical* *transitions will occur if landscape changes have put an adequate amount of pressure on the regime, destabilising it and creating a window of opportunity for the transition to occur"* (Lopolito, Morone and Sisto, 2011:27) – again highlighting the inseparable relationship between transitions and landscape developments. Developments at the landscape level do not determine changes at the regime and niche levels, but they provide *"deep structural 'gradients of force' that make some actions easier than others"* (Geels and Schot, 2007: 403). And, sustainability, once it is established as a guiding norm – due to landscape developments – for societal development, can become such *"a deep structural gradient of force that [it] facilitate[s] action towards sustainability"* (Schilling, Wyss and Binder, 2018:3).

This then brings us to another crucial argument that has to be considered, and what is termed here 'the capacity of a system to deal with a lack of capacity'. A number of transition failures have been defined (see Section 6.1.2.4): lock-in, system breakdown, and backlash (Brugge and Rotmans, 2007). Weber and Rohracher (2012) defined four transformational failures: directionality failure, demand articulation failure, policy coordination failure, and reflexivity failure (see Section 6.1.2.4). Of these defined failures, some refer to the failure of reaching the desired or required higher state of sustainability (i.e., lock-in, backlash, and all four transformational failures), which will also lead to a failed sustainability transition; societal functions, albeit not in an adequately sustainable manner, will still be fulfilled. 'System breakdown' occurs, however, when the regime is destabilising and there is no viable alternative or substitute, thus it no longer has the capacity to fulfil (to some degree or another) societal functions. Yet, a system does not (necessarily) collapse when the demand exceeds the capacity; thus, when the system does not have the capacity to fulfil societal functions in its entirety, it does not necessarily bring about system collapse or breakdown. It is thus important to distinguish between:

i. a successful transition (which has two aspects: one is that it has reached the desired sustainable future state, while the other is that it is progressing and moving towards the desired sustainable system state); and
ii. a failed transition, which also has two aspects: (i) the desired system state is not reached (i.e., lock-in), or backlash, as defined by Van der Brugge and Rotmans (2007), occurs, but the societal functions are still fulfilled) or (ii) when societal functions are no longer fulfilled and results in either system collapse or system breakdown. In the latter case, the new sustainable system is not reached, nor is the system progressing towards a system state with a higher level of sustainability, and societal functions are not fulfilled.

In order to fulfil societal functions, the socio-technical system has to have sufficient capacity to fulfil such functions. Moreover, in order for a transition to be resilient, societal functions have to be met. For a system in transition, both the incumbent technology (domain) and the emerging/alternative technology (domain) contribute towards the capacity of the system to fulfil societal needs. However, given that the destabilisation of a regime needs to create windows of opportunity for alternative technologies to diffuse, the capacity of the system to deal with the lack of capacity must have to be taken into account.

Given the requirements for a transition to be resilient, the capability of a system to transition thus entails a co-dependence on both technology domains, as the dependence gravitas moves away from the (unsustainable) incumbent technology domain to the (more sustainable) emerging or alternative technology domain. Whether a transition is then considered successful depends on the system performance and/or sustainability targets or vision, and how this relates to the contribution of the respective technology domains to the system performance or sustainability

7.3.4 Unit(s) of analysis and empirical- and analytical levels

A socio-technical system may be defined at one of several empirical levels (Berkhout, Smith and Stirling, 2004). For example, a regime in the electricity domain can be studied at the level of primary fuel (coal, gas, etc.), or at the level of the entire system (production, distribution and consumption of electricity). This is important in the context of transitions. as what may look like a transition (or regime shift) at one level, may be viewed as incremental change at another (Geels and Schot, 2007). Alternatively, a transition at a lower level may be considered as a niche activity with "*regime transforming potential within a higher-level regime*" (Berkhout, Smith and Stirling, 2004:55). This theoretical ambiguity highlights the nature of how transition management recognises transformation mechanisms to "*flow upward through a widening stream of changes*" (Berkhout, Smith and Stirling, 2004:55) – and thus, even though transitions can be delineated in a particular system, they are always conceptualised as the outcome of the interaction and dynamics at, and between, multiple levels (Kemp, Schot and Hoogma, 1998). The most basic distinction between levels within a socio-technical system, and one that is widely accepted within the transitions literature and referenced throughout this study, is the distinction between landscape, regime (dominant/incumbent socio-technical configuration), and niches (alternatives). But still, as mentioned earlier, the concept of transitions implies a nested hierarchy; the transition that is being focused on is also part of a higher-level transition, and includes lower-level transitions. From an analytical perspective, this means that the transitions are always related to their context (Loorbach, Frantzeskaki and Avelino, 2017).

Here it is argued that transitions, as the object of analysis, exist in nested levels. However, for the proposed framework, even though the object of analysis is seen as a nested hierarchy, the empirical level of analysis is determined by considering the 'system' that fulfils a societal function, and, given that the framework aims to not be technology specific, it is geared towards the level of the entire system, although the framework may be applicable to analysis at more granular levels of analysis. Given the nested nature of transitions, Geels and Schot (2007) suggest that the empirical level of analysis is first demarcated before the multi-level perspective is operationalised.

7.3.5 Key underlying (theoretical) assumptions

Although it is recognised that other literature concerned with transformations exists, the selected focus of this study is on the literature that focuses on the co-evolution of social and technological innovation processes to address grand societal challenges. While an integration of technology management and transitions concepts could also take place at an analytic level of micro- and macro-level system dynamics, it is argued that a coherent framework that defines and describes a premise for the integration of technology management with sustainability transitions can be developed without 'unifying' these approaches at these levels; similar approaches are followed in the literature (Weber and Rohracher, 2012). The key theoretical assumptions further include that the framework is not attuned to a technology-specific innovation system; and, the framework assumes a 'single-incumbent technology domain, single-emerging/alternative technology domain' scenario. It is acknowledged that this is a simplification of the reality; however, this methodological choice is seen in most transition investigations (Walrave and Raven, 2016). From an empirical analysis perspective, it is argued that the concepts within the proposed framework are robust enough to extend beyond a single regime, single niche scenario, although the number of elements to consider will noticeably increase.

The proposed framework is further based on the following general management principles that underpin transition management (Brugge and Rotmans, 2007):

i. The phase of a transition acts as a guideline for employing management strategies and instruments;
ii. A mix of top-down steering, network steering, and self-steering instruments should be used, depending on the relevant transition dynamics;
iii. Multi-level governance is required in which the objectives and instruments vary at the different levels, but have to be attuned to reinforce each other;
iv. Stakeholders have to participate and be aligned;
v. Long-term goals must be adaptive to emergent innovations and macro-developments; and
vi. Timing and type of intervention is critical.

Furthermore, the framework aims to represent a ‘nested hierarchy of s-curves’. This essentially means that, within a transition that is represented by an s-curve (Rotmans, Kemp and Van Asselt, 2001) and that progresses through four transition phases, each transition phase can be conceptualised as another s-curve. This then implies that (i) the various transition phases influence one another, and (ii) the succeeding phases should be used to identify and define transition goals and objectives.

Lastly, the notion that a system in transition is never completely ordered and stabilised, requires the continued attention to readjustment the categories and metrics according to which it is analysed, described, and measured (Turnheim *et al.*, 2015).

7.4 The integrated technology management-oriented sustainability transitions framework

In this section, the concepts highlighted throughout the development of the integration strategy (i.e., the set requirement specifications), which provided the necessary foundational concepts as well as the construct guidance provided above, are amalgamated into a conceptual framework – ***the integrated technology management-oriented sustainability transitions (ITMST) framework***. This framework aims to adhere to the requirements set out in Chapter 6. Research efforts are culminated into a schematic representation of the developed framework shown in Figure 38 and Figure 39, and discussed below. Thereafter, the operationalisation of the framework is discussed in Chapter 8.

7.4.1 Key features of the framework

The requirements discussed in Section 6.3.1 are translated into five key features of the proposed ITMST framework. The functional requirements, user requirements, design restrictions, attention points and boundary conditions thus guided the formation of the key features of the framework, as well as the operationalisation of the framework in Chapter 8. The key features of the framework are shown in Table 37, and discussed and elaborated on below.

Table 37. Key features of the ITMST framework

FRAMEWORK FEATURE
Transition value creation
Collective and individual consideration of transition progress, transition capability and system performance
Co-management of incumbent and emerging/alternative technology domains
Context-specificity
Contribution-requirement view

7.4.1.1 Transition value creation

Sustainability challenges our traditional view of technology and how we create value through technology, and thus also challenges our traditional view of how we manage technology. The transition value creation feature of the ITMST framework is incorporated through the inclusion of a 'transition perspective' (see Figure 35) to allow for a broader and more inclusive set of perspectives to take into account for technology management. Transition value creation is grounded in the argument that the traditional management of technology supports value creation for the 'system' (i.e., system performance elements) as well as for organisations (i.e., commercial perspective); however, the management of technology within the context of socio-technical transitions also requires additional and complementary perspectives that support the creation of value for the transition.

The proposition of transition value creation manifests in the developed framework in the transition perspective, and accommodates the management of technology and interactions among technology domains within a broader set of perspectives. The transitions perspective acts as an interfacial layer between the incumbent technology domain, the emerging/alternative technology domain, the concept of transitioning towards sustainability, and the management of technology within the context of socio-technical transitions – all with the aim of elucidating the considerations required to create value for the transition as well as for the system and the technology domains. In order for a transition to be successful, the transition has to be resilient[38]; and from a technology management perspective, the dimensions defined within the transition perspective are then proposed to be the guiding principles that should drive, together with the technological and commercial perspective, the management of technology, thus ensuring that technology is managed to support transition value creation too.

Figure 35 shows a diagrammatic representation of the transition perspective in relation to the technological and commercial perspectives of technology management. As discussed in Section 2.1.2, the relationship between the traditional perspectives of technology management (i.e., the commercial and technological perspectives) means that the commercial perspective informs the required technological capability, and the technological perspectives informs the commercial capability of an organisation (Cetindamar, Phaal and Probert, 2010). The relationship between the 'broader and more inclusive perspective' brought about by the aim to also create value for the transition, the inclusion of a transition perspective into technology management considerations, results in the following aspects being considered:

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[38] Within the context of socio-technical systems, resilience is described as *"the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks"* (Walker *et al.*, 2004).

i. The ***contributions*** from the respective technology domains towards transition progress, transition capability and system performance;
ii. The ***requirements*** from the respective technology domains in terms of the need for the system to change (transition progress and transition capability) and to maintain and/or improve the system performance; and
iii. The ***risks and opportunities*** to the technology domains brought about by the transition – i.e., in all transitions there will be 'winners and losers' – a concept highlighted across the transitions literature (Huxham, Muhammed and Nelson, 2019; Schilling, Wyss and Binder, 2018; Smith and Stirling, 2008; Turnheim *et al.*, 2019).

The risks and opportunities are essentially derived from the evaluation of the contributions and the requirements mentioned above. The transition perspective is thus proposed, in addition to the technological and commercial perspectives in technology management, as a perspective that is required in order to elucidate technology management considerations within the context of sustainability transitions to facilitate the understanding of how to create value for the transition.

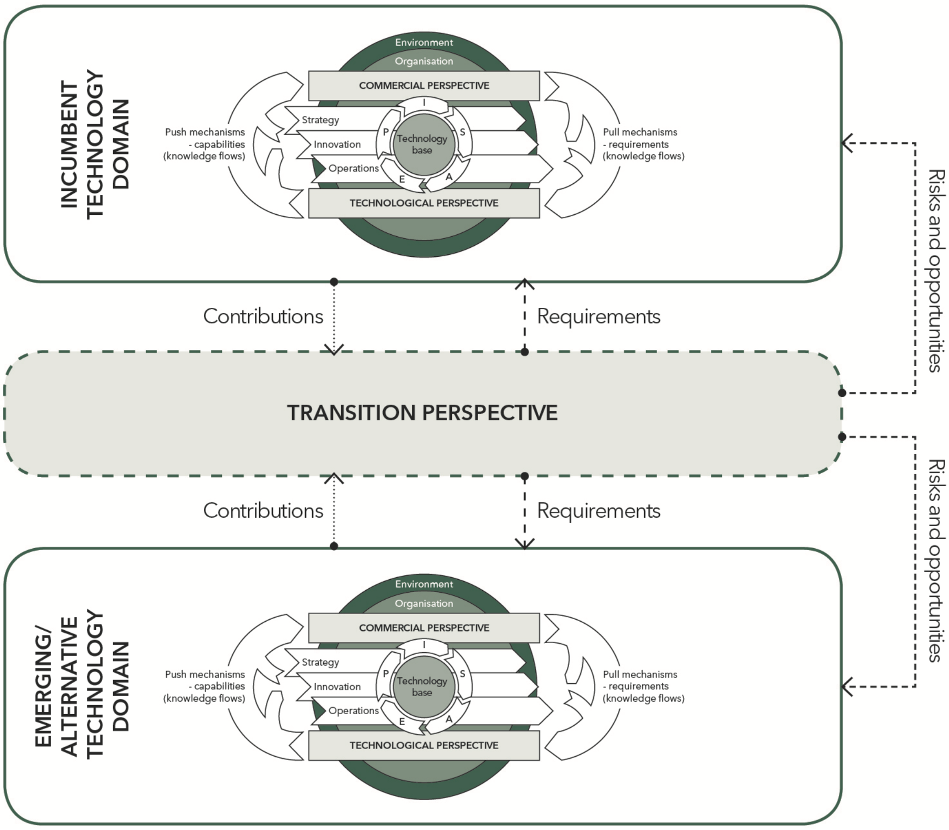

Figure 35. Schematic representation of the transition perspective

As mentioned above, the transitions perspective allows for transition requirements with respect to both technology domains to be set. Both the incumbent and the emerging/alternative technology domain provide for, or contribute towards, the capability of a socio-technical system to (i) function (system performance) and (ii) transition (progress and transition capability). It is also important to highlight again the interconnectedness between a socio-technical system retaining its functionality and its capability to transition. Both incumbent and emerging/alternative technology domains and actors, and/or a (lack of) functions and institutions in the respective technology domains may also resist or hinder transitional change. Therefore, the 'contribution' of the technologies or technology domains may be positive or negative.

The transition perspective also include the capacity of a socio-technical system to deal with a lack of capacity, and thus, the thresholds of the socio-technical system before it fails or collapses (see Figure 39). Both the incumbent and the emerging/alternative technologies and technology domains contribute towards the fulfilment of societal functions, , the extent depending on the phase of the transition, and therefore also play a part in guarding against system collapse or breakdown, and thus ultimately transition failure.

Furthermore, when attempting to elucidate technology management considerations within the context of, and with the aim of, contributing towards moving towards a higher level of system performance/sustainability it is evident that such technology management considerations should transcend the incumbent and emerging/alternative technology domains. What should be considered is not the change in one technology domain or in independently considering transition capability and/or system performance, but the change across domains and dimensions.

The ITMST framework consequently considers transition progress, transition capability and system performance as a function of the contribution of both incumbent and emerging/alternative technology domains. Transition value creation is thus defined as the value that is created for the transition through transition progress, transition capability and system performance – so the net contribution to support the transition.

7.4.1.2 Collective and individual consideration of transition progress, transition capability and system performance

It is necessary to be cognisant of the following: (i) the existence and role of transition progress, transition capability and system performance within the context of a socio-technical transition, (ii) the interrelationship and mutual non-exclusivity of transition progress, transition capability and system performance within the context of a socio-technical transition and (iii) the impact of (i) and (ii) on the management of technology within the context of a socio-technical transition. This is primarily the case as a result of a system often being deemed unsustainable because (a) system performance element(s) is/are not sustainable, whilst other system performance elements may perform satisfactorily and/or be deemed 'sustainable'. It may also be that, for example, all system elements' performances are unsatisfactory, but not all system performance elements require purposive renewal to transform to an acceptable level of performance.

The seeming contradiction between being cognisant of all three elements and recognising them individually is important, because all three of these perspectives (i) are important within the context of a socio-technical system in transition, (ii) require differentiated approaches to managing the technology based on the respective perspectives, and (iii) the technology may positively contribute towards one of these perspectives, and negatively towards another (see the descriptions 1, 2 and 3 in Figure 36), thus necessitating the need to have a more nuanced view of the perspectives individually as well as collectively.

Recognising the mutual non-exclusivity of the three perspectives speaks to the abovementioned need to understand the collective, integrated nature, and the interrelationships that exist between, transition progress, transition capability and system performance. The overlaps, denoted as 1, 2 and 3 in Figure 36, are:

1. Transition progress is the extent to which a system has transformed, and it is also a dimension that contributes towards transition capability. For instance, a system that holds higher transition capability will show greater advancement in transition progress than a system with a lower level of transition capability;
2. System performance influences transition capability in that how a system performs and the contribution it makes towards, for example, stability (a transition capability dimension) affects a system's capability to transition; and
3. Given that (the need for) a transition is brought about by the unsustainability of one or more system performance elements (for example, the environmental unsustainability of a socio-technical system), the overlap between transition progress and system performance is that transition progress will thus (ideally) bring about change in system performance (i.e., making it more sustainable).

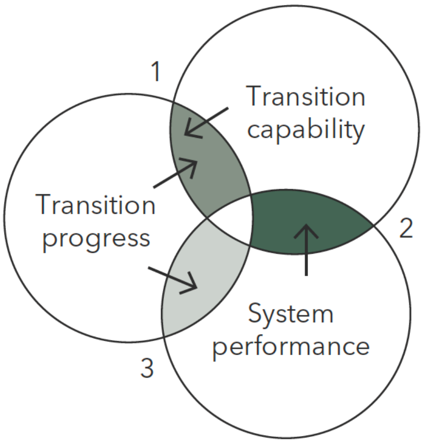

Figure 36. Schematic representation of the interrelationships and overlap between transition progress, transition capability and system performance

It is thus argued that a ***premise for the integration between technology management and the concept of sustainability transitions*** requires a nuanced view of transition progress, transition capability and system performance.

7.4.1.3 Co-management of incumbent and emerging/alternative technology domains

The framework advocates for both incumbent and emerging/alternative technology domains to be managed coherently, as both have an impact on (i) a socio-technical system's progress towards sustainability, (ii) its capability to transition towards a more sustainable system state, and (iii) its performance. A socio-technical system, as defined by Geels (2004), aims to fulfil certain societal functions. And, when sustainability, or put differently, a more sustainable future system state, is the objective, then 'fulfilling societal functions' relies on both incumbent (unsustainable) technologies, as well as on emerging/alternative (more sustainable) technologies, and thus on both of the respective technology domains. The dynamics, role and prominence of the respective technologies and technology domains across transitional phases, however, differ – and hence the transition context (discussed under context specificity) must also be a key feature of the developed framework.

The framework, and more specifically the requirement of co-management, brings forward two aspects relating to the management of technology within the context of sustainability transitions:

i. The recognition that both incumbent and emerging/alternative technologies contribute towards the progress of sustainability transitions, the capability to transition towards a more sustainable system state, and the socio-technical system's performance; and
ii. The need for 'metrics' or 'standard definitions' that may (or should) guide technology management efforts within the context of sustainability transitions.

How to navigate both incumbent and emerging/alternative technology domains through transitions, as well as how to support and facilitate a successful transition, is vital for all actors, whether they are set to lose or gain from it. Assisting the particular technology domains to navigate through the opportunities and risks associated with transitions is an economic, environmental and social imperative.

7.4.1.4 Context-specificity

It is argued that sufficiently incorporating context is necessary from two points of view: (i) first, based on transition phases, and thus transition progress over time; and (ii) second, the transition perspective, which allows the defining of transition capability through context-specific considerations and the incorporation of the relevant system-specific performance dimensions. Similarly, 'sustainability' (or system performance) has to be defined within each context – specifically given the notion that all transitions exist in relation to a higher-level transition. The purpose of this is two-fold: to allow for (i) a broader view of sustainability, and (ii) the fact that 'sustainability' and transition progress, transition capability and system performance in one context may differ from another. It is thus argued that transition capability dimensions (i.e., progress, stability and adaptability) must be defined for a specific context, within a specific transitional phase.

Furthermore, since transitions typically unfold in several phases that invite different policy strategies, the framework incorporates the distinction between the transition phases, as well as the prominence of transition capability dimensions across transition phases. Also, the framework, and specifically the transition capability perspective, as well as the context specificity features, allow for an analysis of transition risks in respective contexts, and will assist with the identification of potential economic, social and political barriers to actions that either drive or hinder transitional change.

7.4.1.5 Contribution-requirement view

As indicated, both technology domains contribute towards transition progress, transition capability and system performance (either positively or negatively); moreover, given the specific landscape pressures (and thus sustainability challenges) associated with a socio-technical system, specific sustainability/system performance goals may be set, which, in turn, may be translated into transition goals. These sets of targets may then be translated into requirements, which should include the context-specificity considerations outlined in Section 7.4.1.4. These requirements then inform the required contribution towards transition progress, transition capability and system performance from the respective technology domains, which in turn influences such (future) requirements. It should be noted that, even though the starting point of a transition are the landscape pressures, the analytical process can start from the requirements, the capability (i.e., transition progress, transition capability and system performance) or the contribution point of view. Figure 37 shows a diagrammatic representation of the requirement-contribution view.

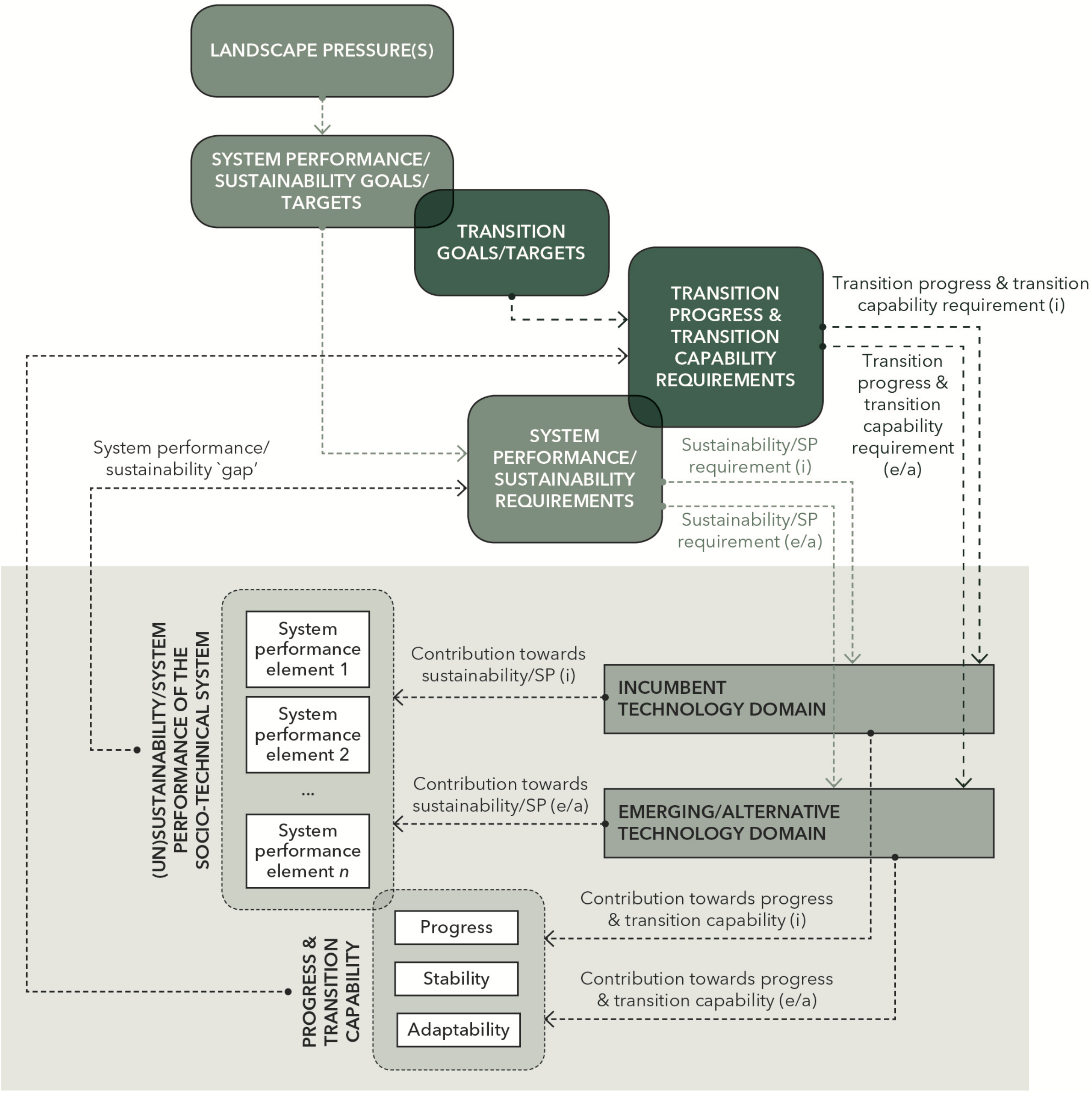

Figure 37. Diagrammatic representation of the requirement-capability-contribution view

Given the above conceptualisation and description of the contribution-requirement view, transition risk or failure is then conceptualised as the difference between the requirement and the contribution. And, as explained above, the transition perspective (see Figure 38) acts as a linking mechanism in it being a common purpose that both technology domains should ideally aim to serve when seeking to facilitate a transition. Knowledge flows from the transition perspective towards the respective technology domains are the transition requirements (pull mechanisms). The knowledge flows from the incumbent and emerging/alternative technology domains are primarily concerned with the contribution of the respective technologies/technology domains towards transition progress, transition capability and system performance, and are thus push mechanisms.

7.4.2 Supporting features of the framework

In addition to the key features of the framework outlined above, three supporting framework features (i.e., transition monitoring, points of focus, and actors, power and agency) are defined and discussed below. These supporting features enable and/or are enabled by the key features. Furthermore, the supporting features of the framework also assist in guiding the operationalisation of the framework (see Chapter 8).

7.4.2.1 Transition monitoring

When aiming to evaluate sustainability transitions, Turnheim et al. (2015) argue that what we need to understand is: (i) where do we stand, (ii) where are we heading, and (iii) how can we get there? Essentially, this is then an understanding of the ***current state*** of a system, while the transition is an understanding of a desired (possible) ***future state***(s), and a ***progression state*** that considers the actions and pathways needed to achieve said future state. This conceptualisation of transitions across different states advocates for (i) monitoring of the transition, (ii) defining and setting of transition goals to inform requirements to facilitate such a transition, and (iii) identifying, analysing and setting of actions/interventions (i.e., technology management considerations) to contribute towards a successful transition. The transition capability dimensions (defined within the transition perspective), within the context of transition monitoring, may act as indicators for the monitoring of a transition. However, context specific indicators have to be defined when progress, stability and adaptability are defined. Transition phases, and the conditions for change that are necessary (but not necessarily sufficient) to facilitate transition progress in each phase, allow for future transition states to be conceptualised; thereafter, the progression state defines any discrepancies and/or differences that may exist between the current and future states, and this further supports and facilitates the monitoring of transitions.

7.4.2.2 Points of focus

The framework presented above, of which a schematic representation is shown in Figure 38 and Figure 39, suggests that technologies that fulfil societal functions and that contribute towards socio-technical system transitions require actions (policy goals, strategies, measures, etc.) at specific focus areas and points of interactions among the respective technology domains and the contexts within which they exist. The framework further suggests that the facilitation of a sustainability transition can only make sense when developments among the technology domains, the landscape and context are well aligned. Meelen and Farla (2013) proposed five points of intervention (refer to Section 6.1.2.6) where, in order to support radical, sustainable innovations and system transformation, certain actions are required. What should be considered within the boundaries of this framework, is the interaction between the landscape developments and the regime, and the concept that both technology domains contribute towards the same socio-technical system. This then calls for points of focus, and by implication also points of intervention, which include:

i. Landscape-incumbent regime and landscape-emerging/alternative (more sustainable) niche – this is integrated in the transition perspective, as this is where sustainability/system performance and also the transition requirements are set;
ii. Socio-technical system/environment-incumbent regime and socio-technical system/environment-emerging/alternative niche – which is incorporated into the contribution of both technologies towards (i) system performance/sustainability, (ii) transition progress and (iii) transition capability;

iii. Incumbent regime-emerging/alternative niche – which is considered in the co-management of the technology domains as well as the transition perspective;
iv. Incumbent internal technology domain focus; and
v. Emerging/alternative internal technology domain focus.

7.4.2.3 Actors, power and agency

Even though the framework does not explicitly include actors, the arrows between the two technology domains and the transition perspective carry suggestions of teleology[39] and functionalism[40]. Given the nature of sustainability transitions, a wide range of actors are present – the framework is therefore not intended for a specific group of actors, but rather to provide guidance across actor perspectives. As mentioned earlier, there is a strong focus on cross-actor understanding.

Given that it is unlikely that 'sustainable' innovations will replace incumbent 'unsustainable' technologies without changes in economic frame conditions like taxes, subsidies and regulatory frameworks, changes in policy will be required. This power and agency, which plays a prominent role in the governance and facilitation of sustainability transitions, and also regarding the management of technologies as vested interests, will try to resist such changes (Geels, 2011). The ITMST framework is not intended to directly address and deal with power and agency. However, it is argued that facilitating an improved understanding of the requirements, contributions and capabilities outlined above may also facilitate dealing with power and agency.

7.4.3 Diagrammatic representation of the framework

Figure 38 and Figure 39 show diagrammatic representations of the ITMST-framework. Figure 39 shows the embeddedness of a socio-technical system within a larger system as well as within a transition (i.e. transition phases).

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[39] The explanation of phenomena in terms of the purpose they serve rather than of the cause by which they arise.
[40] The theory that all aspects of a society serve a function and are necessary for the survival of that society.

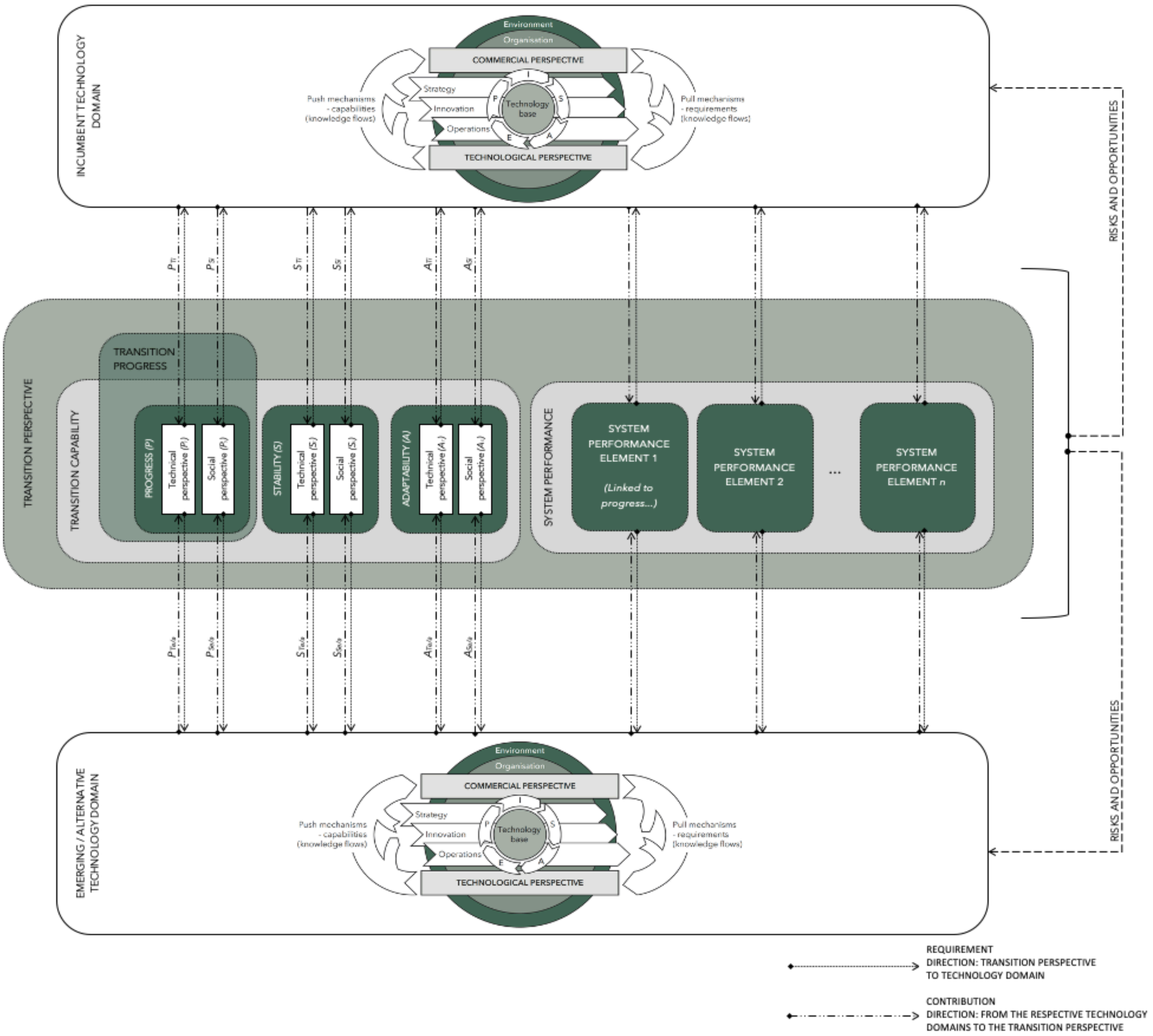

Figure 38. The ITMST framework – key features

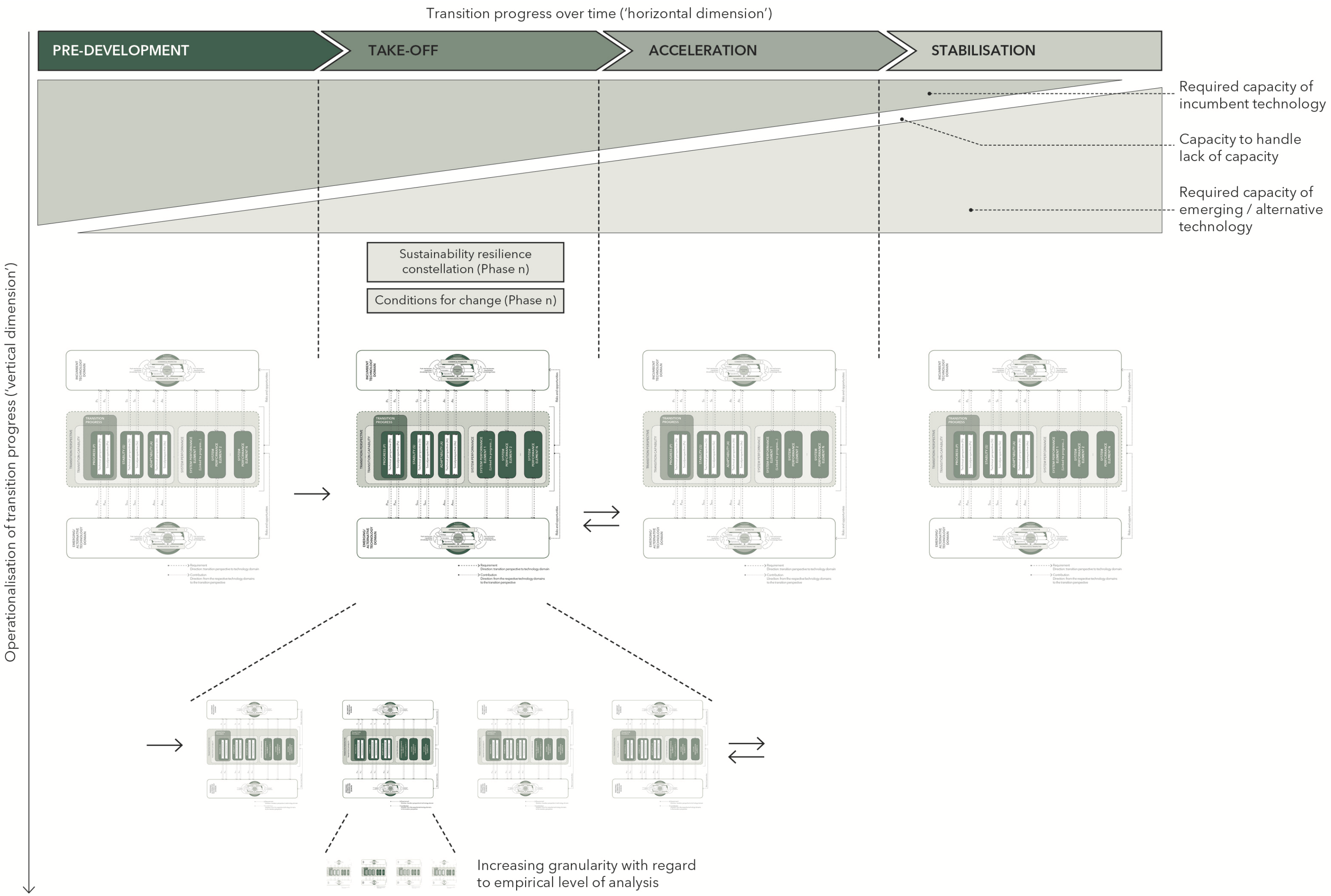

Figure 39. The ITMST framework as a nested hierarchy

7.5 Conclusion: Chapter 7

This chapter proposed and discussed the ITMST framework as the designed result of the requirement analysis presented in Chapters 5 and 6. The framework consists of five key features that collectively provide the premise for the integration between technology management and socio-technical transitions, namely: transition value creation; collective and individual consideration of transition progress, transition capability and system performance; co-management of incumbent and emerging/alternative technology domain; context-specificity; and contribution-requirement view. Given the conceptual nature of the ITMST framework and the stated importance of practical utility, the proposed framework can be operationalised by translating the framework into a methodology. The operationalisation of this ITMST framework is presented in Chapter 8.

Chapter 8.

Operationalisation of the integrated technology management-oriented sustainability transitions (ITMST) framework

As stated in Chapter 1, practical utility is of key importance. This chapter is consequently dedicated to the operationalisation of the ITMST framework, by developing the ITMST methodology. In the initial sections of the chapter, an overview of the operationalisation is presented, followed by a detailed discussion and explanation of the various analytical perspectives and phases of the proposed ITMST methodology.

8.1 Overview of the operationalisation of the integrated framework

When transitions occur, there is no guarantee that a new and more sustainable regime will be established – transitions and transition dynamics are not deterministic, and the sequences of events in transitions are not automatic (Geels and Schot, 2007). Frameworks and approaches are (always) ideal, but their application to empirical cases requires care and evaluation and the balancing of arguments (Geels and Schot, 2007). However, despite these qualifications, it is maintained that the developed ITMST framework has a significant internal logic, constituted by transitions concepts. Nonetheless, it is acknowledged that, in order for the theoretical constructs to add value, such constructs have to be operationalised. The focus of this chapter is thus on the ITMST framework as a ***methodology,*** in contrast with the presented constructs in Chapter 7 focussing on the conceptual framing of a ***premise for the integration between technology management and socio-technical transitions***. This chapter essentially outlines the practicability of the framework to support decisions on the management of technology within the context of a sustainability transition. And thus, it addresses the second part of the research aim, ***which is to provide the basis for a robust analysis to identify and define technology management considerations within the context of sustainability transitions.*** Figure 40 provides a high-level schematic representation of the proposed ITMST methodology. A number of phases and sub-phases outlined in Figure 40 are aligned with the cyclical coordinated multi-actor transition management process (Van der Brugge and Rotmans, 2007), which is organised around four co-evolving activity clusters, namely: (i) system structuring, establishment of transition arena and envisioning; (ii) developing coalitions and transition agendas; (iii) mobilising actors and executing projects, and (iv) evaluating and monitoring the transition process. This alignment is primarily due to the similar aims shared by transition management and the framework and methodology presented in this research, namely: to contribute towards increasingly effective and efficient management practices within the context of sustainability transitions. Transition management provides the basis for managing transitions from an operational perspective (Loorbach, 2010).

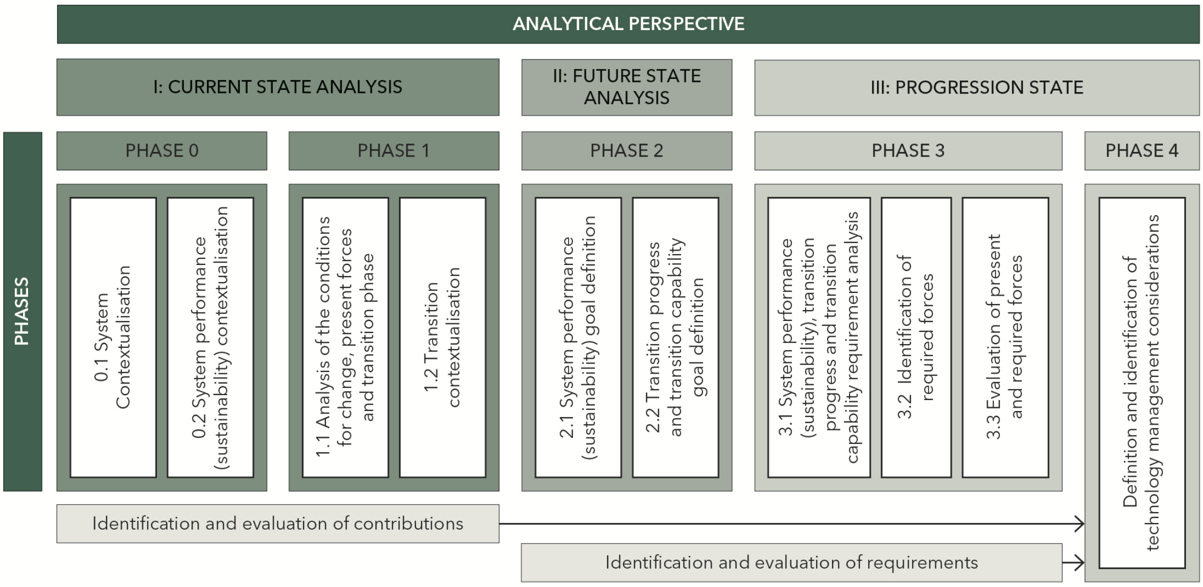

Figure 40. Phases and analytical perspectives of the ITMST methodology

8.2 The detailed ITMST methodology

The ITMST methodology consists of four phases, which are aligned to three analytical perspectives, namely the analysis of the current, (required) future, and progression states of a system in transition (as shown in Figure 40). Phases 0 and 1 refer to the demarcation of the current state of the system and the transition respectively, and are associated with the current state analysis. Phase 2 delineates the required future state and is thus associated with the future state analysis. Phases 3 and 4 are concerned with the evaluation of the change required to move towards the required future state, and are thus associated with the progression state analysis. Phase 3 essentially translates the future state into transition requirements, and identifies the necessary forces to bring about the required transitional change. In Phase 4, the objective is ultimately to identify and define technology management considerations, based on the identification and evaluation of the contributions towards, and requirements for: (i) transition progress, (ii) transition capability, and (iii) system performance from the respective technology domains. Figure 41 illustrates the process that constitutes the ITMST methodology. The complementary and supporting frameworks, tools and techniques to assist with carrying out the various activities across the phases are also discussed.

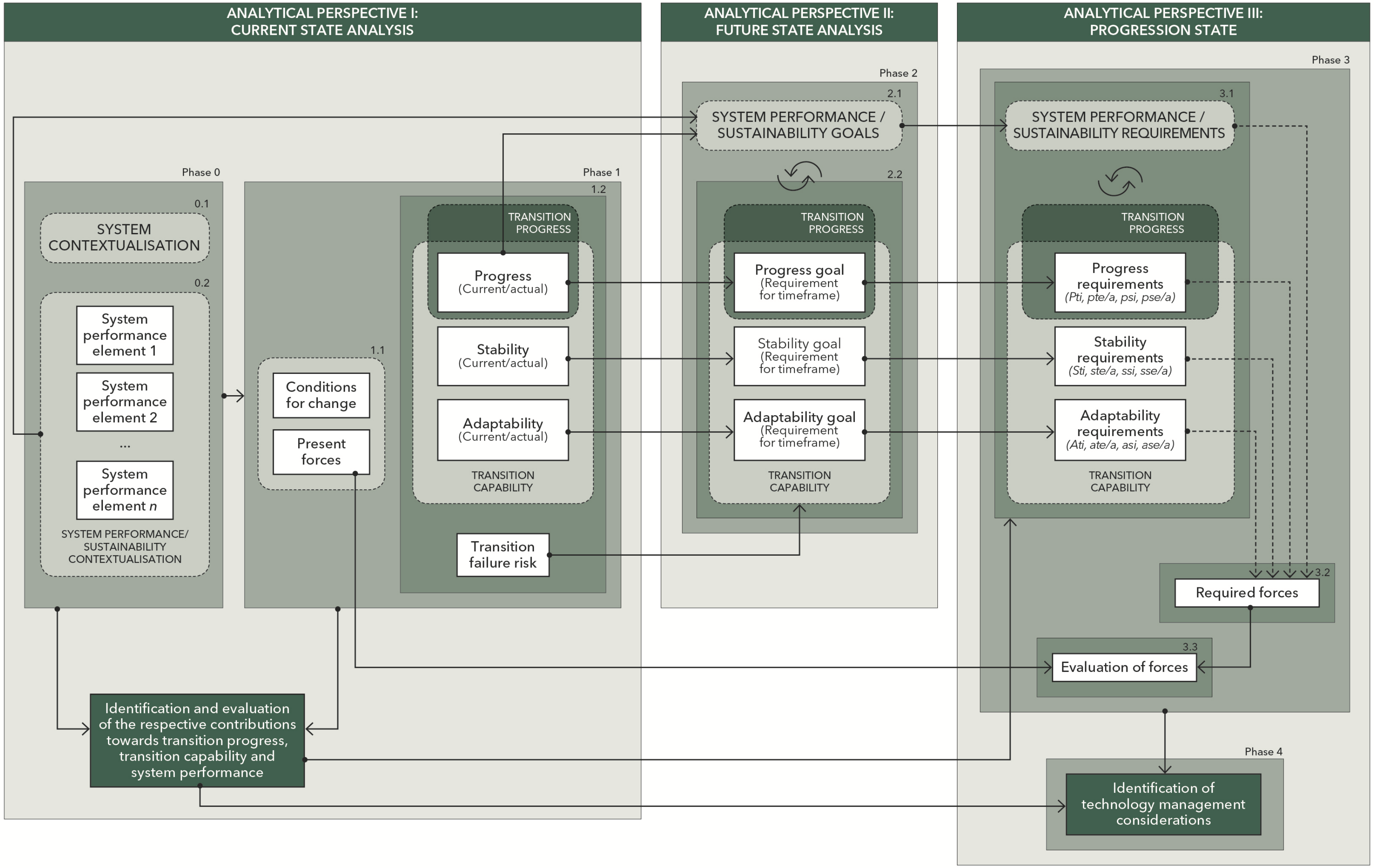

Figure 41. ITMST methodology as a process

8.2.1 Analytical perspective I: Current state analysis

Phase 0 and Phase 1 demarcate the current state of the system and the transition respectively, and are associated with the current state analysis. The analytical perspective concludes with the identification and evaluation of the contributions from the respective technology domains towards transition progress, transition capability and system performance (see Figure 41).

8.2.1.1 Phase 0

Phase 0 is focused on (i) the contextualisation of the system under consideration (Sub-phase 0.1), and (ii) the contextualisation of the system performance within the setting under consideration (Sub-phase 0.2). Thus, the phase defines sustainability, which is typically expressed as part of the system's performance, within the context of the system under consideration, gaining an understanding of the current state of sustainability / system performance of a system, including gaining an understanding of, or establishing a, sustainability vision. Phase 0 may then also be used as a baseline. The sections below provide a detailed outline of each of the sub-phases. Figure 42 highlights Phase 0 in the ITMST methodology.

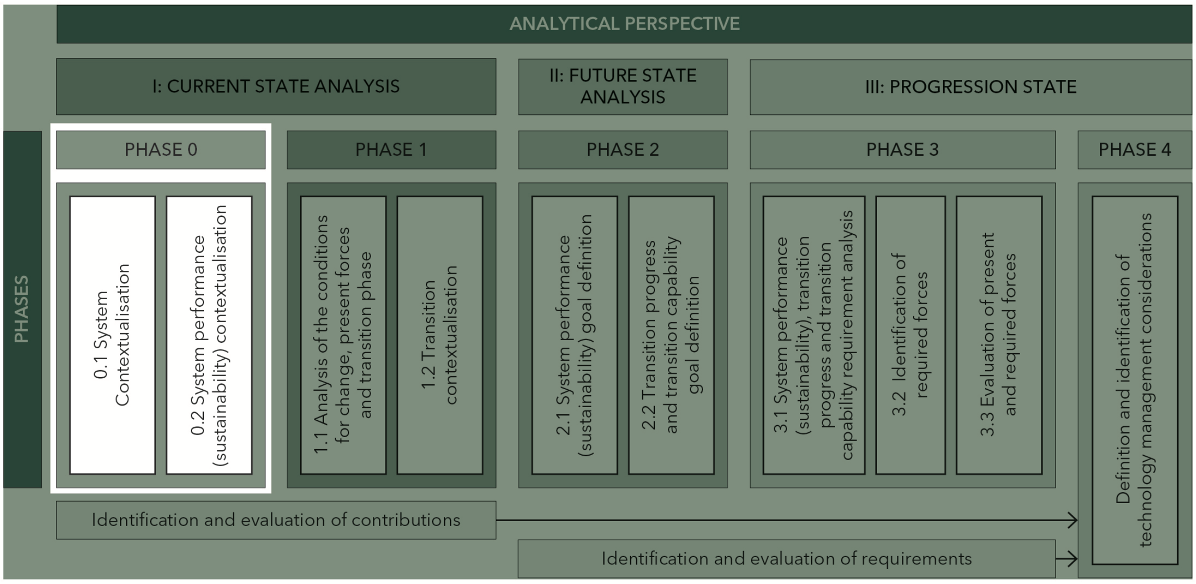

Figure 42. Phase 0 of the ITMST methodology

8.2.1.1.1 Sub-phase 0.1: System contextualisation

The system contextualisation sub-phase is geared towards (i) demarcating the system under consideration, and (ii) understanding the system constellation and multi-level structure with specific attention to the technology domains. The objective of this step is to gain a sound understanding of the socio-technical system, and to identify the societal functions fulfilled by the system, as well as the role of the respective technology domains in fulfilling such functions.

8.2.1.1.1.1 System demarcation

The starting point in using the ITMST methodology is what would most likely be the starting point for any socio-technical transitions analysis, i.e., the demarcation of the system under consideration. This implies carefully defining the unit of analysis (De Haan and Rogers, 2019). Furthermore, De Haan and Rogers (2019) propose that the system demarcation has to be done from three perspectives: (i) functional – i.e., what system and what set of societal needs is under analysis; (ii) temporal – i.e., defining the period containing the developments that are the reason for the investigation; and (iii) spatial or jurisdictional – i.e., where does the transition happen, typically at global, national, regional, or local level (although the organisation level may also be considered).

Unit of analysis

Since this research focuses on the transition from one socio-technical system to another, the unit of analysis will be a socio-technical system that is defined around technology (Geels and Schot, 2007). Properly defining the unit of analysis will assist in avoiding the exclusion and/or omission of important stakeholders and aspects in the socio-technical system, and will also support the distinction between internal and external influencing factors (Lachman, 2014).

Demarcation

As mentioned above, the demarcation of the system under consideration has to be done from three perspectives:

i. *Functional demarcation*
Here, the key focus is on outlining which societal functions are fulfilled by the system under consideration; socio-technical systems are systems that evolved to fulfil societal needs (Haan et al., 2014). Such societal needs include, for example, electricity supply, transport, and health care.

ii. *Temporal demarcation*
De Haan and Rogers (2019) state that, in order to define the temporal demarcation of the system under discussion the smallest period of time, during which the developments that are the reason for the analysis happened, should be defined. When considering such temporal demarcation, it is suggested that the initial demarcation be bounded before and after by periods of relative stability.

iii. *Spatial demarcation*
Here the geographic and/or jurisdictional boundaries for analysis have to be defined. As stated above, the spatial demarcation aims to highlight 'where' the transition happens, and will typically be a national, regional, or other governance area.

8.2.1.1.1.2 Identification of the multi-level structure

The MLP (Geels, 2002) can be readily used in this context to elucidate the structure of the socio-technical system under consideration. The MLP consists of the landscape level, the regime level, and the niche level. The key objective here is to identify and describe the incumbent and the emerging/alternative technology domains, as defined in the conceptual framing of the ITMST framework.

Landscape level: Here, the set of developments that are exogenous to the system under consideration have to be identified. These developments place pressure on, and create tension within, the regime. The landscape pressures in the context of sustainability transitions are often due to the negative environmental impact of socio-technical systems. As mentioned earlier, landscape developments only exert pressure on the regime if they are perceived and acted on by actors in the system (Geels and Schot, 2007).

Regime level: The regime consists of three interrelated elements: (i) a network of actors and social groups that developed, or need to develop, over time; (ii) a set of formal and informal rules that guide the activities of actors who produce, reproduce and maintain the elements of the socio-technical system; and (iii) material and technical elements (Geels, 2004; Lachman, 2014). Regimes represent the dominant system that fulfils societal needs, and changes in regime require changes in the system in which the regime functions. As long as the regime is stable, and landscape pressures are absent, regimes create a strong alignment between system elements, thereby making the system path dependent.

Niche level: The micro-level of a socio-technical system is formed by technological niches, which are the origin for radical innovations (Geels, 2006). The developments in niches are often focused on addressing the problems and challenges that exists in regimes. Niches are considered critical system innovations because they provide the seeds for change (Geels, 2006).

Technology domains: To meet societal needs, various inventions, solutions, and technologies exist – and new innovations to meet such societal needs are continuously being developed. Given the 'social embeddedness' of technology, and thus also the nature of the conceptualisation of socio-technical systems, the success of 'solutions' or technologies has to be accompanied by social institutions, i.e., organisations, norms, rules and regulations that enable them to perform their need-fulfilling functions (De Haan and Rogers, 2019). Even though the 'solutions' that fulfil societal needs will have been alluded to in the system demarcation, a specific focus on this is necessary. The ITMST framework and methodology defines two general technology domains: (i) the incumbent technology domain, and (ii) the emerging/alternative technology domain. The incumbent technology domain represents the incumbent regime level (and within the context of sustainability transitions, this is often deemed unsustainable in respect of one or more system performance element). The emerging/alternative technology domain represents the niche level (an alternative that could potentially replace the incumbent technology domain and thereby address the system performance element that is deemed unsustainable). Some technology domains meet a larger proportion of societal needs than others, thus the dependence to fulfil societal needs in the different technology domains differs, and in order for a transition to occur, the respective proportions should change, as the system under consideration moves through the transition phases. This proportion of dependency contributes towards a measure of the 'power' and 'agency' of a technology domain (De Haan and Rogers, 2019; De Haan and Rotmans, 2011).

In the ITMST methodology, the power and agency of a technology domain is conceptualised as a factor of (i) the capability (both from a technological and a social perspective) of the technology domain to fulfil a societal function, as well as (ii) the requirement for each technology domain, given the sustainability state and transition requirement of the socio-technical system. In other words, the 'power' of a technology domain is seen as the dependence of a socio-technical system on a technology domain in terms of the contribution towards meeting the societal need(s), as well as the dependence on the technology domain to contribute towards transition resilience and the sustainability of the socio-technical system.

8.2.1.1.2 Sub-phase 0.2: System performance (sustainability) contextualisation

As part of Phase 0, the system's performance has to be defined. There are 'universally accepted' guidelines of what constitutes system performance within the context of 'sustainability'. However, defining what system performance is, especially within a specific context and socio-technical transition, is important. 'Sustainability' may mean different things in different systems, and it is also considered an indicator of system performance. The key consideration when aiming to define the system performance of a socio-technical system is to identify the system performance elements that constitute the overall system performance or sustainability. As mentioned previously, a socio-technical transition is 'necessary' when one or more system performance elements are deemed unsustainable; however, all system performance elements have to be identified and/or defined.

To understand the (un)sustainability of one or more system performance elements, it is necessary to identify, describe and understand – when considering the 'system performance: (i) how sustainability is defined within the context under consideration, (ii) the ***contribution*** of the socio-technical system towards the system performance elements, and (iii) the system performance ***requirement***, and thus what is the system performance goal (or target) for the socio-technical system. What may be challenging here is to identify whether or not any such goals or targets are aligned with a sustainability vision – which in turn may not necessarily be an agreed upon vision. It is important to note that the system performance in terms of sustainability is considered from the perspective of the landscape pressures and developments that result in the need for a socio-technical transition. Therefore, the system performance goal (for the timeframe or transition phase under consideration) that is established in Phase 2, is thus also guided by the perceived unsustainability (of one or more system performance element) due to landscape pressures.

Sustainability is determined by three parameters: environmental sustainability, social sustainability, and economic sustainability (World Economic Forum, 2015). Sustainable development is understood as social and economic development that should be environmentally sustainable (Moldan, Janoušková and Hák, 2012). A widely used sustainable development framework is the Sustainable Development Goals (United Nations, 2015) developed in 2015, which aim to guide, *inter alia*, the elimination of extreme poverty, fight inequality and injustice, and resolve climate change. Figure 43 shows the 17 Sustainable Development Goals[41] – a globally accepted framework developed by the United Nations. Each goal is supported by a set of indicators that serve as metrics for the respective goals.

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[41] Http://unstats.un.org/wiki/display/SDGeHandbook

Figure 43. Sustainable development goals[41]

The outlook, and as conceptualised as part of the ITMST framework and methodology, is thus that (i) both incumbent and emerging/alternative technology domains contribute – either positively or negatively – towards the system performance of a socio-technical system (i.e., sustainability (*e/a*) as shown in Figure 37), (ii) the state of the performance of the socio-technical system may be misaligned with system performance targets or desired levels of sustainability, and (iii) any such (perceived) misalignments should be translated into requirements – i.e., the desired contribution from the technology domains. However, it should be noted that the ability of a technology domain to contribute towards the sustainability of the system may result in the contribution not being equal to the required contribution.

8.2.1.2 Phase 1

In Phase 1, the current state of the transition for the specific system and context has to be demarcated. Here the conditions for change and forces present and that bring about the current state of the transition have to be identified (Sub-phase 1.1). The current state of the transition, i.e., transition progress and transition capability have to be investigated (Sub-phase 1.2). The context specificity of the phase in which the transition is in also has to be considered here. Figure 44 highlights Phase 1 in the ITMST methodology.

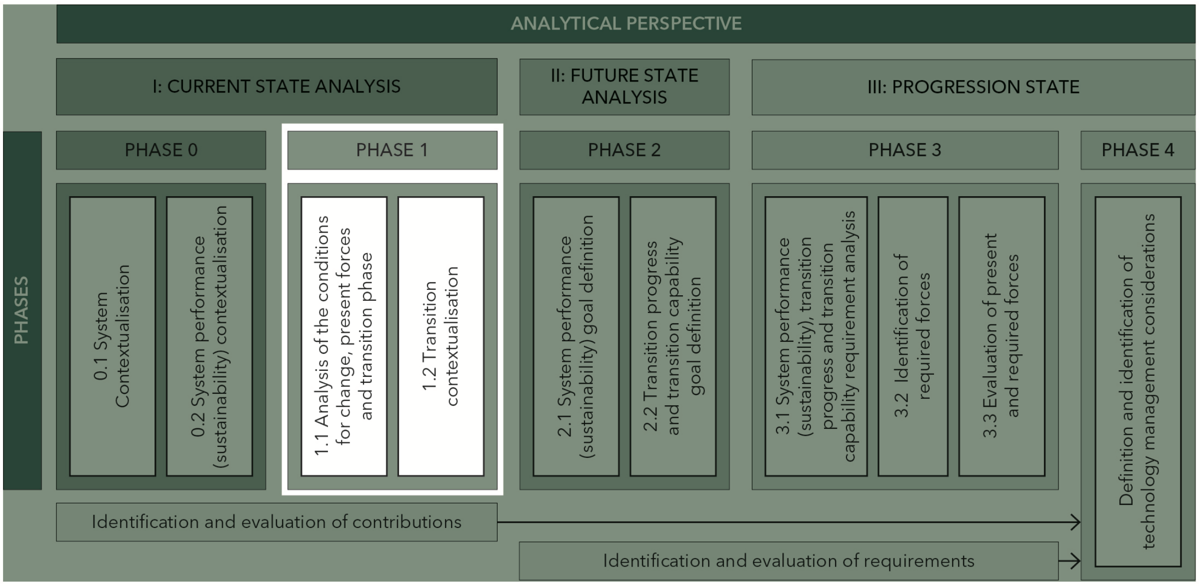


Figure 44. Phase 1 of the ITMST methodology

8.2.1.2.1 Sub-phase 1.1: Analysis of the conditions for change, present forces and transition phase

In Sub-phase 1.1, the conditions for change as well as the forces that are present in the socio-technical system present have to be identified. Then, the current state of the transition (i.e., the transition phase) has to be identified.

8.2.1.2.1.1 Conditions for change and present forces

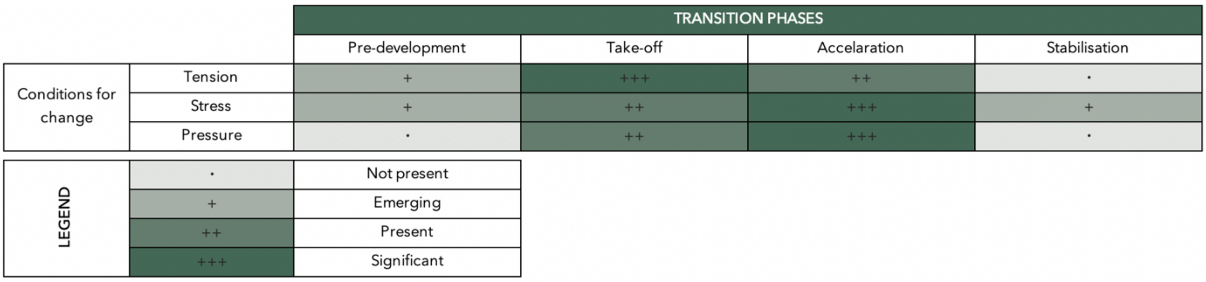
As mentioned, conditions for change are necessary but not necessarily sufficient conditions to drive transitional change (Frantzeskaki and De Haan, 2009). Therefore, the forces that 'set the stage' for these conditions have to be identified. It should be noted that (and this highlights the importance of the phased approach to transitional progress, as well as the consideration of the dimensions of resilient transitions) a force that contributes to transformational change in one phase might hinder transitional change and/or transition capability in another, whereas a force that contributes positively towards one transition capability dimension may deduct from another dimension. This again highlights the importance of context specificity (both in terms of the socio-technical system state, i.e., system performance and/or sustainability and the transition phase it is in).

Frantzeskaki and De Haan (2009) state that the forces (i.e., a descriptive variable of the system state during a transition) that set the stage for such conditions for change have to be identified, as well as the forces that drive transitional change. Similarly, the forces that are resisting transitional change for both the incumbent and emerging/alternative technology domains have to be identified. Frantzeskaki and De Haan (2009) provided a set of 10 forces that drive transitional change, and that can either stimulate or inhibit the desired transition. Panetti *et al.* (2018) identified seven drivers of technology transitions, as well as the sub-factors that act on them. The forces driving transitional change and the drivers of technology transitions are shown in Figure 31 and Table 77 (in Appendix D) respectively. These sets of forces can be used as a guideline to identify the current forces either driving or resisting transformational change. Whether a force is driving or resisting transformational change depends on the system in which these forces are at play, as well as the transition phase.

8.2.1.2.1.2 Transition phase (current state)

The conditions for change that are present in a socio-technical system delineate the transition phase that the socio-technical system is in. Understanding the conditions for change not only allows for an understanding of the current transition state, but also guides the development of the future state. Table 38 shows the conditions for change for the respective transition phases; the attributes of the conditions can facilitate the identification of the current state of the transition in terms of which phase the transition is in.

Table 38. Conditions for change across transition phases (author's own representation based on Frantzeskaki and de Haan, (2009) and (Geels (2002)



		TRANSITION PHASES			
		Pre-development	Take-off	Accelaration	Stabilisation
Conditions for change	Tension	+	+++	++	·
	Stress	+	++	+++	+
	Pressure	·	++	+++	·

LEGEND		
	·	Not present
	+	Emerging
	++	Present
	+++	Significant

8.2.1.2.2 Sub-phase 1.2: Transition contextualisation

As part of the system demarcation, or more specifically the identification of the multi-level structure of the system, the landscape developments are identified. It is generally accepted that the perspective from which a system under consideration in the contexts of socio-technical transitions is viewed, has an orientation towards sustainability. However, the guiding force in these situations are the landscape developments that render a socio-technical system unsustainable, at one empirical level or another, in other words, in relation to one system performance element or another. This unsustainability creates the need for a system to transition to a higher (improved) level of system performance (sustainability). This 'transition' need can be defined as an ultimate goal, but within the context of this framework, and in line with suggestions from other transition scholars, transition and system performance (sustainability) goals should be defined (and re-evaluated) across transition phases. The transition contextualisation phase is thus geared towards crystallising the current state of the transition (i.e., transition progress) and the current state of transition capability.

8.2.1.2.2.1 Progress (current state)

Progress is arguably the most fundamental characteristic of a transition, as it defines the degree to which the required or desired system change is experienced (Mühlemeier, Binder and Wyss, 2017). In terms of transition capability, this dimension depends on two aspects: ***drivers*** of transitional change, and ***resistance*** to transitional change (Schilling, Wyss and Binder, 2018). However, 'actual' progress should also be considered – i.e., to what extent has progress been made to reach a higher level of system performance. Interventions relating to transition progress should thus be geared towards ***exploiting the drivers of transitional change*** (given the specific transition goals and objectives defined) and ***managing resistance to transitional change***. It is necessary to consider the extent to which the incumbent technology domain and the emerging/alternative technology domain contribute towards ***transition progress*** (i.e., contribution towards transition progress and transition capability (*i*) and contribution towards transition progress and transition capability (*e/a*) in Figure 37). The latter involves the step referred to as 'identification and evaluation of the respective contributions towards transition progress, transition capability and system performance' – discussed in Section 8.2.1.3 (also see Figure 41).

8.2.1.2.2.2 Stability (current state)

Stability consists of three sub-dimensions: (i) stability of the sustainability goals, (ii) stability of the transition pathway(s), and (iii) system resilience. Since transitions mostly occur in uncertain and unpredictable environments (Grin, Rotmans and Schot, 2010), systems under transition are exposed to unpredictable events and risks that could potentially cause changes in the transition direction (i.e., away from the original sustainability goals), or even threaten the transition process in its entirety (Schilling, Wyss and Binder, 2018). The overall stability of the transition process is affected by (i) the stability of the envisioned system state with the corresponding sustainability goals, and (ii) the stability of the transition pathway that is supposed to lead to the envisioned state.

Along with the stability of the system performance (sustainability) goals (i.e., the more sustainable future state) and the pathway (i.e., how to realise the future state) discussed above, the stability of the system under transition also forms part of the 'stability equation', and is referred to as 'system resilience' (Schilling, Wyss and Binder, 2018). Essentially, this refers to the fact that a system has to maintain functionality throughout a transition, and thus not collapse. Therefore, when transitions are considered, the basic structures and functions of the system that will protect against system collapse should be identified (Binder, Mühlemeier and Wyss, 2017). However, systems in transitions go through (necessary) periods of instability as the incumbent regime has to be destabilised to create 'windows of opportunity'. Such events, necessary for the progression of transitions, also bring with them 'cracks' and tensions in the system (Köhler *et al.*, 2019), and this tension and/or interplay between stability and change is central to approaches like the MLP (Geels, 2002).

It is necessary to consider the extent to which the incumbent technology domain and the emerging/alternative technology domain contribute towards ***stability*** (i.e., 'contribution towards transition progress and transition capability (*i*)' and 'contribution towards transition progress and transition capability (*e/a*)' in Figure 37).

8.2.1.2.2.3 Adaptability (current state)

Similar to stability, the adaptability of a system in the context of transitions complements the basic understanding of transition capability. Adaptability is the capacity of system actors to manage and adapt the system, and is thus conceptualised as the *"extent to which the transition process can be adapted, if necessary"* (Schilling, Wyss and Binder, 2018:13). In order to elucidate the adaptability of a system, the 'adaptive capacity' and existing 'lock-ins' have to be considered.

It is further necessary to consider the extent to which the incumbent technology domain and the emerging/alternative technology domain contribute towards ***adaptability*** (i.e., 'contribution towards transition progress and transition capability (*i*)' and 'contribution towards transition progress and transition capability (*e/a*)' in Figure 37).

8.2.1.2.2.4 Transition failure risks

As discussed in Section 6.1.2.4, transitions fail when a socio-technical system no longer progresses towards an improved level of system performance (higher level of sustainability), when it does not reach the desired level of system performance/sustainability, or when the system breaks down. The transition failures that have been defined are: lock-in, system breakdown, and backlash (Brugge and Rotmans, 2007). Weber and Rohracher (2012) defined four transformational failures: directionality failure, demand articulation failure, policy coordination failure, and reflexivity failure.

The transitional forces and the risk of transition failure should be considered in parallel, as it essentially is, similar to transition resilience, the presence, absence, or 'quality' of these forces that contribute towards (the risk of) transition failure.

8.2.1.3 Identification and evaluation of the respective contributions towards transition progress, transition capability and system performance

Subsequent to conducting Phases 0 and 1, the contributions of the respective technology domains have to be identified and evaluated. The evaluation of system performance elements, and the contribution of the respective technology domains towards system performance results in a set of contribution perspectives of 2 x the number of performance elements – see Table 39.

Table 39. Respective contributions towards system performance elements from the incumbent and emerging/alternative technology domains

	CONTRIBUTION TOWARDS SYSTEM PERFORMANCE	
	INCUMBENT TECHNOLOGY DOMAIN	EMERGING / ALTERNATIVE TECHNOLOGY DOMAIN
SYSTEM PERFORMANCE ELEMENT 1	contribution 1(i)	contribution 1(e/a)
SYSTEM PERFORMANCE ELEMENT 2	contribution 2(i)	contribution 2(e/a)
…	…	…
SYSTEM PERFORMANCE ELEMENT *n*	contribution n(i)	contribution n(e/a)

LEGEND		
	Significant negative contribution	- - -
	Negative contribution	- -
	Slight negative contribution	-
	No contribution	·
	Slight contribution	+
	Positive contribution	++
	Significant positive contribution	+++
	Contribution unknown	?

Similarly, the evaluation of transition progress and transition outlined above thus results in 12 contribution perspectives that have to be considered. These respective perspectives are shown in Table 40.

Table 40. Respective perspectives within the ITMST methodology

	CONTRIBUTION TOWARDS TRANSITION PROGRESS ANS TRANSITION CAPABILITY					
	PROGRESS		STABILITY		ADAPTABILITY	
	PT	PS	ST	SS	AT	AS
INCUMBENT TECHNOLOGY DOMAIN	contribution PT(i)	contribution PS(i)	contribution ST(i)	contribution SS(i)	contribution AT(i)	contribution AS(i)
EMERGING / ALTERNATIVE TECHNOLOGY DOMAIN	contribution PT(e/a)	contribution PS(e/a)	contribution ST(e/a)	contribution SS(e/a)	contribution AT(e/a)	contribution AS(e/a)

LEGEND		
	Significant negative contribution	- - -
	Negative contribution	- -
	Slight negative contribution	-
	No contribution	·
	Slight contribution	+
	Positive contribution	++
	Significant positive contribution	+++
	Contribution unknown	?

8.2.2 Analytical perspective II: Future state analysis

The second analytical perspective of the ITMST methodology, in other words, the future state analysis, consists of one phase (i.e., Phase 2) and is focused on delineating the required future state of the (i) system performance, (ii) transition progress, and (iii) transition capability.

8.2.2.1 Phase 2

The future state analysis is concerned with translating the findings of Phases 0 and 1 into system performance, transition progress, and transition capability goals in order to address the gap that exists between (i) the desired level of system performance (sustainability) and the current state of system performance (sustainability), and (ii) the required transition progress and transition capability and, thus, the current state of the transition. An important distinction here is that the focus here is transition timeframe- and phase-specific, meaning that the system performance/sustainability vision for the system has to be translated in to system performance/sustainability goal(s) for the timeframe and phase under consideration, and similarly the transition progress and transition capability goals have to be defined. Furthermore, it is important to note that the system performance/sustainability goal(s), the transition progress goals and the transition capability goals inform each other – see Figure 41. Figure 45 highlights Phase 2 in the ITMST methodology.

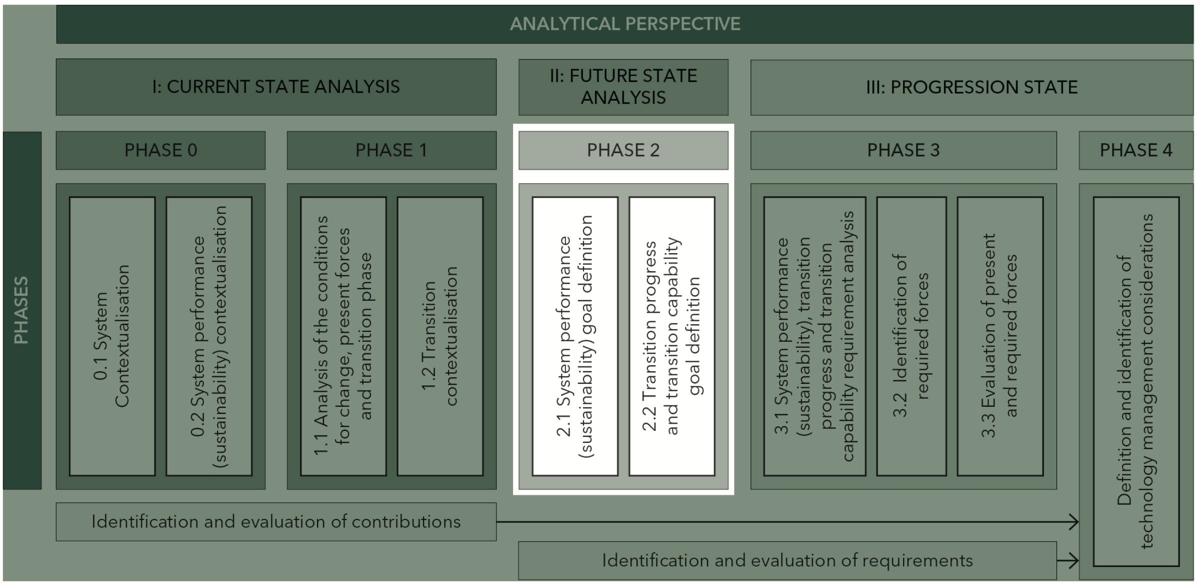


Figure 45. Phase 2 of the ITMST methodology

8.2.2.1.1 Sub-phase 2.1: System performance (sustainability) goal definition

The unsustainability of a system, across one or more system performance elements, supports the establishment of a system performance/sustainability vision – a future state in which the system is no longer unsustainable. Throughout the transition towards such a state of improved system performance/sustainability, intermediate system performance/sustainability goals may be set. Within the context of this framework, the system performance/sustainability goals are guided by the system performance/sustainability vision, the extent to which progress has been made towards such a vision (i.e., system change), and the transition phase within which the system is situated.

Given the system performance/sustainability vision for the socio-technical system and the current transition progress (transformational change) towards such a vision, system performance/sustainability goals for the timeframe and/or transition phase under consideration may be defined. The system performance/sustainability goals essentially express the desired system change for the period under consideration. It is important to note that these goals are guided by the sustainability vision, and thus the landscape developments and the perceived tension that results from such landscape developments, and that brought about the need for a sustainability transition (see Figure 37).

8.2.2.1.2 Sub-phase 2.2: Transition progress and transition capability goal definition

The goals in terms of the transition progress and the transition capability dimensions for a particular timeframe or transition phase should then be defined – thus, the progress, stability and adaptability goals. The definitions of these goals are guided by the current state of these dimensions, as well as the system performance/sustainability goals. The progress, stability and adaptability goals are also then indications of transition failure mitigation goals, i.e., these goals are set in terms of what is required to facilitate a successful transition.

8.2.2.1.2.1 Progress goal

First and foremost, the desired/required change in the system has to be defined; thus, to what extent is (further) change in the socio-technical system required?

8.2.2.1.2.2 Stability goal

Similar to progress, the stability goal is defined in relation to the current state of stability. It is important to note that, unlike progress (unless in the event of a stabilised transition that has thus been ‘completed’), since progress by definition warrants change, a goal in terms of stability may be to ‘maintain status quo’.

The stability goal should thus be set in terms of (i) the stability of the sustainability goals, (ii) the stability of the transition pathway(s), and (iii) the system resilience.

8.2.2.1.2.3 Adaptability goal

Depending on the transition phase, as is the case with the other transition resilience dimensions, adaptability is either more or less important. Thus, the adaptability goal of the timeframe under consideration should be defined in terms of the desired adaptive capacity among system actors and existing pathway lock-ins.

8.2.3 **Analytical perspective III: Progression state analysis**

Phases 3 and 4 are concerned the evaluation of the change required to move towards the required future state, and thus associated with the third analytical perspective – i.e., the progression state analysis.

8.2.3.1 Phase 3: Requirement analysis

Phase 3 demarcates the first phase in the progression state by firstly understanding the requirements brought about by the system performance/sustainability goals, as well as the requirements brought about by the progress, stability, adaptability and transition failure mitigation goals respectively, and then further unpacking these across the respective technology domains. Subsequently, the forces required to support these requirements are identified and evaluated. Figure 46 highlights Phase 3 in the ITMST methodology.

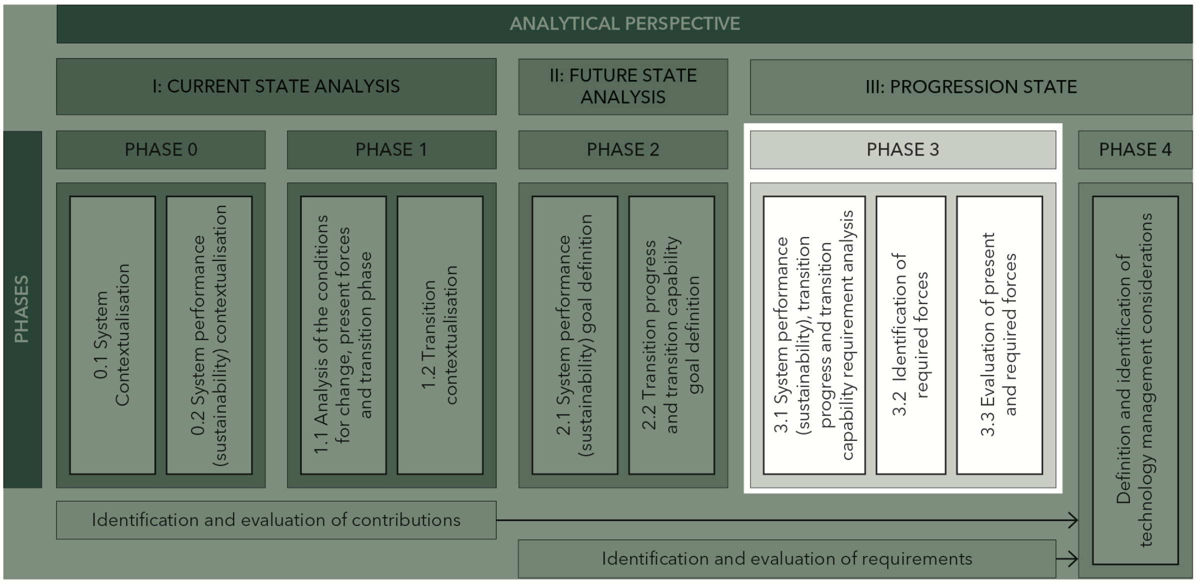


Figure 46. Phase 3 of the ITMST methodology

8.2.3.1.1 Sub-phase 3.1: System performance (sustainability), transition progress and transition capability requirement analysis

In Sub-phase 3.1, the transition requirements are evaluated and set. Since system performance, transition progress, and transition capability depend on, and are influenced by, both incumbent and emerging/alternative technology domains, the requirements for these three elements have to be defined for both technology domains. Given that transitions have to occur from both a social as well as a technological perspective, the requirements in terms of the transition progress and transition capability then have to be determined across progress, stability and adaptability, from both a social and a technological perspective, as well as for both the incumbent technology domain and the emerging/alternative technology domain. This results in a set of number of system elements x 2 requirements for system performance, and 12 requirements (similar to the contributions discussed in Section 8.2.1.3) for transition progress and transition capability combined being developed in Sub-phase 3.1. The set of requirements essentially pertains to (i) ***system performance***, i.e., the change across all system performance elements required as well as the required contributions from the respective technology domains; (ii) ***transition progress***, i.e., the required change (degree to which the system – i.e., the respective technology domains – has to transform) over a particular period of time from both a technological and social perspective; and (iii) the requirements from both technology domains in terms of the ***stability*** of transition process and the system resilience in order to ensure that the system changes towards the desired more sustainable state, and to guard against system collapse, and ***adaptability***, which is the extent to which the transition process can be adapted if required, are then translated into an adaptability requirement for the respective technology domains.

In order to realise the system performance, transition progress and transition capability goals, the required change has to be understood across the respective technology domains. The requirements are conceptualised as the ***required contribution*** in order to foster a 'successful' transition (i.e., 'system performance/sustainability requirements (i)', 'system performance/sustainability requirements (e/a)', 'transition progress and transition capability requirement (*i*)' and 'transition progress and transition capability requirement (*e/a*)' in Figure 37).

8.2.3.1.2 Sub-phase 3.2: Identification of required forces

Subsequently, the forces required to address each of the requirements identified and defined in Sub-phase 3.1 should be identified. Again, the forces as defined by Frantzeskaki and De Haan (2009) and Panetti et al. (2018) may be used as guide to identify and define such forces.

8.2.3.1.3 Sub-phase 3.3: Evaluation of present and required transitional forces

Sub-phase 3.3 is concerned with the evaluation of the required forces, as well as the forces that are present in the socio-technical system. Forces may (i) either be present or absent, (ii) either drive or resist the required transitional change (i.e., transition progress), (iii) contribute either positively or negatively towards transition capability (i.e., progress, stability and adaptability), and/or (iv) contribute (either positively or negatively) towards system performance.

Now that the required forces have been identified, it has to be established whether the required forces are present or absent in the socio-technical system, whether they drive or resist transition progress, whether they contribute positively or negatively towards transition capability and/or system performance, and what the impact of the forces are on transition progress, transition capability and system performance. In addition, forces should be considered that are not present but that have a possibility to develop and/or, if developed, will create a resistance to the required transitional change and/or system performance.

Figure 47 proposes guiding principles to clarify the nature of the forces that are present or absent in a socio-technical system. The specific frameworks for transition progress, transition capability, and system performance are shown in Figure 48.

Present forces that drive progress or positively contribute towards transition capability should be exploited, and present forces that impede progress or negatively contribute towards transition capability and/or system performance should be managed. Forces that are necessary, but not present (i.e., absent drivers/positive contributors – top left quadrant) should be created or developed. An additional (horizontal) dimension is proposed that considers the 'quality' of the force; the mere presence of a force might not be sufficient to drive the required transitional change, or resist it – when considering resource allocations. This is an important factor, as a force that by nature will resist transitional change might not be sufficient within the context of the socio-technical system in transition, and therefore the intervention and resources required might differ.

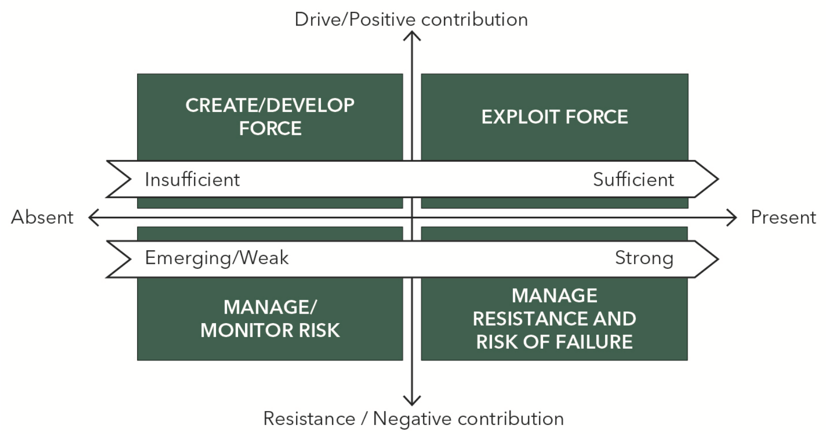


Figure 47. Framework to guide the evaluation of present and required forces

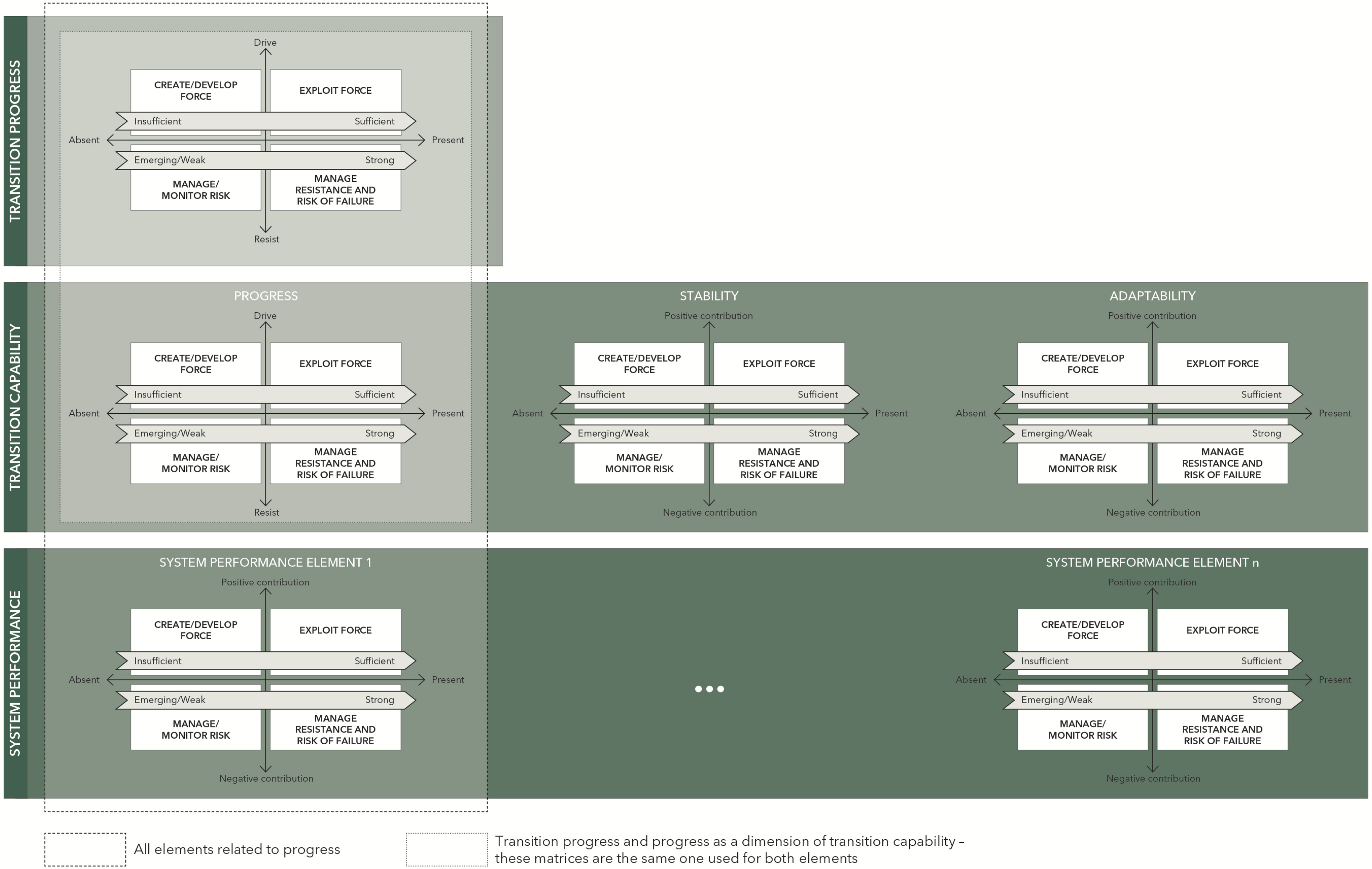


Figure 48. Framework to guide the evaluation of present and required forces for transition progress, transition capability and system performance

In addition to a force being present or absent, the framework outlined above also considers the quality of the force. In terms of the forces that are required, they can be:

i. Present and either:
    a. insufficient,
    b. sufficient, or
    c. excessive (such 'excessive' forces are typically forces that resist progress of the transition, but the force is nonetheless necessary or required to allow for transition capability and/or prevent the transition from failing); or
ii. Absent.

Forces that are present, and the ones that drive the transition are included in (i) above, and the forces that are present but resist transitional change may be present above, in that they resist progress, but contribute towards the other dimensions of transition capability, or they have to be managed as risks. The forces that are present, but not required – and that thus resist the required change – also have to be identified.

In summary, the required forces are identified from each specific perspective, i.e., the forces required for transition progress, transition capability and system performance. The status of the forces required for a specific perspective also have to be evaluated for the other perspectives. For example, the status of a force of the required forces for transition progress, for the other perspectives (for example, transition capability and system performance), also have to be considered in order to identify the opportunities and risks across the three perspectives. The framework presented in Figure 48 may be used for this analysis.

8.2.3.2 Phase 4: Definition and identification of technology management considerations

Phase 4 is the second phase of the progression state analysis and is concerned with the identification and definition of technology management considerations. As was conceptualised in Section 7.4.1, and as was indicated in Figure 40 and Figure 41, the technology management considerations that should be taken into account within the context of sustainability transitions should not only be from a commercial and technological perspective, but should also include a transition perspective in order to support transition value creation. This thus requires identifying and defining technology management considerations that are geared towards and/or aligned with the ***contribution*** of the respective technology domains towards (i) ***transition progress***, (ii) ***transition capability***, and (iii) ***system performance***, and the ***requirements*** from the respective technology domains to bring about the desired change in (i) ***transition progress***, (ii) ***transition capability***, and (iii) ***system performance***. These may then be translated into opportunities and risks for transition progress, transition capability, and system performance, as well as risks and opportunities from a commercial and technological perspective. It should be noted that the insights, in order to guide technology management considerations based on the identification and evaluation of the requirements, may be refined, based on the identification and evaluation of the respective required forces, the status of such forces and the action required.

It should be noted that contributions and requirements may result in contradictory actions for a specific force across (i) transition progress, transition capability and system performance (i.e., a force that positively contributes towards system performance may negatively contribute towards transition progress and/or transition capability and vice versa), and (ii) transition capability dimensions and system performance elements (i.e., a force may contribute positively towards one transition capability dimension, but negatively towards another, and the same is the case for system performance elements). Figure 49 highlights Phase 4 in the ITMST methodology.

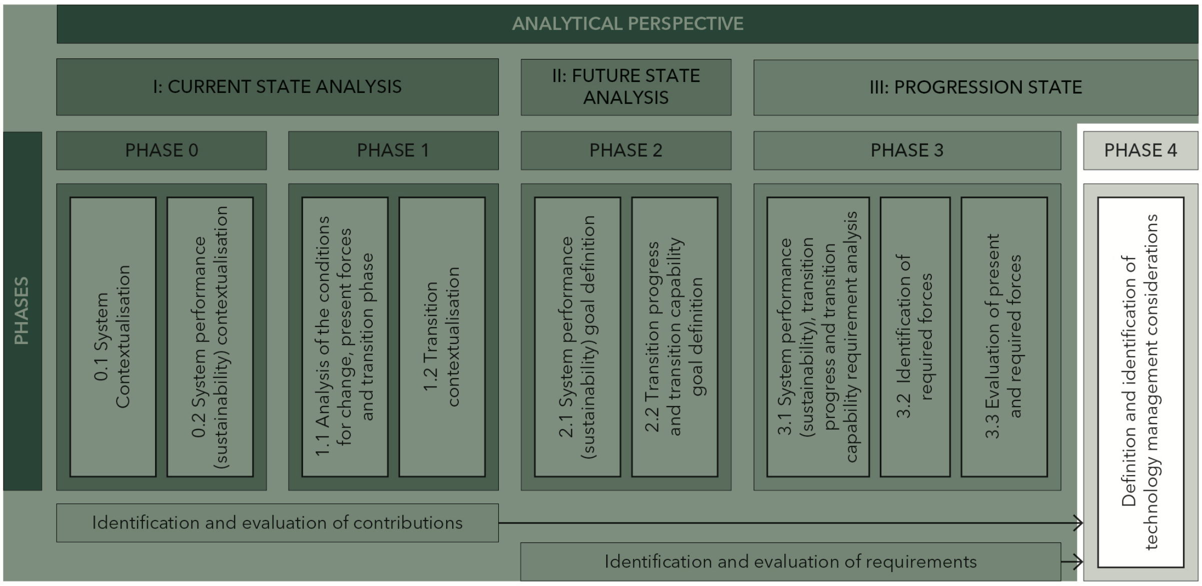


Figure 49. Phase 4 of the ITMST methodology

8.2.3.2.1 Technology management considerations from the perspective of technology domain contributions

The theoretically possible contribution scenarios are shown in Table 41. Firstly, scenarios D, E, G and H are highly unlikely/not feasible: a technology domain that does not contribute positively towards at least one system performance element has no place in the socio-technical system and is therefore highly unlikely to exist. Furthermore, scenario C, where a technology domain does not contribute towards one of the transition capability dimensions (i.e., stability, adaptability and progress), is also deemed not realistic, given that a technology domain by nature of its existence contributes towards fulfilling a societal function and thus contributes towards system performance. This, in turn, means that a technology domain at least contributes towards stability (i.e., resilience). Similarly, considering scenario F, if a technology domain contributes towards system performance, even though not towards progress or the system performance element that is related to progress, similar as mentioned above, it does contribute towards stability in that it contributes towards fulfilling the societal functions. Therefore, only scenarios A and B remain are representative of real-world cases.

Table 41. Possible contribution scenarios

	A	B	C	D	E	F	G	H
Contribution towards progress	✓	✗	✓	✓	✓	✗	✗	✗
Contribution towards transition capability	✓	✓	✗	✓	✗	✗	✓	✗
Contribution towards system performance	✓	✓	✓	✗	✗	✓	✗	✗

In addition to the contributions shown in Table 41, the detail of the transition capability and the system performance must also be considered (see Table 42). Scenarios A and B in Table 41 are then elaborated on in terms of the possible contributions towards these detailed elements and dimensions (see Table 42), and shown in Table 43.

Table 42. Consideration detail

CONSIDERATIONS	
Contribution towards progress*	
Contribution towards transition capability	Progress
	Adaptability
	Stability
Contribution towards system performance	System performance element linked to *'progress'*
	System performance element 2
	…
	…
	System performance element n

Table 43. Variations on scenario A and B

CONSIDERATIONS		VARIATIONS ON SCENARIO A							VARIATIONS ON SCENARIO B		
		A1	A2	A3	A4	A5	A6	A7	B1	B2	B3
Contribution towards progress*		Drive	Drive	Drive	Drive	Drive	Drive	Drive	Resist	Resist	Resist
Contribution towards transition capability	Progress										
	Adaptability	Positive	None / neg	Positive	Positive	None / neg	None / neg	Positive	Positive	None / neg	Positive
	Stability	Positive	Positive	None / neg	Positive	Positive	None / neg	None / neg	Positive	Positive	None / neg
Contribution towards system performance	System performance element linked to *'progress'*	Positive	Positive	Positive	Positive	Positive	Positive	Positive	Negative	Negative	Negative
	System performance element 2	Positive	Positive	Positive	None / neg	None / neg	None / neg	None / neg	Positive	Positive	Positive
	…	…	…	…	…	…	…	…	…	…	…
	…	…	…	…	…	…	…	…	…	…	…
	System performance element n	Positive	Positive	Positive	None / neg	None / neg	None / neg	None / neg	Positive	Positive	Positive

In scenario A, a technology domain contributes towards transition progress, transition capability and system performance. Firstly, if a technology domain contributes to transition progress, the technology management efforts may be geared towards actions that will ensure the long-term sustainability of the (element of the) technology domain. When a technology domain does not contribute towards progress but contributes to transition capability as well as system performance (i.e., Scenario B), there are still opportunities for the technology domain, however the risks are also clearly evident.

In Scenario B, given that the technology domain then contributes towards either the adaptability and/or the stability of the transition capability, the technology domain still has a role to play in the transition and therefore there still exist opportunities for the technology domain. This, however, should ideally be limited to the minimum necessary capacity required, and thus limited to no opportunities for growth (in terms of the predominant, unsustainable technology in the technology domain). The key opportunities here are to exploit the existing infrastructure, or then to include alternative more sustainable technologies into the technology domain. Furthermore, the transition phase context specificity should be taken into account (see Table 21 and Table 38). For example, if the transition is in the 'take-off phase', and the technology domain does not significantly contribute towards adaptability, or restricts such adaptability, there is firstly an increasing risk that has to be managed, given that adaptability becomes increasingly important in the subsequent phase. Moreover, if the technology domain does not increasingly contribute towards – in this example – adaptability, the necessity (i.e., the contributions) from such a technology domain becomes less. This can thus also be translated into an opportunity; if we take the same example of adaptability, given that the need for adaptability significantly increases in the subsequent domain, the technology management considerations may be geared towards increasing the possible contribution of the technology domain towards adaptability. Similarly, stability should be considered.

In Scenario B, the mere nature of the existence of a technology domain means that it contributes towards the system performance and thus towards fulfilling a societal function. However, if a technology domain does not contribute towards progress (i.e., change in the part of the system from which the need for a transition originated), Table 44 shows the technology management considerations from the perspective of technology domain contributions towards transition progress, transition capability, and system performance.

Table 44. Technology management considerations from the perspective of technology domain contributions

Progress	Drive	PT	If a technology domain contributes to driving progress, the technology management efforts may be geared towards actions that will ensure the long-term sustainability of the (element of the) technology domain. The technology management considerations may be geared towards ***exploiting*** these technologies that allows for the drive towards progress, and ***protecting*** such technologies.
		PS	When a technology domain drives progress form a social perspective, the management of technology should be geared towards towards exploiting the relevant technologies to ensure that the social demands that if met will support transitional change remain addressed.
	Resist	PT	When a technology domain does not contribute towards progress (thus resists it), but contributes to transition capability (i.e. stability and/or adaptability) as well as system performance there is still opportunities for the technology domain, however the risks are also clearly evident. If a technology domain resists progress, the technology management considerations include: (i) understanding the contributions (if any) towards transition capability and system performance; (ii) technology exploitation considerations should be geared towards short- and medium term (depending on the transition phase); (iii) technology management considerations should be geared towards incorporating decommissioning and phasing out of the technologies in the technology domain that resists progress. Technology management considerations may be geared towards the identification, selection and acquisition of technologies that may support progress.
		PS	If the technology domain resists progress from a social perspective, technology management considerations should be geared towards ***identifying*** technologies that will address the social concerns, and ***learning*** / critically reflecting on technology and related projects on how they
Stability	Positive	ST	As mentioned, all technology domains contribute (at least) towards stability in terms of system resilience because they contribute towards a system's capacity to fulfil a societal function. Technology management considerations may thus be towards ***exploiting*** the technologies that contribute towards stability, but should be considered in relation to whether or not the technology domain contributes towards progress or not.
		SS	Positive contributions towards stability requires technology management considerations that include the identification of the elements and dimensions of the technology domain that supports stability form a social perspective, and ***exploiting*** those. It also requires technology management considerations to be geared towards learning and reflecting on the contributions of the technology domain towards stability in order to ***protect*** such elements and dimensions.
	Negative	ST	If a a technology domain negatively contributes towards stability, and taking the transition phase into consideration, technology management efforts should be geared towards ***identification*** of areas where technological aspects of the technology domain negatively affects system resilience and the stability of the sustainability transition. ***Identification, selection*** and ***acquisition*** of technologies for the technology domain that supports stability should be considered.
		SS	If the technology domain has a negative contribution towards stability from a social perspective, this is primarily linked to the technology domain not contributing towards the stability of the transition pathway. Technology management considerations should therefore included understanding and highlighting the alignment (or lack thereof), of the technology domain to the envisioned (increasingly sustainable) envisioned state for the system, identifying technologies that will allow for increased alignment to the envisioned system state, and translating technology contributions into the contributions towards sustainability or transition goals.
Adaptability	Positive	AT	A positive contribution towards adaptability from a technological perspective requires technology management considerations across a number of technologies (hence the adaptability). The considerations should further be geared towards identifying possible future lock-in risks.
		AS	If a technology domain positively contributes towards adaptability from a social perspective, technology management considerations should be geared towards highlighting these social aspects that contribute towards the adaptability of the socio-technical system and exploit such elements in order to ensure sustainable adaptability in the system.
	Negative	AT	A technology domain that negatively contributes towards adaptability essentially means that the technology domain is responsible for lock-in; technology management considerations should be geared towards identifying technology developments that may improve adaptability and reduce lock-in. From a technological perspective, technology management considerations should be geared towards understanding the implications of lock-in of both the system performance as well as the transition capability, and to identify both technological aspects as well as the social implications should the lock-in be addressed in order to plan to manage the change from both a social and technological perspective.
		AS	A negative contribution towards adaptability from a social perspective requires technology management considerations that reflects on the impacts on adaptability. Technology management considerations should include the translation of technology domain elements into the negative long-term effects of a system that is not adequately adaptable.
System performance element linked to 'progress'	Positive		If a technology domain positively contributes towards the system element that is linked to progress, the technology management considerations should include exploiting the technology to increase the contribution to this system performance element. Consideration should also be given to the impact of the technology domain on other system performance elements as well as the transition capability dimensions. If a technology domain positively contributes towards this specific system performance elements, but does not adequately also contribute to the other system performance elements, technology management considerations should be geared towards identifying and developing capabilities to increase the contributions of the technology domain towards other system performance elements.
	Negative		If a technology domain negatively contributes towards the system performance element that is linked to 'progress', the technology management considerations are aligned with the considerations proposed in the case of a technology domain negatively contributing towards progress; identifying alternative technologies that can contribute towards other system performance elements (i.e. fulfil societal functions), but also contribute towards improving the system performance elements that is linked to progress.
System performance element 2	Positive		A positive contribution towards a system performance element should be exploited to improve any under performance, or maintained if the level of performance is adequate. However, if the technology domain negatively contributes towards the system performance element that is linked to progress, and positively towards this system element, technology management considerations should be geared towards managing the negative impact on the system performance element whilst upkeeping the positive contribution towards this system performance element.
	Negative		A negative contribution towards a system performance element that is not linked to progress should be addressed by identifying, selecting and acquiring technologies to support the improvement of this system performance element.
...			
System performance element n	Positive		Same as other system performance elements that are not linked to progress.
	Negative		Same as other system performance elements that are not linked to progress.

8.2.3.2.2 TM considerations form the perspective of the requirements from the respective technology domains

The output from Phase 3 is the evaluated forces (required and present), highlighting the status of the respective forces, as well as the actions required (see Figure 48). The forces that influence (either positively or negatively) (i) transition progress, (ii) transition capability, and (iii) system performance thus bring about the need for the following actions:

i. exploiting existing forces that drive transitional change (i.e., progress) and/or contribute positively towards transition progress, transition capability, and system performance;
ii. creating or developing forces that are absent, but required to drive transitional change (progress) and/or contribute positively towards transition capability and/or system performance;
iii. manage forces that are present, but allow for resistance against transformational change (progress) and/or negatively influence transition capability and/or system performance; and
iv. monitor risks, i.e., forces that are not present but that pose a risk of resistance and/or negative contribution if developed towards transition progress, transition capability, and/or system performance.

The technology management considerations that have to be taken into account can now be evaluated from alternative perspectives in order to align such actions with resources and to be resource efficient in order to (i) exploit the forces, (ii) manage resistance, (iii) create or develop the forces, or (iv) manage or monitor the risk (depending on the ‘quality’ of the force).

The forces that are identified as present and required forces are (i) formation forces, (ii) supportive forces, and (iii) triggers. Formation forces, being related to the potential for (societal) innovation, thus require technology management considerations that include the identification, selection, acquisition and/or development of technology(ies) and/or processes to support system performance and transition progress and capability from both a technological and a social perspective. Supportive forces are geared towards strengthening or weakening existing operations, and the technology management considerations here are geared towards exploiting existing technologies and/or managing the risk that such technologies pose through considerations, such as the phasing out and decommissioning of technologies. Furthermore, the technology management considerations from a social perspective require the translation of the technical output of a technology domain into the social consequences, as well as the translation of the supportive forces from a social perspective into the effect that this has on the selection of technologies.

8.2.3.2.3 Risks and opportunities

When identifying risks and opportunities, it is important to note that the risks for the transition, for the technology domains, and for the system performance should be taken into account. Given that technology management is primarily focused on creating value at an organisational level (Cetindamar, Phaal and Probert, 2010), in order to identify risks and opportunities for organisations the relationship between the transition perspective and the commercial perspective of technology management is thus conceptualised as follows:

i. From a technological perspective, an organisation contributes, either positively or negatively, towards the transition progress, transition capability, and system performance - the individual and collective consideration of these contributions may then facilitate the identification of risks and opportunities for the organisation;
ii. Similarly, the required contribution (futures perspective) from a technology domain may highlight risks and opportunities – it is important to note that risks and/or opportunities may not be imminent, but may only realise in the future. Again, individual and collective consideration is necessary to effectively identify risks and opportunities across the socio-technical system and the transition;
iii. The transition perspective then also, given ii and ii above, facilitates the identification of risks and opportunities from a commercial perspective for the respective technology domains; and
iv. Current and future commercial and technological capabilities of the respective technology domains pose risks and opportunities to transition progress, transition capability and system performance.

The approach outlined in Section 8.2.3.1.3 may further facilitate the identification of risks and opportunities for the technology domains (or then respective organisations within the technology domains), for the transition (transition progress and transition capability), and for system performance. As mentioned, once risks and opportunities are defined and identified, these may be exploited (opportunities) or managed (risks). However, it should be noted that such exploitation or management may in turn have a negative impact on the transition progress, transition capability and/or system performance – highlighting the upmost importance of a shared, cross-actor, and cross-domain understanding of the contributions and requirements from the respective technology domains to facilitate a successful transition and improved system performance/sustainability. Finally, this also highlights the importance of a shared vision and/or goal(s) for system performance/sustainability. Even though the attainment of such a shared vision and/or goal does not fall within the scope or focus of this dissertation, the processes outlined and captured within the ITMST framework and methodology may contribute towards improved understanding of the barriers and enabling factors to such shared visions and/or goals.

8.3 Chapter 8: Conclusion

This chapter presents the operationalisation of the ITMST framework (presented in Chapter 7), as the ITMST methodology. The ITMST methodology satisfies the requirement for a research output that provide practical utility. The ITMST methodology complements the conceptual nature of the ITMST framework by providing a systematic and structured approach that operationalises the key features of the ITMST framework in order to provide the basis for the definition and identification of technology management considerations within the context of socio-technical transitions.

Chapter 9.

Evaluation of the ITMST framework and methodology

This chapter deals with the evaluation (i.e., verification and validation) of the developed framework and methodology. The verification of the framework is based on the set of requirements that was developed in Chapter 6, as well as on the theoretical verification of the framework. For validation purposes, a case study is subsequently performed to provide confidence in the applicability and practicability of the developed framework and methodology.

9.1 Verification of the framework and methodology

A two-part verification is conducted. First, the verification of the requirements set for the framework, and how these are addressed in the developed framework and methodology, shows how the framework and methodology adhere to the guidelines and restrictions provided through the literature analysis and synthesis. The second part of the verification comprised of semi-structured interviews with subject matter experts in order to verify the theoretical integrity of the developed framework and to facilitate the emergence of refinements.

9.1.1 Evaluation of requirement specifications

The purpose of verification is to assess whether the framework was developed according to its specifications, thus verifying whether the system was built correctly, whereas validation considers whether the right system was built (Boehm, 1984). The requirements for the development of the framework were categorised into five categories in Chapter 7, namely: functional requirements; user requirements; design requirements; attention points; and boundary conditions. Each of these requirements was verified individually (i) by considering whether they are satisfied by the developed framework, and (ii) by indicating whether they are addressed by a specific element or embedded across the ITMST framework features or ITMST methodology elements and/or phases. The verification thus consisted of evaluating how the requirements (rows) are addressed by the framework elements and features (columns). The outcome of the verification process is shown in Table 45, Table 46, Table 47, Table 48 and Table 49. It should be noted that some of the requirement specifications are not linked to specific features or phases, but rather related to the framework and/or methodology in a conceptual manner.

Table 45. Functional requirements verification

		KEY FEATURES OF THE ITMST FRAMEWORK					PHASES OF THE ITMST METHODOLOGY									
							CURRENT STATE ANALYSIS				FUTURE STATE ANALYSIS		PROGRESSION STATE ANALYSIS			
							PHASE 0		PHASE 1		PHASE 2		PHASE 3			PHASE 4
REQUIREMENT NUMBER	REQUIREMENTS	TRANSITION VALUE CREATION	COLLECTIVE AND INDIVIDUAL CONSIDERATION	CO-MANAGEMENT OF TECHNOLOGY DOMAINS	CONTEXTUAL SPECIFICITY	CONTRIBUTION-REQUIREMENT VIEW	0.1 SYSTEM CONTEXTUALISATION	0.2 SYSTEM SUSTAINABILITY CONTEXUALISATION	1.1 TRANSITION CONTEXTUALISATION	1.2 ANALYSIS OF CONDITIONS FOR CHANGE, AND PRESENT TRANSITIONAL FORCES	2.1 SUSTAINABILITY GOAL DEFINITION	2.2 TRANSITION GOAL DEFINITION	3.1 SYSTEM PERFORMANCE AND TRANSITION REQUIREMENT	3.2 IDENTIFICATION OF REQUIRED FORCES	3.3 EVALUATION OF PRESENT VS. REQUIRED TRANSITIONAL FORCES	IDENTIFICATION OF TECHNOLOGY MANAGEMENT CONSIDERATIONS
Overarching functional requirements																
FR1	The framework should contribute towards understanding, identifying and/or analysing of technology management considerations within the context of sustainability transitions.	✓	✓	✓	✓	✓		✓		✓			✓		✓	✓
FR2	The framework should incorporate the socio-technical nature of systems that fulfil societal functions.				✓		✓		✓			✓				
FR3	The framework should contribute towards an understanding of the capability of a socio-technical system to transition from the perspective of the management of technology.	✓	✓	✓		✓			✓	✓			✓		✓	
FR4	The framework should be used to consider sustainability from a systems perspective, and it should not employ a one-dimensional or narrowly defined view of sustainability.	✓	✓	✓				✓			✓					
FR5	The framework should facilitate cross-actor understanding of the contributions and requirements from the incumbent regime and emerging or alternative niche respectively.			✓		✓							✓	✓	✓	
Conceptual functional requirements																
FR6	The framework should consider both the incumbent regime and the emerging or alternative niche, as both influence the (un)sustainability of a system as well as the capability to transition. The framework should therefore encompass: i. the incumbent regime; and ii. the emerging or alternative niche.			✓												
FR7	The framework should allow for contextual specificity in terms of: iii. the environment within which a socio-technical system exists; and i. the transitions phase within which the system is located.				✓		✓		✓							
FR8	The framework should support the cross-actor understanding of: v. The contributions towards the (un)sustainability of the socio-technical system of: a. The incumbent regime; and b. The emerging or alternative niche. vi. The required contribution(s) towards sustainability of: a. The incumbent regime; and b. The emerging or alternative niche. vii. The contributions towards the capability of a socio-technical system to transition from: a. The incumbent regime; and b. The emerging or alternative niche. viii. The required contribution(s) towards transition capability of: a. The incumbent regime; and a. The emerging or alternative niche.	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓	

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Operational functional requirements																
FR9	The framework should provide decision support in transition management pertaining to the management of technology within the context of a sustainability transition.	✓														✓
FR10	The framework should guide transition goals and objectives to be aligned with technology management goals and objectives of both incumbent and emerging or alternative technologies.	✓														✓
FR11	The framework should support and/or enable the development process of technology management considerations, to facilitate transitional change from a technology management perspective.	✓	✓	✓		✓										✓

Table 46. User requirements verification

		KEY FEATURES OF THE ITMST FRAMEWORK					PHASES OF THE ITMST METHODOLOGY									
							CURRENT STATE ANALYSIS				FUTURE STATE ANALYSIS		PROGRESSION STATE ANALYSIS			
							PHASE 0		PHASE 1		PHASE 2		PHASE 3			PHASE 4
REQUIREMENT NUMBER	REQUIREMENTS	TRANSITION VALUE CREATION	COLLECTIVE AND INDIVIDUAL CONSIDERATION	CO-MANAGEMENT OF TECHNOLOGY DOMAINS	CONTEXTUAL SPECIFICITY	CONTRIBUTION-REQUIREMENT VIEW	0.1 SYSTEM CONTEXTUALISATION	0.2 SYSTEM SUSTAINABILITY CONTEXTUALISATION	1.1 TRANSITION CONTEXTUALISATION	1.2 ANALYSIS OF CONDITIONS FOR CHANGE, AND PRESENT TRANSITIONAL FORCES	2.1 SUSTAINABILITY GOAL DEFINITION	2.2 TRANSITION GOAL DEFINITION	3.1 SYSTEM PERFORMANCE AND TRANSITION REQUIREMENT	3.2 IDENTIFICATION OF REQUIRED FORCES	3.3 EVALUATION OF PRESENT VS. REQUIRED TRANSITIONAL FORCES	IDENTIFICATION OF TECHNOLOGY MANAGEMENT CONSIDERATIONS
UR1	The framework should be practicable.						✓									
UR2	The framework should be considered a management aid, both from a technology management perspective, as well as from a sustainability transition perspective.	✓		✓					✓			✓	✓			✓
UR3	The framework should provide clear definitions and explanations to cater for a broad range of levels of experience in the technology management and/or transitions disciplines.	✓ *					✓ *									
UR4	The framework should be sufficiently general to be applicable in a wide variety of contexts, while simultaneously being specific enough to be useful without a thorough and deep understanding of the theoretical bases.	✓					✓									

*In terms of the breadth of the developed constructs, the conceptual part of the framework may appeal more to an academically inclined audience, given the conceptual and abstract nature, whereas the ITMST methodology is more practically oriented and may appeal to a more practically oriented audience.

Table 47. Design restrictions verification

		KEY FEATURES OF THE ITMST FRAMEWORK					PHASES OF THE ITMST METHODOLOGY									
							CURRENT STATE ANALYSIS				FUTURE STATE ANALYSIS		PROGRESSION STATE ANALYSIS			
							PHASE 0		PHASE 1		PHASE 2		PHASE 3			PHASE 4
REQUIREMENT NUMBER	REQUIREMENTS	TRANSITION VALUE CREATION	COLLECTIVE AND INDIVIDUAL CONSIDERATION	CO-MANAGEMENT OF TECHNOLOGY DOMAINS	CONTEXTUAL SPECIFICITY	CONTRIBUTION-REQUIREMENT VIEW	0.1 SYSTEM CONTEXTUALISATION	0.2 SYSTEM SUSTAINABILITY CONTEXTUALISATION	1.1 TRANSITION CONTEXTUALISATION	1.2 ANALYSIS OF CONDITIONS FOR CHANGE, AND PRESENT	2.1 SUSTAINABILITY GOAL DEFINITION	2.2 TRANSITION GOAL DEFINITION	3.1 SYSTEM PERFORMANCE AND TRANSITION REQUIREMENT	3.2 IDENTIFICATION OF REQUIRED FORCES	3.3 EVALUATION OF PRESENT VS. REQUIRED TRANSITIONAL FORCES	IDENTIFICATION OF TECHNOLOGY MANAGEMENT CONSIDERATIONS
DR1	The conceptual framework and the operationalisation thereof are not meant to include an exhaustive set of tools and methods to elucidate the technology management requirements or transition capabilities in each transitional phase at any of the possible levels of analysis, but they should be comprehensive enough to provide guidance on the requirements set out in Section 6.3.2.	Each feature and/or phase of the framework and methodology provides constructs, tools and/or methods which should be comprehensive enough to provide sufficient processes and perspectives to elucidate considerations for the management of technology in order to support socio-technical transitions.														

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DR2	The framework is intended for a systems level analysis, but may be applicable to analysis at a lower level of analysis.	There are constructs, features and processes in the developed framework and methodology that are (clearly) also applicable to lower levels of analysis than at systems level, however this has not been validated and is suggested as future research. Consideration for lower level of dynamics will however be required when the framework and methodology is applied to, for example, organisational level.
DR3	The framework is not a policy or regulatory guide, and thus input required for such items should be obtained from subject matter experts. However, the framework is intended to support the development of systems level interventions to facilitate sustainability transitions and therefore can also contribute towards policy and regulatory development processes.	The framework and the methodology does not venture into the policy and regulatory spheres, partly due to UR3 (the need for generic qualities, and the legal and regulatory frameworks that govern socio-technical systems may differ vastly, and also due to the focus of research not being on policy and regulatory perspectives. However, it is argued that the insights gained from the framework and the methodology may elucidate policy and regulatory requirements.
DR4	The framework does not guarantee improved transition capability or transitional change due to a multitude of factors that influence such an outcome. However, it does aim to provide principles and guidelines that will contribute towards the capability of a socio-technical system to transition and for a transition to be resilient from a technology management perspective	The framework and methodology proved, as per the aim of this research, a premise for the integration of the concept of socio-technical transitions and technology management in order to contribute towards contribute towards increasingly effective and efficient management practices within the context of socio-technical transitions. However, the guidelines and insights presented in the framework and methodology highlights the technology management considerations (amongst others) and are thus only part of a much wider set of considerations required to evaluate, analyse, govern, facilitate and/or support socio-technical transitions.

Table 48. Attention points verification

		KEY FEATURES OF THE ITMST FRAMEWORK					PHASES OF THE ITMST METHODOLOGY									
							CURRENT STATE ANALYSIS				FUTURE STATE ANALYSIS		PROGRESSION STATE ANALYSIS			
							PHASE 0		PHASE 1		PHASE 2		PHASE 3			PHASE 4
REQUIREMENT NUMBER	REQUIREMENTS	TRANSITION VALUE CREATION	COLLECTIVE AND INDIVIDUAL CONSIDERATION	CO-MANAGEMENT OF TECHNOLOGY DOMAINS	CONTEXTUAL SPECIFICITY	CONTRIBUTION-REQUIREMENT VIEW	0.1 SYSTEM CONTEXTUALISATION	0.2 SYSTEM SUSTAINABILITY CONTEXUALISATION	1.1 TRANSITION CONTEXTUALISATION	1.2 ANALYSIS OF CONDITIONS FOR CHANGE, AND PRESENT TRANSITIONAL FORCES	2.1 SUSTAINABILITY GOAL DEFINITION	2.2 TRANSITION GOAL DEFINITION	3.1 SYSTEM PERFORMANCE AND TRANSITION REQUIREMENT	3.2 IDENTIFICATION OF REQUIRED FORCES	3.3 EVALUATION OF PRESENT VS. REQUIRED TRANSITIONAL FORCES	IDENTIFICATION OF TECHNOLOGY MANAGEMENT CONSIDERATIONS
AT1	The framework should be seen as a reflection of early onset practice within two ever-evolving fields.	The key reasons why this research is a reflection of early best practice from the perspective of integrating the concept of socio-technical transitions and technology management are: (i) academic literature / research that considers both technology management and socio-technical transitions are (very) limited as found in the analysis of the scientific networks pertaining to technology management and socio-technical transitions (refer to Chapter 3 and 4), and (ii) both the field of technology management and that of sustainability transitions are ever-evolving fields of knowledge and the framework should be elaborated and expanded as concepts that integrate these fields emerge.														
AP2	Due to the nature of the framework, a number of opportunities for integration with other complementary management approaches and frameworks are envisioned. However, it falls outside the scope of this research study to explicitly address such opportunities or to provide and/or develop such management approaches or frameworks.				✓		✓	✓	✓							
AP3	It should be noted that, even though the integration strategy and developed framework provide for the integration of transition concepts with those of technology management at a conceptual level, and the integration or linking of technology management concepts with that of sustainability transition concepts at an increasingly operational level, the framework is developed from the perspective of sustainability transitions. Thus, it is primarily focused on informing the role of technology management within the context of sustainability transitions, and not on informing the role of transitions concepts in technology management.	✓			✓											✓

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AP4	The developed framework is a high-level framework that supports the understanding of key aspects of technology management within the context of sustainability transitions. As a result, this framework may also be seen as an emerging and potentially integrative approach to understanding newer, sustainability-oriented sources of competitive advantage to organisations.	✓	✓	✓												✓

Table 49. Boundary conditions verification

		KEY FEATURES OF THE ITMST FRAMEWORK					PHASES OF THE ITMST METHODOLOGY									
							CURRENT STATE ANALYSIS				FUTURE STATE ANALYSIS		PROGRESSION STATE ANALYSIS			
							PHASE 0		PHASE 1		PHASE 2		PHASE 3			PHASE 4
REQUIREMENT NUMBER	REQUIREMENTS	TRANSITION VALUE CREATION	COLLECTIVE AND INDIVIDUAL CONSIDERATION	CO-MANAGEMENT OF TECHNOLOGY DOMAINS	CONTEXTUAL SPECIFICITY	CONTRIBUTION-REQUIREMENT VIEW	0.1 SYSTEM CONTEXTUALISATION	0.2 SYSTEM SUSTAINABILITY CONTEXUALISATION	1.1 TRANSITION CONTEXTUALISATION	1.2 ANALYSIS OF CONDITIONS FOR CHANGE, AND PRESENT	2.1 SUSTAINABILITY GOAL DEFINITION	2.2 TRANSITION GOAL DEFINITION	3.1 SYSTEM PERFORMANCE AND TRANSITION REQUIREMENT	3.2 IDENTIFICATION OF REQUIRED FORCES	3.3 EVALUATION OF PRESENT VS. REQUIRED TRANSITIONAL FORCES	IDENTIFICATION OF TECHNOLOGY MANAGEMENT CONSIDERATIONS
BC1	The framework should be used in an ethical way. It is assumed that the framework will be applied so that it adheres to governance and other relevant governing bodies that might exist within environment of the socio-technical system under consideration.	The framework and methodology should be used for its intended purpose, and be aligned with an objective that seeks an increasingly sustainable socio-technical system. Even though, as mentioned previously, the framework and methodology may hold value to alternative applications than what is evaluated in this research, such evaluations have not been evaluated. Furthermore, the framework and methodology does not stand in contention with any governing bodies, but aims to highlight considerations to support decision making (criteria).														
BC2	The framework should not be used to exploit stakeholders negatively, and risks and opportunities should be highlighted across the system under consideration.	An important assumption of the framework and methodology is that a higher, more sustainable future state is desired. And that this inevitably means that, as clearly highlighted in literature, will bring about 'winners and losers'. However, the framework implicitly aims to facilitate participatory decision making (FR5 & FR6 for example) across a system as a whole.														
BC3	The framework should promote value for all parties, thus assuming that a common goal and vision of what is meant by sustainability of the socio-technical system has been established.	The 'value for all parties' does not necessarily refer to the expansion or growth, but rather to value in terms of insights to the contributions, requirements and/or risks and opportunities of the technology domains towards transition progress, transition capability and system performance elements – which provides decision support.														

Each requirement across the five requirement categories as defined by Van Aken *et al.* (2006) is considered in the tables presented above, and each requirement is compared to either a specific element or feature of the developed framework or methodology, or across framework elements and features, or to the use of the framework conceptually. From the evaluations outlined in Table 45, Table 46, Table 47, Table 48 and Table 49 the requirements are verified to have been satisfied by the ITMST framework and methodology, its use and its intention.

9.1.2 Theoretical verification and framework refinement

The theoretical verification and framework refinement was done through a series of semi-structured and unstructured consultations and interviews with subject matter experts. Even though some interviews were conducted during the framework development process (at crucial stages of the framework development process, i.e., after the development of the integration strategy), the majority were conducted after the development of a preliminary framework and methodology for the purpose of theoretical validation and framework refinement.

The key objective of the theoretical verification is to evaluate whether the proposed solution (the ITMST framework and methodology) is fit for its intended purpose. During the theoretical verification, the question that should be addressed is whether the developed framework and its concepts make sense, not only to the researcher, but also to other scholars and practitioners; thus, the question asked is, does the framework *"present a reasonable theory for scholars studying the phenomenon"* (Jabareen, 2009:54). The semi-structured interviews were thus constructed around and guided by the following six questions:

i. Will the stated requirements contribute to addressing the stated objective?
ii. Will the framework achieve the stated purpose?
iii. What do you consider to be the key strengths of the proposed framework and methodology?
iv. What do you consider to be the key weaknesses of the proposed framework and methodology?
v. Where do you think the framework would fail, if implemented?
vi. Are there any bodies of literature that you feel have been excluded that should be considered for inclusion in the development of the proposed framework?

The subject matter experts who were included in the theoretical verification and framework refinement interviews are listed in Table 50. They were selected based on experience and expertise in technology management, sustainability management and/or socio-technical transitions.

Table 50. Subject matter experts (SMEs) interviewed as part of the framework verification process

	POSITION AND RELEVANT EXPERIENCE
SME1	SME1 is the Managing Director of an organisation that operates in the knowledge industry to provide business consulting in the management and commercialisation of knowledge, technology and innovation. He is also a part-time academic in the Graduate School of Technology Management at the University of Pretoria, holds a PhD. Research focus include the dynamics of socio-technical change in the modern era.
SME2	SME 2 holds a PhD in Engineering with specialisation in Technology Management from the University of Pretoria. He is Professor in Technology Management and also Head of the Department of Engineering and Technology Management at the University of Pretoria.

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SME3	SME3 is an associate professor at the Postgraduate School of Engineering Management at the University of Johannesburg. SME3's research focus is on solving cross-discipline industry problems through the application of engineering management principles. Research focus include requirements engineering, systems engineering and engineering management,
SME4	SME 4 is the Chief Operating Officer of an international engineering organisation, holds a PhD and is registered as a professional engineer. SME 4 is involved in the governance of systems in transition in practice.
SME5	SME5 is an Associate Professor at the Energy Institute and at the Institute of Sustainable Resources at University College London in the UK. Research focus include innovation studies and sustainability transitions.
SME6	SME6 is a senior research fellow at the international research centre for regional development and planning in Stockholm. SME6's research focuses on the area of urban and territorial sustainability. They participated in several research projects funded by European and national programmes, designing tools for a circular economy and for sustainability assessment schemes. SME6 holds a PhD.
SME7	SME 7 is a Senior Research Associate at University College London and specialises in policy analysis, foresight and evaluation in the area of innovation and sustainable development. Their focus is on public policies and innovations transforming the world towards long-term sustainability. Research focus include transitions from the perspective of green economies.
SME8	SME8 is a Professor at King's College London. SME8's recent work has been concerned with science, technology, policy and sustainability, and the governance of sustainable socio-technical transitions.

9.1.2.1 Recommendations and comments used for framework refinement

The most noteworthy influences from the SMEs are the following suggestions, critique and comments to refine the developed framework:

i. All the requirements were not sufficiently captured in the diagrams, and thus Figure 38 and 39 were subsequently updated;
ii. Even though practical utility was deemed important, a significant number of the SMEs advised on the formal operationalisation of the framework explicitly to showcase the usability of the conceptual framings. The operationalisation (i.e., the ITMST framework) was a direct outflow from these discussions;
iii. Similar to the point above, the usefulness of a general framework was pointed out, but the transferability to a wide selection of cases is often not possible within the constraints of a PhD research endeavour;
iv. Suggestions were made to simplify the set of requirements and the framework. The author thus critically reflected on the set of requirements and the framework, and simplified these where deemed possible;
v. It was pointed out that technology and the management thereof within the context of socio-technical transitions is only one of many parts that have to be considered within the context of socio-technical transitions, and that the limitations of the 'singular' focus should be clearly highlighted;
vi. The specific focus (as discussed in Section 7.3.1) was narrowed to allow for less complexity and simplification based on the feedback from the SMEs;
vii. The only three areas of literature that the SMEs highlighted that were not included in the research are TIS, policy mix literature, and constructive technology assessment (CTA). These fields were investigated and their relevance to this research evaluated:
    a. TIS approaches: Innovation systems literature lists innovation system evaluation criteria, referred to as 'functions of innovation systems' that can be used to evaluate the functioning of innovation systems. Focussing on such functions allows for the performance of the innovation system to be addressed (Hekkert *et al.*, 2011). It is important to note the reason

for the focus on the functions of the innovation system in particular permits the performance of an innovation system to be addressed, and the structure of an innovation system allows for insights into who the active parties within the system are, whereas the functions allows for insights into what such actors are doing and whether these actions are sufficient to develop successful innovations (Hekkert *et al.*, 2007, Hekkert *et al.*, 2011). Even though the innovation system literature, and more specifically the literature focussing on technological innovation systems, places emphasis on the factors that hinders or supports the successful development of innovations, authors such as Geels (2002) and Johnson and Jacobson (2001) argue that the TIS-approach is in principle not restricted to the evaluation of emerging technologies. It is thus argues that the TIS approach may add value to the understanding of technology management within the context of sustainability transitions if the ITMST framework is extended to also consider the innovation system functions that either provide for the creation of value, or hinders the value creation (for organisations, the system, and/or the transition. Even though the TIS would possibly be a logical choice for further elaboration of the ITMST framework and methodology, the focus of this research was rather to uncover the links between transition progress, transition capability, system performance and the technology domain as a whole rather than the individual functions of the respective technology domains.

  b. CTA offers insights on social learning processes and highlights the importance of protected spaces for the management of socio-technical transitions (Schreuer, Ornetzeder and Rohracher, 2010). The approach is focused on the decision-making process on technology development rather than the management of technology across a socio-technical system nor does it aim to understand the management of technology within the context of socio-technical transitions. It is related to SNM as the focus is on the importance of niches Schreuer, Ornetzeder and Rohracher, 2010).
  c. Policy mix literature: As mentioned elsewhere, even though the ITMST framework and methodology may be informed by policy and/or inform policy, the focus of this research study was not on policy development or evaluation, but rather on uncovering the foundational concepts that support the development of a premise for the integration between technology management and socio-technical transitions and then on the development of such a premise. Similar to the abovementioned, extending the ITMST framework and methodology to also include policy (mix) evaluation and analysis perspectives may be a logical future extension of the work presented in this research (also discussed in Section 10.4) but falls outside of the scope of this dissertation.

viii. A number of questions relating to the literature were asked by the SMEs, for example *"what are the challenges technology management face within the context of sustainability and socio-technical transitions?"* and *"has the need for the framework been articulated?"*. Their questions and comments related to a number of concepts that were discussed and investigated during the introductory sections of the research, but that, for the sake of brevity, were not included in the document outlining the preliminary framework that was sent to the SMEs before the interviews;

ix. A number of SMEs emphasised that the application of the framework to a case study would greatly enhance the value of the framework. This was accepted to be most relevant during the theoretical verification stage, given that the framework at that stage had not yet been applied;

x. A suggestion was made to change the hierarchy between the transition capability dimensions and the social and technical perspectives in the framework; this was regarded as a valuable suggestion and was thus implemented;

xi. The context was considered to be not addressed explicitly enough in the preliminary framework, which resulted in a critical reflection and definition on the context for which the framework is developed (see Section 7.3.1);

xii. Limitations and weaknesses that were highlighted include:

    a. *Lack of focus on change management* – even though this is a valid observation, change management falls outside of the scope of the research focus; similarly, change management is not explicitly addressed in the socio-technical transitions literature, however, the concepts and constructs developed do provide guidance for efforts relating to change management. It is agreed that adding a change management module to the developed framework and methodology would add value.

    b. The specific users of the framework are somewhat ambiguous – even though this is the case, it is considered a necessary ambiguity, especially given the requirement for cross-actor understanding (FR8 in Section 6.3.2).

    c. The framework does have a lot of 'moving parts' – in addition to the critical reflection with the aim of simplification discussed above, the remaining complexity is deemed necessary to capture the complexities associated with the management of technology within the context of socio-technical transitions.

    d. The explicit integration of technology management concepts with those of technology management was highlighted to pose too great a challenge for a single research project – the preliminary framework and framework purpose descriptions may have been too broad, in that the expectation of such an explicit integration rather than the provision of a premise for the integration was created. The framework description and framework purpose were revised and subsequently aligned more strongly with the research aim.

    e. Linked to the above, *the framework does not explicitly address the resistance of the incumbents* – again, it is argued that this is a valuable and true observation and comment, but a specific focus on resistance rather than focussing on resistance as an element of transition progress is (i) not deemed necessary to achieve the research aim, and (ii) would detract slightly from the research focus.

    f. An SME argued that the *operationalisation might be too detailed for some types of projects* – even though the operationalisation may be too detailed for some projects, given that the need may not always be to conduct such an extensive analysis, it is argued that the combination of the conceptual framework and its operationalisation provide for different levels of detail that may make them more widely applicable.

    g. *The power dynamics in socio-technical systems vary between actors in a socio-technical system and this is not addressed in the framework* – an explanation was incorporated with regard to how the framework addresses actors, power and agency (see Section 7.4.2.3) to explicitly state the limitations of the framework in this regard, and to justify and substantiate these limitations.

The SMEs did not highlight any critical elements that would result in the framework failing to achieve its stated objective(s). In addition to the comments, suggestions and critique summarised above, two additional noteworthy refinements were made to the ITMST framework. These refinements cannot be attributed to a specific comment, critique or suggestion from any of the SMEs, but the process of engaging with numerous experts guided the critical reflection to arrive at the following refinements:

i. The conceptualisation of the collective and individual consideration of the *transition progress, transition capability and system performance* feature of the framework was refined; in the preliminary framework, this was not explicitly stated, but it was integrated in a previous feature referred to as the 'transition perspective', which forms part of the second noteworthy refinement;
ii. A feature in the preliminary framework was the 'transition perspective' feature. This was refined to a *'transition value creation'* feature. The refined feature was firstly considered to be more representative of a 'feature' than a 'transition perspective', and secondly, the need to create value for the transition through the technologies that are employed is now explicitly emphasised in the framework.

Following the requirement and theoretical verification, a validation to showcase the applicability and practicability of the developed framework and methodology was done, and this is discussed below.

9.2 Validation of the ITMST framework and methodology

Various types of validation approaches exist, including: (i) subject matter interviews, (ii) questionnaires, (iii) practical implementation, and (iv) case studies (Ungerer, 2015). The validation of the ITMST framework and methodology are done concurrently, in that the methodology is applied to the case study and then inferences are made about the key features of the ITMST framework and their applicability to a practical case. In other words, the case study findings are used to illustrate that the conceptual framings presented in the ITMST framework are representative of real-world phenomena. The case study provides a practical example of the applicability and practicability of the developed framework.

During the validation stages of this research, secondary empirical data was used to conduct an in-depth case study, which enabled the evaluation of the developed conceptual framework and methodology.

9.2.1 Validation: Case study

In this section, the case study selection and approach are outlined, and thereafter, the case study is discussed.

9.3 Case study selection and approach

The global rise in demand for energy, geo-political challenges around the location of remaining fossil fuel reserves, and climate change challenges all place significant pressure on electricity sectors around the world (Walker, Hope and Bentley, 2014). The global energy system has to transition towards a system that can (i) reduce annual carbon emissions from energy consumption, and (ii) ensure access to affordable, reliable, and modern energy services to support a good standard of living (Energy Transitions Commission, 2017). These objectives have been quantified at a global level to provide access to 80-100GJ per person per annum (which is likely to decrease with energy productivity gains), and to reduce carbon emissions from energy systems to 20 Gt by 2040 – less than half of the expected emissions in a 'business as usual' scenario. Achieving a transition towards such a system undoubtedly calls for supply-side and demand-side management and interventions, and will require (rapid) progress along 4 dimensions: (i) the decarbonisation of power, combined with extended electrification, (ii) the decarbonisation of activities that cannot be effectively electrified, (iii) acceleration in the pace of energy productivity improvements, and (iv) optimisation of fossil fuel use within overall carbon budget constraints. Of these four dimensions, the first dimension (i.e., decarbonisation of power combined with extended electrification) is considered to be the area that will have the most significant impact on carbon emission reductions up to 2040, as decarbonising electricity systems is expected to contribute significantly towards mitigating climate change (Wang, Wei and Brown, 2017). This will, quite obviously, mean that zero-carbon sources (i.e., renewable energy sources) should account for the majority of the global power mix, and that coal-fired power generation needs to decline as steeply as possible (*Ibid.*). Figure 50 shows the current energy per capita across the world. It is evident that this measure varies significantly across regions, thus highlighting the importance of context specificity.

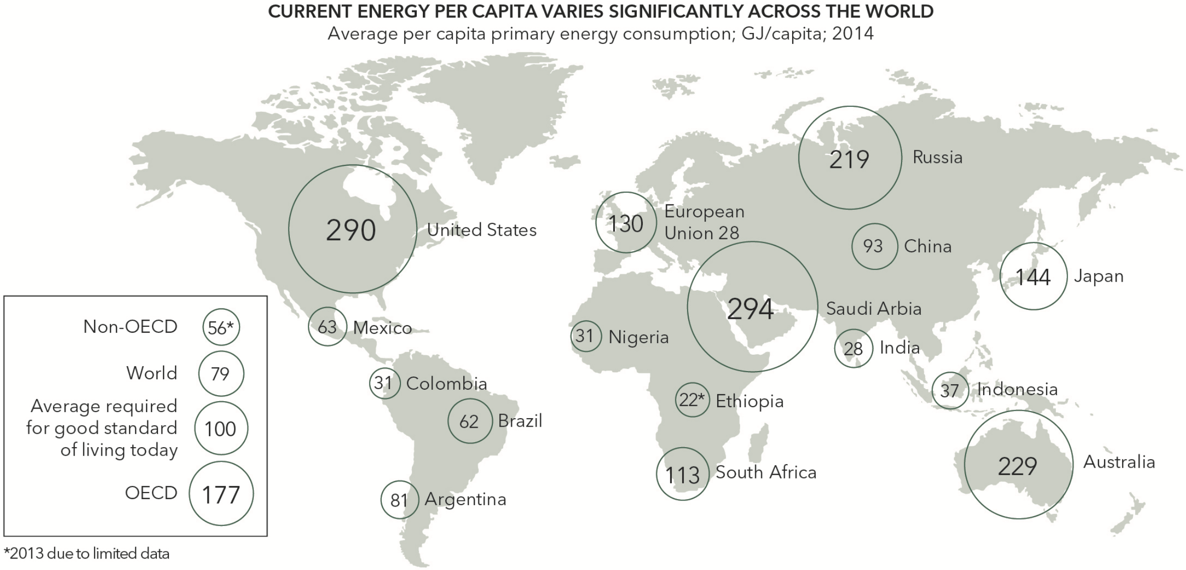

Figure 50: Current energy consumption per capita (Energy Transitions Commission, 2017)

For the purposes of investigating the applicability and practicability of the developed framework and methodology, a case study was selected that is, firstly, aligned with the context and scope for which the developed framework is intended – i.e., a socio-technical system that is deemed unsustainable. Secondly, the unsustainability of the system investigated in this case study manifests in societal challenges, and the incumbent technology is in fact causing the unsustainability. Additionally, a case study was selected that is (i) material in the context of an economy, (ii) exposed to landscape developments, and (iii) where the direction of the impact of such changes is significant enough to lead to meaningful insights. Therefore, the South African electricity sector is selected as the case to which the developed framework and methodology are applied.

The aim of this case study is to employ the developed methodology to conduct a critical analysis of the electricity sector in South Africa and the imminent and imperative transition that is required of this sector in order to be sustainable. The objective of this case study is to showcase the applicability, usability and practicability of the developed ITMST framework and methodology.

Even though a vast array of documented information, data, literature and qualitative and quantitative evaluations and analysis of the South African electricity system exists, and although these sources of information are sufficient for the case study, subject matter experts were consulted in specific instances, i.e., in the sections concerned with the identification and evaluation of forces within the electricity system. The subject matter experts are summarised in Table 51.

Table 51. Subject matter experts (SMEs) used for consulted for input for the case study

	POSITION AND RELEVANT EXPERIENCE
SME9	SME9 is the Managing Director of an energy and infrastructure economics advisory firm based in Cape Town. SME9 is an infrastructure and regulatory economist in South Africa with more than 25 years' experience in the electricity, gas and liquid fuels sectors. In December 2018, President Cyril Ramaphosa appointed him to the Eskom Sustainability Task Team, while in 2019, the President appointed him to the Presidential Economic Advisory Council.
SME10	SME10 is a senior researcher at the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University. SME10's research areas include energy policy and finance, energy modelling and local government.
SME11	SME11 is the Energy and Finance Programme Manager at Green Cape, a non-profit organisation that drives the widespread adoption of economically viable green economy solutions in the Western Cape.
SME12	SME12 is a Professor Emeritus and Senior Scholar at the University of Cape Town, where he directs the Power Futures Lab at the Graduate School of Business. SME12's research and teaching focuses on governance and regulatory incentives to improve utility performance, the political-economy of power sector reform, power investment challenges, and linkages to electricity access and sustainable development.

9.4 The case of the South African electricity system

In the following sections, the three analytical perspectives, and the respective phases and sub-phases of the ITMST methodology, for the South African electricity system, are presented.

9.4.1 Analytical perspective I: Current state analysis of the South African electricity system

As presented in Section 8.2.1, the current state analysis consists of two phases – Phases 0 and 1. Phase 0 is concerned with the contextualisation of the system in question, and Phase 1 is concerned with the contextualisation of the transition of the system under consideration.

9.4.1.1 Phase 0: South African electricity system and system-sustainability contextualisation

Phase 0 has two phases. In sub-phase 0.1 the South African electricity system is contextualised, and in sub-phase 0.2 the system performance/sustainability of the South African electricity system is discussed.

9.4.1.1.1 Contextualisation of the South African electricity system (Sub-phase 0.1)

The South African electricity system has been inextricably bound up with the country's dependence on coal resources and cheap labour for the generation of electricity (Baker, 2015). This high dependence on coal is due to the natural endowment of the country, and coal has thus been critical to the development of South Africa's industrial capability and diversification (WWF, 2017). Coal was a key enabler in South Africa becoming the most industrialised economy in Africa, but it has also resulted in a path-dependence on coal. There is a strong link between coal and the South African economy, as the country relies on coal-powered electricity, with about 90% of its electricity being generated by coal (Huxham, Muhammed and Nelson, 2019; Van Niekerk, 2019)[42]. The energy sector contributes close to 80% of total emissions, 50% of which come from electricity generation and liquid fuel production (Department of Energy, 2019). However, as South Africa was among the 195 signatories to the 2015 Paris accord, the country aims to peak greenhouse gas (GHG) emissions by 2025, to plateau for a decade and then to decline emissions after 2035 (Department of Energy, 2018), highlighting a commitment to sustainability and climate change efforts.

While South Africa's electricity regime is broadly defined as a coal-fired, publicly-financed, state-controlled electricity sector, it does include a niche: a developing cluster of renewable energy independent power providers (IPPs), which form part of a procurement process for privately generated renewable energy (Baker, 2015). In addition to the introduction and deployment of these IPPs, recent changes in the electricity sector have included rising tariffs, resulting in a growing demand for access to affordable and equitable electricity, and supply-side crises.

How different services within the electricity sector have evolved over time can be broken down into time periods of relative stability, characterised by specific drivers and developments: these include the significant improved access to electricity since 1994 due to the national electrification programme, the emergence of environmentalism, the identification of the Renewable Energy Independent Power Producers Programme Process (REIPPPP) as one of the climate change flagship programmes in 2011, and the electricity-supply crisis, marked by intermittent electricity outages due to Eskom (South Africa's public electricity utility) not being able to supply enough electricity to meet demand. Ting and Byrne (2020) identified four key periods in the electricity sector from 1998 to 2018. These periods, as well as the types of resistance evident in the regime's transition to an electricity sector that is increasingly reliant on renewable energy sources, and the challenges faced by the niche (conceptualised as the renewable energy sector), are shown in Table 52[43].

Table 52. Different periods of the South African electricity sector, as well as the types of regime resistance and niche challenges over time (adapted from Ting and Byrne, 2020).

A SUMMARY OF THE CASE STUDY AND THE TYPES OF REGIME RESISTANCE AND NICHE CHALLENGES OVER TIME		
CASE STUDY PERIOD	REGIME-RESISTANCE	NICHE-CHALLENGES
1998 - 2006 Energy sector reforms	Eskom used its power over their regime's discursive structure to persuade decision makers to maintain the status quo	There was no appreciable niche at the time as this was only the early stage of renewable development. Consequently we see no discernible niche challenges.
2007 - 2009 Major electricity crisis	Eskom blocked market reforms through delayed decisions in contracting IPP bidders	Refit was initiated, catalysing learning processes associated with the design, technical, legal and regulatory framework needed for promoting renewable energy in South Africa.
2009 - 2015 Layering of the RE 14P	Eskom tried to keep electricity-sector debates hidden from public scrutiny by making use of its organisational networks and capacity	The RE 14P was implemented in a transparent manner, shifting debate into the public domain. This influenced the regime's discursive structure, changing the terms of debate by introducing new facts and gaining public support.
2015 - 2018 Evolution of Eskom's resistance strategy	Eskom moved debate into the public domain, provoking key trade unions in its organisational networks to engage in industrial action by promoting a job-losses narrative. It also delayed finalisation of PPAs and changed the grid rules to impose extra cost on niche actors.	Niche actors engaged in policy debates, strengthening their relations with the regime's governance institutions, resulting in growing influence over the regime's discursive structure.

Key stakeholders in the electricity sector include: the national Department of Energy (DoE), the National Energy Regulator of South Africa (NERSA), the National Treasury, the Department of Trade and Industry

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[42] However, there are differences in reports on the percentage of electricity that is being generated via coal-fired generation.

[43] For a full account of these periods evident in the South African electricity sector, see Ting and Byrne (2020).

(DTI), the Department of Public Enterprises (DPE), the Department of Economic Development, the Department of Environmental Affairs (DEA), Provincial departments and municipalities, and Independent Power Producers (IPPs). Table 53 briefly outlines the mandates of the various role players, while Figure 51 shows the institutional governance structure of the South African electricity sector.

Table 53. Key role players in the South African electricity sector (WWF, 2017)

ROLE PLAYER	MANDATE
Department of Energy (DoE)	Custodian of policy and planning for the energy sector, focusing on energy security through diversifying the country's energy mix to include renewable energy sources
National Energy Regulator of South Africa (NERSA)	Regulates the energy sector in the context of national policy and planning, licenses new energy infrastructure and regulates electricity and hydrocarbons infrastructure tariffs
National Treasury	Governs fiscal and procurement policies
Department of Trade and Industry (DTI)	Develops local industries and trade with a particular focus on green industries and job creation; works to attract foreign investment
Department of Public Enterprises (DPE)	Shareholder in Eskom the sole power off-taker
Department of Economic Development	Sets and develops economic policy, economic planning and economic development; focuses on employment creation and the green economy
Department of Environmental Affairs (DEA)	Sustainable development and environmental integrity; grants environmental authorisations in terms of the National Environmental Management Act (NEMA)
Provincial departments and municipalities	Regulate private renewable energy generation (embedded generation) through by-laws and policies

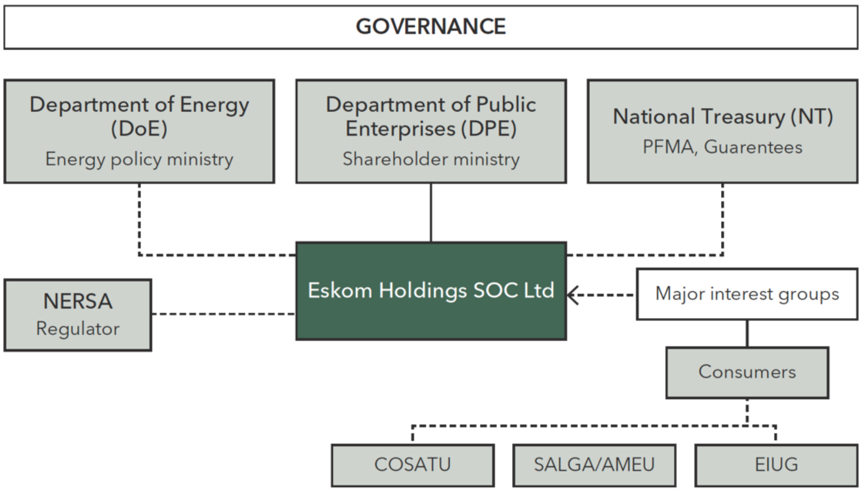
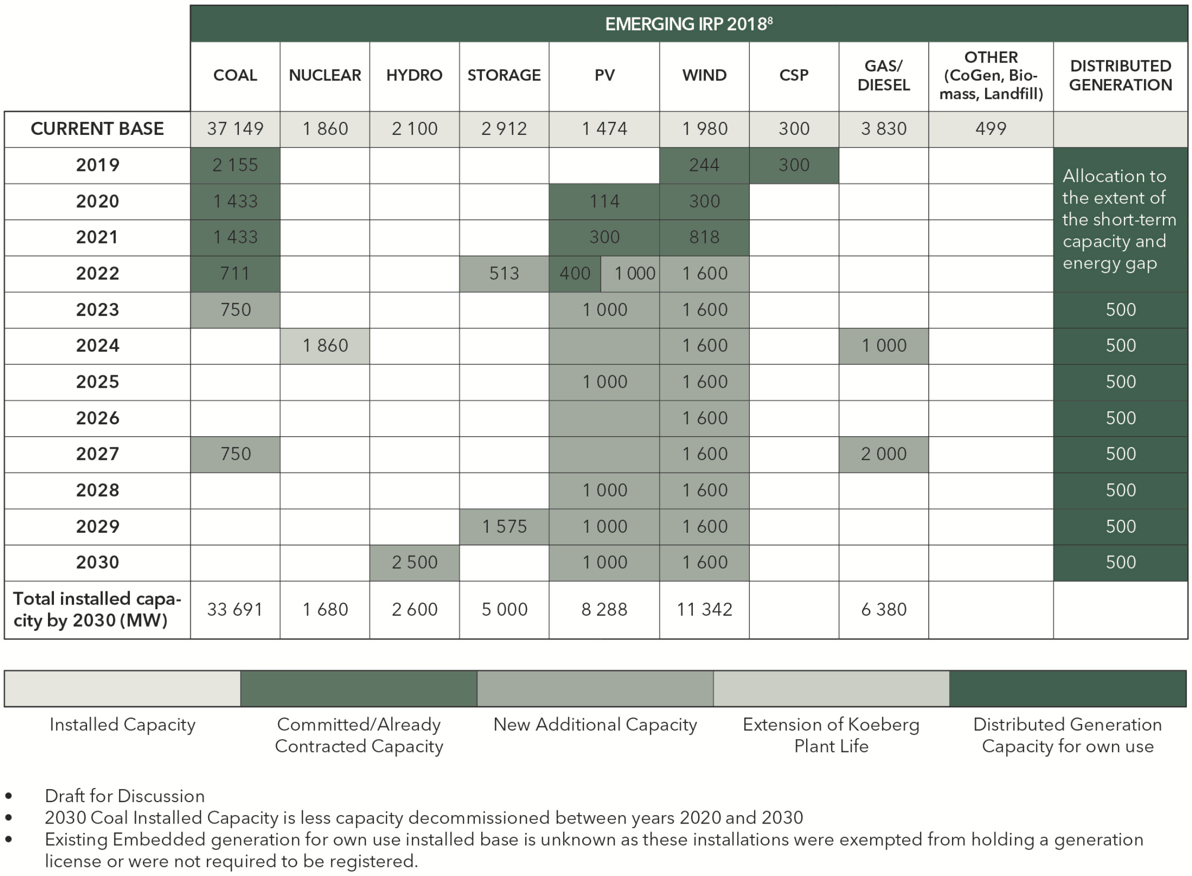


Figure 51. Institutional governance structure of the South African electricity system (Ting and Byrne, 2020)

South Africa’s electricity sector, similar to electricity systems around the world, is subject to a number of landscape pressures, such as climate change, political will towards environmental issues, population growth and the need for economic growth.

The Integrated Resource Plan (IRP) – a national government document that outlines the country’s electricity demand, the planned generation capacity to meet the anticipated electricity demand, and the cost related to supplying this electricity for the period up to 2030 – outlines the proposed updated plan for electricity generation. The installed capacity, committed or already contracted capacity, the new additional capacity and the embedded generation capacity (generation for own use) are show in Table 54. Noticeably, however, even though the proportion of the energy mix of coal decreases, the absolute capacity of coal is reduced by just over 9%. The total planned installed capacity by 2030 is 76970 MW, compared to a current installed capacity 49192 MW.

Table 54. Summary of updated energy mix (Department of Energy, 2019)



	EMERGING IRP 2018[8]									
	COAL	NUCLEAR	HYDRO	STORAGE	PV	WIND	CSP	GAS/ DIESEL	OTHER (CoGen, Biomass, Landfill)	DISTRIBUTED GENERATION
CURRENT BASE	37 149	1 860	2 100	2 912	1 474	1 980	300	3 830	499	
2019	2 155					244	300			Allocation to the extent of the short-term capacity and energy gap
2020	1 433				114	300				
2021	1 433				300	818				
2022	711			513	400 1 000	1 600				
2023	750				1 000	1 600				500
2024		1 860				1 600		1 000		500
2025					1 000	1 600				500
2026						1 600				500
2027	750					1 600		2 000		500
2028					1 000	1 600				500
2029				1 575	1 000	1 600				500
2030			2 500		1 000	1 600				500
Total installed capacity by 2030 (MW)	33 691	1 680	2 600	5 000	8 288	11 342		6 380		

Installed Capacity

Committed/Already Contracted Capacity

New Additional Capacity

Extension of Koeberg Plant Life

Distributed Generation Capacity for own use

- Draft for Discussion
- 2030 Coal Installed Capacity is less capacity decommissioned between years 2020 and 2030
- Existing Embedded generation for own use installed base is unknown as these installations were exempted from holding a generation license or were not required to be registered.

9.4.1.1.2 *Contextualisation of system performance and sustainability of the South African electricity sector (Sub-phase 0.2)*

The key sustainability objectives outlined in the National Development Plan (NDP) of South Africa are to: (i) eliminate poverty, (ii) deliver environmental protection, and (iii) promote economic development and growth (South African Government, 2012; WWF, 2014). South Africa is burdened by unemployment, is notorious for having one of the world's highest wealth gaps[44], and there exists an urgent need for economic growth that creates job opportunities for a largely unskilled workforce. South Africa has also seen a steady degradation of the environment and ecosystem resilience (WWF, 2014). Furthermore, factors such as population growth and urbanisation are increasingly placing pressure on the food, water and energy supply. Resources are not infinite – and this is clearly evident in natural resources becoming harder to access.

As mentioned, South Africa is highly dependent on fossil fuels for electricity generation, and the catastrophic environmental and health effects of electricity powered by coal should be reason enough to shift to alternative, more sustainable means of electricity generation. Across the world, societies are moving to alternative means of electricity generation not only because of the negative effects of fossil fuel powered

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[44] According to the World Bank's Gini Index, South Africa is the most unequal society in the world, with a Gini coefficient of 0.63 in 2015 (https://www.worldbank.org/en/country/southafrica/overview).

electricity generation, but because the cost of renewable energy is lower (Cock and Fraser, 2019). However, South Africa also faces additional challenges.

South Africa's limited fiscal space following recent downgrades, resulting in the country no longer having an investment grade sovereign credit rating, and the deterioration of the financial position of Eskom, brings about a decline in the reliability of electricity supply in South Africa (Huxham, Muhammed and Nelson, 2019). Furthermore, South Africa – a society with high levels of unemployment and poverty – has seen electricity prices increase by over 400% in the past decade (Cock and Fraser, 2019). Even though millions of people have been connected to the grid since 1994, 16% of South Africans still do not have formal access to electricity, and many more struggle to pay the increasing price of electricity (Van Niekerk, 2019).

South Africa's reliance on coal has created confusing and contradictory social dynamics; this includes a spectrum of intense opposition to profound dependence on coal, support for the current coal-dominant regime, and everything in between (Cock and Fraser, 2019).

The imperative of delivering access to equitable electricity services to all, without (further) harming the environment, is imminent and a good thing; but it is not uncomplicated. Electricity sectors contribute towards the environmental sustainability, social sustainability and economic sustainability of the society within which they exist. A widely used framework for energy system performance, and one that is also applicable to electricity systems, is the energy triangle that considers a system's ability to do the following (World Economic Forum, 2019):

i. Support inclusive economic development and growth;
ii. Provide secure and reliable access to electricity; and
iii. Be environmentally sustainable.

The challenges that South Africa experiences in terms of these three elements of the electricity system's performance is evident. In summary, the South African electricity sector/system faces the following sustainability challenges:

i. Environmental unsustainability – a high dependence on coal for electricity generation and thus a significant contributor to climate change;
ii. Challenges in providing access to reliable and affordable electricity; and
iii. A system that supports inclusive economic development and growth – a number of socio-economic challenges are linked to the sustainability transition of the electricity sector.

It is important to note that a socio-technical change where external resources are required (see Section 7.3.1) is not necessary in all areas where the South African electricity sector is deemed to be under-performing. For example, reducing energy poverty and moving towards universal access to electricity may be addressed by improved capacity and efficiencies within the existing electricity regime/incumbent technology domain. But, it is widely acknowledged that the expansion of unchanged electricity systems, thus retaining anything close to the current CO_2 emissions would likely lead to over 4°C global warming towards the end of the century (Energy Transitions Commission, 2017). However, the electricity sector of South Africa, as is the case with all electricity sectors, contributes – either positively or negatively – towards environmental, social, and/or economic sustainability of a country. Furthermore, as scholars (Van Den Bergh, Truffer and Kallis, 2011; Wagner, Bachor and Ngai, 2014) have highlighted, a transition will inevitably result in 'winners' and 'losers', which means that all the goals might not be addressed to the same level of fulfilment.

As mentioned, the World Economic Forum measures energy system performance from three perspectives in terms of the energy triangle: (i) environmental sustainability, (ii) security and access, and (iii) economic development and growth (World Economic Forum, 2019). South Africa's overall system performance score is 36 (rated on a scale of 0 to 100), ranking the country in 114th place out of a total of 115 countries evaluated. The performance across the system performance elements is (using a score out of 100 – see Figure 52): 42 for energy access and security, 55 for economic growth and development, and 12 for environmental sustainability. These findings from the World Economic Forum (2019) echo the findings in terms of the progress made by South Africa to establish an environmentally sustainable electricity sector, ensure reliable and secure access to electricity, and ensure electricity supply to support economic growth.

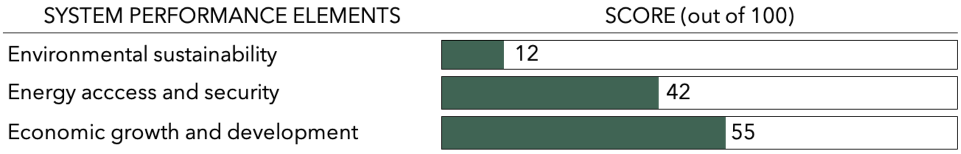

Figure 52. South African energy system performance (Author's own representation based on World Economic Forum, 2019)

9.4.1.2 Phase 1: South African electricity system transition

Phase 1 of the ITMST methodology entails the contextualisation of the state of the transition of the system under consideration. This entails looking at the conditions for change and the forces driving transitional change as well as the current state of the transition of the South African electricity system.

9.4.1.2.1 Sub-phase 1.1: Conditions for change, present transitional forces and transition failure risks in the South African electricity sector

Conditions for change

In an electricity system, such as South Africa in 2020, one can easily identify the regime as being centred on fossil-fuel based electricity generation (the incumbent technology domain). The renewable energy niche (the emerging/alternative technology domain), being a competitive alternative, is also present. The South African electricity sector, as discussed in Section 9.4.1.1, is influenced by a number of landscape developments that result in tension[45] within the current regime, such as the system experiencing tension arising from the imminent depletion of natural resources and the threat of climate change. Furthermore, the regime experiences stress[46] and pressure[47].

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[45] Tension indicates that the 'world moves on' but 'leaves the regime behind', essentially deeming the functioning of the regime outdated (Frantzeskaki and de Haan, 2009).

[46] Stress within a regime refers to internal mismatches in the functioning of the regime (Frantzeskaki and de Haan, 2009).

[47] Pressure indicates a mismatch with emerging net functioning in niches (Frantzeskaki and de Haan, 2009).

The stress in the South African electricity sector reveals itself in problems like load shedding and poor access to electricity where there is an apparent mismatch between the demand for electricity and the system's capacity to meet it. The presence of renewable energy niches provides alternatives and puts pressure on the regime. Tension, stress and pressure are all conditions for change. However, although conditions for change are necessary, they are not necessarily sufficient to drive change in socio-technical systems. Within the ITMST framework and methodology, forces are identified in relation to the transition progress and transition capability, i.e., progress, stability, and adaptability.

When aiming to infer which transition phase the electricity sector of South Africa is in, Table 38 may be used as a guide. It should be noted that models, frameworks and representations like these are a simplification of real-world phenomena, and they are thus suggested merely as a guide in order to infer the transition phase. Given the immense pressure on a global scale for climate change mitigation, and to preserve natural resources and move towards renewable sources of electricity generation, South Africa's electricity system – especially given its high dependence on coal-based electricity generation – may be considered to experience significant tension. The pressure from niches is present, and even though dominant designs (i.e., photovoltaics (PV), and wind) have been established (as outlined in the NDP), renewable energy (hydro, PV, wind, concentrated solar power (CSP) account for only 16% of the energy mix (Department of Energy, 2018), and 10% of electricity generation. Therefore, these niches are not deemed to be significant, as a new socio-technical configuration dominated by renewable energy technology is not yet close to being established – i.e., this would be a configuration in which renewable technologies are considered the dominant and incumbent technology domain that fulfils the societal function. The stress experienced by the incumbent regime is present, but arguably not significant enough (according to the measures provided in Table 38); it is thus considered merely 'Present'. This argument is based on the fact that the regime can, to a large extent, still recover from these stresses (i.e., by overcoming the lack of capacity to provide for the electricity demand). However, recent reports about Eskom show significant challenges, and experts warn that this may ultimately result in system collapse. Eskom, which produces the majority of electricity in South Africa, also faces significant financial difficulties (Huxham, Muhammed and Nelson, 2019). These difficulties do not stem from the pressure from the renewable energy niches, but largely from two ongoing coal megaprojects that are both over budget and not working at full capacity, i.e., Medupi and Kusile power plants. It may thus be inferred that the South African electricity sector is in (initial phases of) the take-off phase in terms of its electricity transition; i.e., displaying significant tension, and with stress and pressure also being present, as outlined above.

Forces driving transitional change

The forces within the electricity sector – that either stimulate or inhibit a transition – have to be identified in order to subsequently investigate if, and to what extent, they (i) contribute (either positively or negatively) towards transition progress, transition capability and system performance (Sub-phase 4.1). A systematic inquiry[48] into the forces present in the South African electricity sector yielded the forces shown in Table 78 in Appendix E.

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[48] Literature and interviews with sector experts.

The forces[49] that are present and that indicate the conditions for change currently experienced in the local electricity sector are, amongst others:

1. Formation forces: these include the presence of a renewable energy niche, increasing demand for clean energy, a growing demand for affordable energy, proposed changes in electricity generation (i.e., the renewable energy niches) in the IRP, and limited proposed demand side interventions. There are also introductions of new functioning in the form of distributed electricity generation.
2. Supportive forces: a constrained policy environment for renewable energy developments, commitments to reduce greenhouse gas emissions, natural endowments of coal, investments into existing and planned coal-fired power plants, parallel investments into both coal-fired power plants and renewable energy developments, decommissioning of coal-fired power plants, lack of provision made to retrain and reskill workers at risk of unemployment due to the decommissioning of power plants, government support for the coal value chain, R&D into renewable energy (albeit insufficient to reach targets), limited R&D into coal-based electricity generation, insufficient research into carbon capture and storage, and protection power over Eskom.
3. Triggers: supply-side crises (load shedding), financial deterioration of Eskom, increases in electricity tariffs, inefficiencies in coal-based electricity generation, deterioration in the reliability of the electricity supply, high inequality of access, and social unrests (strikes), as well as exogenous events, such as the recent drought in the Western Cape Province, and persisting droughts in other parts of South Africa.

9.4.1.2.2 Sub-phase 1.2: Contextualisation of the transition of the South African electricity system

Within the developed framework, the capability of a system to transition relies on (i) progress, (ii) stability and (iii) adaptability. The current state of a transition is also defined by considering the different transition resilience dimensions and context specificity in terms of the transition phase.

Transition progress within the South African electricity system

As described in Section 6.1.2.2, progress is the most fundamental characteristic of a transition, as it defines the degree to which the required or desired system change is experienced (i.e., change in system performance), as well as being a dimension, along with stability and adaptability, that constitutes transition capability. Within the context of the ITMST methodology, when progress is considered, (i) the progress that has been made in addressing the (under)performance/(un)sustainability of the South African electricity system, (ii) the forces that drive transformational change, and (iii) the forces that resist transformational change in the South African electricity system, all have to be considered. Even though progress towards increasing the contribution of the electricity system towards inclusive economic development and growth and secure and reliable access to electricity in South Africa could possibly be achieved by expanding the current electricity sector in terms of addressing energy poverty and ensuring sufficient capacity to support, sustain and facilitate economic growth, a fossil-fuel based electricity system poses risks in terms of a global transition towards a higher level of sustainability of electricity systems. However, when the need to transition towards a low-carbon electricity system is considered (i.e., system performance in terms of environmental

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[49] Formation forces, supportive forces and triggers are discussed in Section 6.1.2.3.

sustainability), purposive renewal (refer to Section 2.2.5) is required in that the incumbent technology domain, due to the technology employed (i.e., fossil fuel based electricity generation technology), is deemed unable to endogenously renew to address the environmental unsustainability of the system. Thus, in order to reach a sustainable future state, progress towards a new socio-technical configuration is the key objective. In the South African electricity system (and arguably in all electricity systems that are dependent on coal-fired electricity generation), this would entail moving from a fossil-fuel based incumbent technology domain to one that is environmentally sustainable and/or carbon-neutral.

Even though progress has been made in increasing electricity generation from renewable energy sources, the proportion of electricity generated by fossil fuels remains more than 90% (Huxham, Muhammed and Nelson, 2019). From a technical perspective, progress has been significant, i.e., renewable energy technologies are mature, numerous studies highlight the feasibility of such technologies in South Africa, major investment through the REIPPPP programme has been, and is being, secured to further develop the renewable energy profile of South Africa, and renewable energy prices are decreasing and are considered cost-competitive (Baker, 2015; Baker *et al.*, 2015; Huxham, Muhammed and Nelson, 2019). From a social perspective, progress has also been made – there is societal and political support for renewable energy in South Africa. Even though the incumbent technology domain still enjoys a significant amount of support, South Africa does not seem to have ‘climate change deniers’. Nevertheless, and as echoed by numerous reports, the South African electricity system still has a long way to go to attaining a low-carbon or carbon-neutral electricity sector. When considering the IRP (refer to Table 54), 44% of installed generation capacity is planned to be coal by 2030. However, the absolute installed coal-based generation capacity is planned to decrease by only 9,31%. Also, earlier reports (Eberhard and Naude, 2017) indicated that the REIPPPP programme seemed to be on track in meeting the target of 7,000MW of operational renewable energy capacity by 2020. However, the recent draft updated IRP reflects 3,754 MW operational renewables (up to 2018) with an additional 958MW committed till 2020 – thus below the 7,000MW target set out in the NDP (South African Government, 2012).

The proportion of the South African population that has access to electricity has increased over the past decades – primarily as a result of the National Integrated Electrification Programme (NEIP). The target of the NEIP is to achieve universal access – which is defined as 97% – by 2025. It is envisaged that 90% of the population will be grid-connected, and that a further 7% of households will be electrified through off-grid technologies. As mentioned, it is reported that 16% of South Africans still lack access to formal electricity. However, the ever-increasing cost of electricity is threatening this projected universal access to electricity. Even though an increasing number of people have been connected to the grid, progress in terms of accessing affordable electricity has come under significant pressure due to the ever-increasing cost of electricity in South Africa. In addition, the challenges faced by Eskom also hinder the reliability of such access to electricity.

To date, there has not been a system collapse, even though the demand outweighing the supply of electricity (sometimes for extended periods of time) did result in the country experiencing periods of load shedding. The capacity to deal with a lack of capacity has not been passed, as the system has not collapsed despite load shedding and/or a lack in capacity to meet the demand. In early February 2019, Eskom escalated load shedding to Stage 4[50]. Load shedding has had significant negative effects on the economy – the economy-wide impact of load shedding highlights the potential cost of risks that have been left unmanaged (Huxham, Muhammed and Nelson, 2019). However, the South African electricity has not always struggled to meet the electricity demand to maintain economic activities; an electricity surplus[51] was evident in since the mid 1980s till the mid 2000s (Baker, 2015). Even though there have not been significant job losses to date within the current regime, primarily because there has not been a significant reduction in fossil-fuel based electricity generation operation, reports do indicate a risk of job losses and impact on the local economy (Huxham, Muhammed and Nelson, 2019).

Globally, the pace of energy transition has slowed down (World Economic Forum, 2019). Even though renewable energy generation is increasing (electricity production from renewable energy sources has increased from 217 billion kWh in 2000 to 1.645 trillion kWh in 2015), global carbon emissions have in fact increased by 1.7% in 2018 (Roberts, 2019) – of course not all from the electricity system or even from energy sectors. Nonetheless, when considering the imperative to move towards a low-carbon world, this is alarming.

Multiple reports indicate that transitioning towards a more sustainable and secure energy system in South Africa has also been far from ideal. South Africa ranks 114th out of 115 economies evaluated in The Energy Transition Index (ETI) 2019[52]. The ETI measures progress in the transition towards a more sustainable and secure energy system, and specifically considers transition readiness scores (World Economic Forum, 2019). In addition, the organisation Climate Action Tracker[53] describes South Africa's climate change commitments as 'highly insufficient' – which characterises commitments as those that will lead to global warming that will be twice that of the global average in sub-Saharan Africa (i.e., 6°C - 8°C). Other countries whose climate change commitments are similarly categorised as 'highly insufficient' include China and South Korea, amongst others. The proportion of the South African population that has access to electricity has increased from below 60% in the middle '90s, to close to over 84% in 2017; however, in 2014, the percentage of the population with access to electricity peaked in 2014 at 86% (The World Bank Group, 2019).

It is important to note that the forces that drive or resist transitional change may differ in the quality of the impact they have on the transition resilience dimensions, and it is therefore necessary to consider the quality of the impact (driver of change or resistance to change). For example, supportive forces in terms of the provision of resources are employed in both the renewable energy technology domain, as well as the incumbent fossil fuel-based technology domain. Progress, however, depends on the relation between driving and resisting forces.

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[50] Stage 4 load shedding means that load shedding is scheduled for 12 times per area over a four-day period for two hours at a time, or for 12 times over an eight-day period for four hours at a time.

[51] 'Surplus capacity' is a technical term and it does not reflect the fact that until 1993, only a third of the South African population was connected to the grid (Baker, 2015).

[52] The Energy Transition Index (ETI) benchmarks countries on the performance of their energy system, as well as their readiness for transition to a secure, sustainable, affordable, and reliable energy future. The ETI scores on a scale from 0 to 100% (World Economic Forum, 2019).

[53] Climate Action Tracker (https://climateactiontracker.org/) is an organisation that follows whether countries are on track to meeting climate change targets.

Drivers for system change

The pattern of change that can be seen due to the tensions experienced in the South African electricity sector is that renewable energy niches are supported and reinforced, and that the societal support for such niches seems to be growing. The forces that support this pattern of change include the provision of resources to renewable energy resources (i.e., investment into the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) programme, renewable energy related R&D, political support for renewable energy, the demonstrated feasibility of renewable energy technologies in South Africa, and societal support for low-carbon electricity options, amongst others), as well as forces internal to the renewable energy niche, such as the fact that the prices of solar and wind energy in the winning REIPPPP bids are lower than Eskom's average cost of supply, and substantially lower than the cost of electricity that will be supplied by the new coal power stations (Eberhard and Naude, 2017), and the standardisation of practices (i.e., international commitments for carbon reductions). A pattern of change that is only starting to emerge is the incumbent technology domain incorporating niche functioning, i.e., Eskom aims to diversify its energy mix, and is procuring funding to build solar pants and wind farms (Takeo, 2019). The plans of Eskom to decommission 5400 MW of electricity from coal generation by 2022 is outlined in the updated IRP (Department of Energy, 2019). Nonetheless, the planned commissioning of new fossil-fuel based power plants is underway, as clearly outlined in the IRP, and as shown in Table 54. It may seem that the incumbent technology domain is contributing towards driving transitional change in the decommissioning of coal-fired power plants, but the planned commissioning of additional fossil-fuel based power plants does not contribute towards transition progress. As discussed elsewhere, in absolute terms, the electricity generated from coal, as outlined in the IRP, will decrease with (only) just over 9% by 2030.

The patterns of change that may be observed due to the stress experienced in the incumbent technology domain are that the renewable energy niche is expanding and becoming empowered, as ecological movements are increasingly acquiring a firm role in environmental policy. In addition, systemic failures in the incumbent technology domain (i.e., increasing cost of electricity, supply side crises, and financial deterioration of Eskom) are all driving transitional change in terms of support for the renewable energy niches. A typical pattern of change, when a regime experiences stress, is that the regime incorporates the niche functioning, but aside from what is mentioned in the preceding paragraph, it may be argued that the incumbent technology domain has in fact not ventured into incorporating the niche functioning; the incumbent technology domain incorporating the functioning of an emerging/alternative technology domain would mean that such alternative practices are welcomed into the technology domain. However, even though Eskom is not openly opposed to renewable energy, the current state of the organisations is not conducive to the diversification of the electricity generation mix.

Even though the forces, which result in the incumbent technology domain being under pressure, are evident (i.e., the presence of a renewable energy niche), the presence of a new functioning (i.e., distributed or privately generated electricity), and the presence of a new demand (i.e., the increasing demand in South Africa for clean energy), the associated pattern of change – the incumbent technology domain adapting towards alternative functioning, i.e., the societal function of electricity generation and supply – is only in its infancy. More than 90% of electricity is currently being generated by fossil fuels within the incumbent technology domain.

Resistance to system change

Conditions for change are often not welcomed by socio-technical systems (Frantzeskaki and de Haan, 2009). In transitions, there will potentially be winners and losers (Köhler *et al.*, 2019), and incumbent technology domains tend to resist change in order to maintain their functioning. In the South African electricity sector, resistance to transitional change is evident, as discussed in Section 9.4.1.1.1., and the incumbent technology domain (i.e., Eskom) has shown varying levels and measures of resistance to a transition across different time periods. The change that is experienced in a top-down direction, i.e., landscape pressures, encounters resistance in the incumbent technology domain towards transitional change, which is expressed in the incumbent technology domain trying to maintain its dominance. Forces employed by the incumbent technology domain include supportive forces, such as the provision of resources to infrastructure developments such as coal-fired electricity generation to guard its dominance. In addition, supportive forces like the natural endowment of coal in South Africa is further providing support to the incumbent fossil fuel-based technology domain and adding to the resistance to transitional change that is currently experienced.

Stability of the South African electricity sector

Stability is the second transition capability dimension, and is concerned with (i) the stability of the transition process (i.e. the stability of the sustainability goals (with the corresponding envisioned system state) and pathway), and (ii) system resilience (i.e. the stability of the system undergoing the transition) (Schilling *et al.* 2018).

Stability of the transition process

The two key elements, as mentioned in Section 8.2.1.2.2.2, which have to be considered are: (i) the stability of the envisioned system state in relation to the corresponding sustainability goals, and (ii) the stability of the transition pathway, and thus the planned way to realise a more sustainable future state (Schilling, Wyss and Binder, 2018). When the stability of the envisioned future is considered, i.e., a more sustainable system state in respect of the South African electricity sector, it is clear that moving towards a low-carbon or carbon-neutral electricity system is not the only guiding norm for a transition, even though it is the worst performing aspect (World Economic Forum, 2019). As highlighted, the South African electricity sector faces numerous challenges that require reform. The goals that are set are relatively clear; the NDP and IRP outlines the sustainability goals set for South Africa and its electricity system.

There are differences in the support provided to the respective technology domains. For instance, the new coal capacity for electricity in the IRP is fiercely opposed by actors' groups, such as the Centre for Environmental Rights, Greenpeace, and the Energy Research Centre; the objections from these groups are based on environmental, climate change and human health related concerns. In addition, these concerns are supported by an investigation into the new coal plants in South Africa's electricity future (Ireland and Burton, 2018), which indicate that the addition of independent coal power producers may well lead to increasing costs of electricity (Halsey, 2018). Support shown for the addition of coal power plants also came from General Electric, which is a manufacturer of steam turbines; the company argued that coal may be used as a flexible generator of electricity, and that international emission reductions can still be met, while employing these coal power plants (Halsey, 2018). The perceived advantages of a low-carbon or carbon-neutral electricity sector – essentially meaning that coal-based electricity generation is replaced by renewable energy generation – are not clear, primarily due to the inevitable negative effects that such a transition will have on the value of assets and income because of climate policy and market transformations, such as a move away from coal-based electricity.

The conflicting support shown for the incumbent and emerging/alternative technology domains in the electricity system, highlights the fact that a vision of the goal system state is not widely agreed upon within the system, and that it therefore cannot exert a significant amount of attraction, nor can it stabilise the sustainability transition process; the transition pathway is thus not stable, as there is no broad, system-wide support for the sustainability transition. However, the integration of renewable energy sources has changed the composition of the South African electricity sector. The incremental nature of the introduction of the transition through the REIPPPP programme has had a stabilising effect on the transition process. The specific properties of the grid, together with the phased addition of renewable energy production entities, have allowed the system to transition, while coping with external and internal shocks.

The transition of the electricity system up to now is only partial, however, and the risk of the system returning to an increasing proportion of coal-based electricity is due to (i) the planned expansion and addition of coal power plants, (ii) the fact that the electricity demand on which the IRP base electricity generation capacity expansion is considered too elaborate (Huxham, Muhammed and Nelson, 2019), and (iii) the ongoing support provided to the incumbent technology domain(i.e., the IRP only outlining partial decommissioning as well as additions of coal-fired electricity generation capacity). Thus, should the demand for electricity not increase as expected, the planned commissioning of coal-based power plants may experience preference due to (i) the incumbency of the investments and South Africa's dependence on coal, and because (ii) they had been planned earlier than the majority of the renewable energy capacity. So, should the electricity demand not be realised, and planned capacity has to be reduced, it will most likely result in additional renewable energy capacity running the risk of not being commissioned.

Groups, such as the African Climate and Development Initiative[54], that support renewable energy and argue for the increasingly important role it should play in the South African electricity sector, oppose the REIPPPP programme (Van Niekerk, 2019). They argue that this programme (i) drives a privatisation agenda, and (ii) imposes costs on the electricity sector, even though the cost of renewable energy is lower than that of traditional sources. When considered in context, this will result in increasing electricity prices, and contribute towards increased energy poverty in South Africa. It is further argued that, due to the notions and beliefs that the REIPPPP serves the interest of investors, will, and even though it will contribute towards reaching climate targets, the programme will result in a loss of public and societal support for the programme, causing a loss of support for renewable energy (Van Niekerk, 2019).

Given the often changing boundary conditions, such as differing and disadvantageous political developments, the uncertainty surrounding the benefits and how the transition risks will be dealt with, i.e., the socio-economic impact of the decommissioning of power plants has not been quantified nor included in the IRP (Department of Energy, 2019), and there is a risk that such uncertainties will result in a loss of support for the proposed pathway, the stability of the transition process is thus questionable. This is further due to (i) the lack of a shared vision of the transition pathway, and (ii) the envisioned future state – as outlined

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[54] http://www.acdi.uct.ac.za

in the IRP, with less than 10% reduction in the absolute amount of electricity generated by fossil-fuel based electricity generation.

System resilience

In order for a transition to progress, system functionality has to be maintained (Binder *et al.* 2017). In this case, the South African electricity sector has to keep providing electricity, even though it is undergoing a transition. Maintaining functionality, thus ensuring system resilience, is required in order to minimise the risk of system-level collapse – in which case the transition will fail. Providing sufficient electricity to maintain and grow economic development and support quality of life to the population (by reducing energy poverty and ensuring access to electricity) is the basic function of the electricity sector, and this has to be maintained. However, as highlighted, a lack in system resilience – at least at sub-system level – may be beneficial to transition progress and may create windows of opportunities for renewable energy technologies and/or niches.

The systemic failures present in the South African electricity sector, i.e., supply-side crises, deteriorating reliability of supply from Eskom, the financial deterioration of Eskom and the increasing cost of electricity, negatively affect the capacity of the electricity sector to meet the electricity demand. As discussed in Section 7.4.1, the capacity of a system to deal with a lack of capacity has to be considered. Even though there were (often extended) periods of time during which the electricity demand could not be met, the system did not collapse. These systemic failures may drive progress, as they create windows of opportunity. However, within the South African electricity sector, the resources being provided to the incumbent technology domain to address such challenges run parallel to, or perhaps even outweigh, the commitments to maintain the functioning of the system by means of renewable energy sources.

A system that is resilient during a transition essentially means that it does not run the risk of collapse or breakdown, i.e., when the regime is destabilising and there is not yet a viable alternative to substitute the regime, and/or the capacity no longer exists to fulfil societal functions. Currently, as mentioned, the majority of electricity in South Africa is supplied by coal-fired generation, and thus the incumbent coal-based technology domain contributes significantly towards fulfilling the societal need for electricity. In addition, South Africa is a net exporter of electricity, as Eskom exports electricity to a number of countries. However, given the systemic challenges experienced within the incumbent technology domain, the renewable energy technology domain also contributes towards the system’s resilience, not only in terms of electricity supply, but also in terms of stability.

Adaptability of the South African electricity sector transition process

The adaptability of the South African electricity sector is evaluated by considering the adaptive capacity[55] and lock-in[56] of the system. Adaptability refers to the extent to which the transition process can be adapted if necessary.

As mentioned, the phased approach to the commissioning of new electricity generation capacity, as outlined in the IRP (Department of Energy, 2019), allows for adaptability and for the transition pathway to be adapted, in response to changes in demand, or if technologies that facilitate increasing levels of sustainability should become available. However, the existing and longstanding lock-in of the electricity sector with coal is being strengthened with additional coal-based electricity generation capacity already committed and/or contracted (i.e., up to 2022 – refer to Table 54), outweighing the already committed and/or contracted renewable energy capacity up to 2022. Given that the estimates of the growth in electricity demand are being deemed an over-estimation (ERC, CSIR and IFPRI, 2017), if the electricity demand should not increase beyond 2024, the installed capacity would remain predominantly coal-based, thus not leveraging the adaptability of a diversified electricity mix – not only between non-renewables and renewables, but also not in relation to the potential further diversification of renewables.

A number of changing market dynamics are being seen globally; *inter alia*, the overproduction of renewable energy in Germany, changes in regulation (i.e., the introduction of micro-grids), and technological developments, such as digitalisation, which may facilitate decentralisation and smart grid solutions, an increasing number of individuals produce their own electricity – which calls for new ways of planning for energy production. In this context, the importance of electro-mobility and storage increases, as this will allow for the storing of surplus energy that can be made available during peak demand. These changing dynamics increasingly call for adaptive capacity.

The ability of a system to be adaptive may be negatively affected by pathway lock-ins (Schilling, Wyss and Binder, 2018). As said, South Africa's electricity generation is heavily dependent on coal, and coal is inextricably linked to the current economic structure of the country, which has evidently resulted in it having a strong influence over the future evolution of the electricity sector. Coal is thus locked in, given the extensive cross-linkages with numerous components of the economy, and the financialisation of coal assets on the JSE (WWF, 2017). In addition, the coal industry is responsible for a significant number of jobs in South Africa, and coal exports remain a large contributor to the economy. Saliem Fakir, head of the Policy and Futures Unit of WWF-SA, argues that coal will not be easily matched by other energy carriers without significant effort and resource availability (WWF, 2017).

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[55] The adaptive capacity of system actors determines whether they are capable to identify, critically reflect, discuss and consensually decide upon adaptations of the sustainability transition progress (goals or transition pathway), if boundary conditions change (Schilling, Wyss and Binder, 2018).

[56] Lock-ins are an extreme form of stability that can cause a very narrow and rigid conception of the transition process and prevent necessary adaptions (Schilling, Wyss and Binder, 2018).

Given that the adaptability of the transition process depends on the relation between the adaptive capacity of system actors and the existing lock-ins in the system (Schilling, Wyss and Binder, 2018), and given the extreme lock-in experienced in terms of the coal-based capacity (and additional planned coal-based capacity), a system that may be considered obsolete in future (i.e., an electricity sector that remains heavily dependent on fossil fuels) may still be highly attractive due to the lock-in of infrastructure and political support, among others. This may prevent the South African electricity sector from adapting to the changed boundary conditions of climate change, the imminent depletion of natural resources, and the growing systemic failures of the incumbent technology domain.

Transition failure risk

The transition failures (see Section 6.1.2.4) that are defined in the literature include: (i) lock-in, (ii) system breakdown, and (iii) backlash. Considering the current transition state of the South African electricity sector, the risks of these types of transition failures should be identified. Lock-in, as discussed in the preceding sections, poses a risk; for instance, in current development plans (i.e., the IRP), it is evident that the incumbent (unsustainable) mode of electricity generation will continue to co-exist with the renewable energy technology domain. Even though the Department of Energy no longer resists the introduction of renewable energy, the IRP illustrates how the conflict between the incumbent coal-based technology domain and the renewable energy domain has been moderated, thus allowing for growth in both domains, but also arguably perpetuating the dominant mode of production (Baker, 2015). The lock-in transition failure will thus mean that a socio-technical transition will not be successful, in that the desired (and in the event of climate change, required) future state of a low-carbon/zero-carbon electricity sector will not being reached, although the societal function – the provision of electricity – will still be maintained, albeit not in an environmentally sustainable manner.

Backlash occurs when the new more sustainable technology domain becomes the dominant player in fulfilling societal functions, but it has not yet stabilised and may therefore still break down. Given that the renewable energy domain is not yet the dominant technology domain, nor close to being stabilised as the new socio-technical configuration, this scenario poses a real risk for the South African electricity transition.

The risk of system breakdown failure is present when there are no technology domains that become self-sufficient and dominant, but all continue to compete for the same resources, ultimately resulting in no viable alternative being available to replace a destabilising incumbent technology domain. Even though the incumbent technology domain in the South African electricity sector is experiencing stress, tension and pressure, numerous resources are being committed from a social and technical perspective to expand and secure the electricity generation capacity from this domain. However, should a change in support be seen, and if resources are no longer committed to the incumbent technology domain, the system may collapse and the existing renewable energy generation capacity will not be able to meet the electricity demand. Such a system breakdown will result in the transition failing, (i) from the perspective of the transition no longer progressing, and (ii) from the perspective that the societal function (providing electricity to the population) is no longer being fulfilled.

In addition to the transition failures conceptualised by Van der Brugge and Rotmans (2007), Weber and Rohracher (2012) identified four 'transformational failures', including: (i) directionality failure, (ii) demand articulation failure, (iii) policy coordination failure, and (iv) reflexivity failure (these were discussed extensively in Section 6.1.2.4).

Directionality failure occurs when an innovation does not contribute towards addressing the broader societal challenges that exist. For example, the development of the renewable energy technology domain may fail to endogenously include sustainability criteria around a socially just transition, such as the imminent job losses that will occur from such a transition. This is further enhanced by the lack of a shared vision regarding the goal and direction of the South African electricity transition process, coupled with unconsolidated efforts to guide the direction of change (as highlighted throughout Section 9.4.1.2.2).

The demand articulation failure is arguably a significant risk, given, as mentioned, the mistrust in the demand forecasts used in development planning efforts like the IRP, the uncertain economic environment, the uncertainty regarding the impact of a global transition towards low-carbon economies on South Africa, and the impact of the electrification of transport on electricity demand.

Policy coordination failures refer to a mismatch in policy coordination across sectors and across sectoral levels in order to address societal challenges effectively. Even though South Africa has an ambitious national climate change strategy, energy policy still remains geared towards meeting the needs of large industrial customers, thus to a large extent excluding the poor and likely natural allies of the Department of Environmental Affairs from policy processes (Baker *et al.*, 2015). Baker *et al.* (2015) further argue that, while there appear to be limited collaborations between the actors developing the environmental policies and the renewable energy industy, there do exist (emerging) coalitions and networks between conventional, energy intensive user groups and renewable energy bodies. However, such emerging and growing networks and collaborations are taking place independently of the initiatives on climate change mitigation that are being done by the Department of Environmental Affairs, and furthermore these are largely done in isolation from the rest of the South African government.

Reflexivity failure, similar to the adaptive capacity of a system, refers to (i) the monitoring and evaluation of progress towards transformational goals, and (ii) the development of adaptation strategies. As discussed earlier, there is a certain level of adaptive capacity within the IRP. However, the long-term planning of the capacity expansion may lead to significant risk of (further) lock-in.

9.4.1.3 Discussion: Current state of the South African electricity system transition and its contributions to system performance, transition progress and transition capability

The context specificity in terms of the specific characteristics of the electricity system under consideration, as well as the environment within which it exists, is investigated in the demarcation of the system and during the analysis of the transition progress and transition capability. However, the importance of the dimensions, as highlighted in Section 6.1.2.2.4, differs across the various transition phases. Given that (i) South Africa experiences turbulence and uncertainty in terms of its economic sustainability and growth and its persistent social sustainability challenges, and given that (ii) the county's electricity system finds itself in a turbulent and uncertain transition phase (i.e., in the take-off phase), which is coupled with system performance challenges – under such conditions when transition capability is considered, (i) adaptability is hardly important, (ii) progress is important, and (iii) stability is very important – and keeping in mind that each of these dimensions has a set of sub-dimensions, then the capability of the South African electricity sector to transition at this stage relates to the status of these dimensions.

Even though the current incumbent technology domain experiences (all three) conditions for change (i.e., tension, stress and pressure), as well as systemic failures (i.e., the electricity system cannot meet the electricity demand), the electricity system did not collapse. Thus, it may be argued that the system resilience is relatively high – unfortunately, this is largely due to the support provided to the incumbent technology domain. In addition, with a currently stabilising and decreasing electricity demand, the system should be able to meet the societal demand for electricity. But, the stability of the transition process is lacking – and identified as a key area that should thus be focused on. Given that South Africa's electricity sector is in a 'turbulent and uncertain phase of the transition', it is necessary to formulate a strong vision that can help to re-focus the sector on sustainability goals. Even though adaptability is not of key importance in the current transition phase, current system dynamics are perpetuating the dominant mode of production – coal-based electricity generation – and thus increasing the risk of a transition failure due to lock-in. Progress, albeit less important than stability in this specific transition phase, is nonetheless important to ensure that this transition does not fail. Stabilising transition aspects have yet to develop in the transition of the South African electricity sector, and strong drivers are needed to push the system through the resistance experienced from the incumbent technology domain. When the transition and failures are considered, there is a risk of system breakdown. However, policy coordination and demand articulation failures are arguably larger risks.

The capability of the South African electricity sector to transition is (significantly) hindered by the existing lock-in to the dominant mode of electricity production, both from a technical, as well as from a social perspective. The renewable energy domain allows for (some) adaptability (albeit limited), but only if the expected growth in electricity demand is realised. A small, yet significant adaptation in the incumbent technology domain is the emergence of the diversification of modes of electricity generation within Eskom; i.e., a 100MW wind farm (Department of Energy, 2019).

When progress towards a new, more environmentally sustainable electricity system is considered, it is clear that the primary contribution comes from the renewable energy technology domain – which is as expected, since environmental unsustainability is the one dimension of unsustainability of the South African electricity sector that required a fundamental shift in the way in which the societal function is fulfilled, i.e., a move away from fossil fuel-based electricity generation. However, the incumbent fossil fuel-based technology domain does also contribute towards progress, i.e., in terms of the decommissioning of power plants and the presence of new functioning, i.e., Eskom bringing on board renewable energy[57]. The contributions towards transitional change from the incumbent technology domain nonetheless run parallel to resistance to change – the most evident indicator being the commissioning of coal-based power plants, both planned and in process, and the continuing support for the incumbent technology domain.

When looking at the contribution of the respective technology domains towards system performance, it is evident that both technology domains contribute positively towards the performance of one or more areas of

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[57] Under the Eskom build programme, the following capacity has been commissioned: 1332MW of Ingula pumped storage, 1588MW of Medupi, 800MW of Kusile and 100MW of Sere Wind Farm.

progress; but it is also evident that the incumbent technology domain's net contribution towards progress in terms of environmental sustainability is negative.

It should be noted that, given South Africa's high dependence on coal – not only for electricity generation and the production of liquid fuels, but also given South Africa's coal exports – the country faces a significant transition impact/risk if/when the global demand for coal reduces (Huxham, Muhammed and Nelson, 2019).

Table 55 shows the respective contributions towards system performance from the respective technology domains present in the South African electricity sector. The incumbent technology domain makes a significant negative contribution towards environmental sustainability. However, the incumbent technology domain does provide for a positive contribution towards economic growth and development, again in the sense that the majority of the country's electricity is provided by this domain. However, the high cost (and thus also price) of electricity, as well as security issues, negatively affect this measure (and therefore do not make it a 'significantly positive' contribution). Also, at this stage in the country's history, economic growth and development are inextricably linked to Eskom, since the utility provides the overwhelming majority of South Africa's electricity. In terms of the emerging technology domain (i.e., the renewable energy niche), the contributions towards system performance are deemed as slight contributions – primarily due to the limited renewable energy generation capacity operational in South Africa. Even though the contribution of renewable energy per se is significantly positive, the contribution towards the environmental sustainability of the South African electricity sector is still limited. The arguments for energy access and security, and economic growth and development, are similar.

Table 55. Technology domain contributions towards system performance elements

	CONTRIBUTION TOWARDS SYSTEM PERFORMANCE	
	INCUMBENT TECHNOLOGY DOMAIN	EMERGING / ALTERNATIVE TECHNOLOGY DOMAIN
ENVIRONMENTAL SUSTAINABILITY	- - -	+
ENERGY ACCESS AND SECURITY	++	+
ECONOMIC GROWTH AND DEVELOPMENT	++	+

LEGEND	
Significant negative contribution	- - -
Negative contribution	- -
Slight negative contribution	-
No contribution	▪
Slight contribution	+
Positive contribution	++
Significant positive contribution	+++
Contribution unknown	?

For a successful transition of the South African electricity sector, a new more (adequately) sustainable socio-technical system has to be stabilised as the dominant/incumbent system, or if not yet stabilised, a transition has to progress – i.e., continue to move towards the stabilisation of a new socio-technical regime. Table 56 summarises the contributions of the respective technology domains towards the transition resilience dimensions, and thus towards the transition capability. The respective contributions of the two technology domains towards the transition resilience domains are summarised in Table 56, and the contributions are discussed below.

Table 56. Technology domain contributions[58] *towards transition progress and transition capability*

	CONTRIBUTION TOWARDS TRANSITION PROGRESS AND TRANSITION CAPABILITY					
	PROGRESS		STABILITY		ADAPTABILITY	
	PT	PS	ST	SS	AT	AS
INCUMBENT TECHNOLOGY DOMAIN	- -	- -	++	- -	- - -	- -
EMERGING / ALTERNATIVE TECHNOLOGY DOMAIN	++	++	+	+	+++	+

LEGEND		
	Significant negative contribution	- - -
	Negative contribution	- -
	Slight negative contribution	-
	No contribution	·
	Slight contribution	+
	Positive contribution	++
	Significant positive contribution	+++
	Contribution unknown	?

9.4.2 Analytical perspective II: Future state analysis of the South African electricity system

The second analytical perspective, the future state analysis, consists of one phase (i.e., Phase 2) and is focused on the delineation of the required future state of the (i) system performance, (ii) transition progress, and (iii) transition capability of the South African electricity system.

9.4.2.1 Phase 2: The future of the South African electricity system

9.4.2.1.1 Sub-phase 2.1: System performance and sustainability goals for the South African electricity system

The sustainability goals for the South African electricity system are contained in documents such as the National Climate Change Response white paper (Department of Environmental Affairs, 2012), which outlines that (i) shifting to lower-carbon electricity options is one of the options with *'the biggest mitigation potential'*, (ii) the commitments at COP 17 demonstrated political commitment to renewable energy, and (iii) the IRP that outlines the planned commissioning of renewable energy capacity (Department of Energy, 2019). These system performance/sustainability goals focus on system performance, i.e., environmental sustainability, energy access and security, and economic development and growth, however, and not on a transition process.

Realising a net-zero carbon electricity sector should be the aim, as this is deemed necessary for sectors that are 'easier to abate', such as electricity, in order to realise a close to 1.5°C climate change. However, as mentioned earlier, the NDP considers planned changes and interventions in the energy system up to 2030. The planned electricity generation methods over the next decade, as set out in the IRP (Department of

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[58] Where (i) P_T is the contribution towards *Progress* from a technological perspective, (ii) P_S is the contribution towards *Progress* from a social perspective, (iii) S_T is the contribution towards *Stability* from a technological perspective, (iv) S_S is the contribution towards *Stability* from a social perspective, (v) A_T is the contribution towards *Adaptability* from a technological perspective, and (vi) A_S is the contribution towards *Adaptability* from a social perspective.

Energy, 2018), were discussed in 9.4.1.1. The goals, described as system performance goals related to the electricity sector towards 2030, are outlined in Section 9.4.1.2.2. Again, these goals are primarily concerned with system performance, i.e., (i) access and security of supply, (ii) economic development and growth, and (iii) environmental sustainability. Within the context of the developed framework, it is argued that when aiming to move towards an increasingly sustainable system, enabling and facilitating the transition process is equally important.

When considering Figure 52, it is clear that improvements are necessary in all three system performance elements. It is also clear that, even though the incumbent technology domain (Eskom), as well as the emerging/alternative technology domain (renewable energy niche) contribute positively towards these – at least to some extent, with the exception of the contribution of the incumbent technology domain towards environmental sustainability. However, it is important to note that the contributions are for different reasons, especially when considering the situation from a transition perspective – thus taking the context specificity and transition capability into account (and hence the importance of the transition requirements). This essentially means that the emerging/alternative technology domain cannot only address environmental sustainability, but also that it has to address energy access and security, and economic growth and development. This highlights the argument that technology management considerations reside within this interplay between system performance, transition progress, transition capability, and context specificity.

In light of the current contributions towards system performance, and the need to move towards increased system performance of the electricity system, the system performance goals may be defined as follows:

i. Reduce the negative impact of the electricity system on environmental sustainability[59];
ii. Improve energy access and security, and economic development and growth; and
iii. Shift the dependence on the incumbent technology domain for energy access and security, and for economic growth and development, towards sustainable technology(ies).

Next, within the context of this framework, the capability of a transition to be successful has to be looked at. Here the focus shifts towards the transition process, and the question, what are the transition goals? The system performance/sustainability goals for the South African electricity system – as discussed above – are well defined, but it is unclear what the implications for the transition process are.

9.4.2.1.2 Sub-phase 2.2: South African electricity system transition goal definition

As previously mentioned, addressing the system underperformance in terms of environmental sustainability requires a purposive socio-technical transition, which is reliant on technology that is not (a prominent or significant) part of the incumbent technology domain. Given the current state of the South African electricity transition process, and when considering the relation between progress, stability and adaptability, the goals, in order to facilitate the South African electricity system's capability to transition, are outlined below in

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[59] It is important to note that this does not simply mean to reduce the amount of electricity generated via coal-fired generation, as the incumbent technology domain also contributes to other system performance elements, as well as other transition resilience dimensions.

Table 57. It should be noted that these goals are based on the conditions that are necessary (but not necessarily sufficient) to drive socio-technical system to change (Frantzeskaki and de Haan, 2009).

Table 57. Progress current state and goals

	GOAL(S)	
PROGRESS	P_T	The progress from a technical perspective is hindered primarily due to the energy system structure (i.e., the share of electricity generation from coal, the natural endowment of coal and the significantly smaller share of electricity generation from renewable energy sources). However, South Africa also has a natural endowment of the natural resources needed for renewable energy technologies. Factors like technology availability and economic and technical feasibility of renewable energy technologies, as well as an innovative business environment in South Africa (World Economic Forum, 2019), drive progress. Furthermore, the capital and investment commitments to renewable energy also drive progress, but the restrictions that are placed on investments (as can be seen from the Investment Freedom Index score of South Africa[60]) negatively affect the capability to progress. Even though it is evident both from a technical and a social perspective that the hindrances towards transitional change outweigh the drivers of transitional change, the capability of the South African electricity sector is primarily hindered by the social support provided to the incumbent coal-based technology domain.
	P_S	From a social perspective, the key contributing factors to the South African electricity sector's capability to transition are the regulations and the political commitment to a low-carbon future and to the promotion of renewable energies. But the sector's capability for transitional change is hindered by an unstable policy environment. Another key factor that hinders the sector's capability to transition is the uncertainty of the impact of transitional change on employment and communities, in addition, existing plans (i.e., the IRP) do not explain how socio-economic development will be addressed in affected areas. South Africa's institutional and governance dimensions also hinder transitional change, in that the country's credit rating and levels of corruption are concerning.

It should also be noted that progress is defined as the desired change in the system, and this aligns with the sustainability goals (i.e., desired changes in system performance). However, given the foundational argument of this research, namely that of managing technology within the context of transitions, it is important to not only focus on system performance, but also on transition capability. Also, it must be borne in mind that progress as a transition resilience dimension is defined as the balance between drivers for system change, and resistance to system change. Progress goals, in terms of transition resilience, are then to:

i. Decrease the negative contributions (resistance) towards progress (system change) in the incumbent technology domain, both from a technological and a social perspective;
ii. Establish and/or strengthen the drivers of system change (progress) in the incumbent technology domain; and
iii. Increase the positive contributions of the emerging/alternative technology domain towards progress from a technological and a social perspective.

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[60] https://www.heritage.org/index/ranking

Table 58. Stability current state and goals

		GOAL(S)
STABILITY	S_T	In terms of stability, from a technical perspective (i.e., system resilience – to maintain functionality and to meet the electricity demand), despite the systemic failures and considering the system's capacity to deal with lack of capacity, the South African electricity sector's ability to maintain functionality contributes to stability. The stability from a technical perspective is currently highly reliant on the incumbent technology domain. Even though the incumbent technology domain experiences significant stress, the (wider) system seems to have sufficient capacity to deal with a lack of capacity. The goal in terms of stability from a technical perspective would be to increase the contribution of the renewable energy technology domain towards stability, while not compromising the ability of the system to maintain functionality.
	S_S	However, from a social perspective, i.e., the vision of the goal system state, and the numerous conflicting views in terms of the transition pathway (probably primarily due to the fact that a vision of a goal future state is not widely agreed upon), the capability to transition is compromised. However, and as previously mentioned, the stability in terms of system resilience is heavily dependent on the incumbent fossil-fuel based technology domain, results in a significant lock-in, which in turn hinders the sector's capability to transition. The envisioned future state (as outlined in the IRP) supports system performance in terms of access and electricity security, but it does not adequately consider environmental sustainability.

Stability goals essentially are to:

i. Decrease the dependence on the incumbent technology domain to ensure system resilience – thus moving the dependence of system resilience increasingly towards the emerging/alternative technology domain;
ii. Decrease the negative contribution from the incumbent technology domain towards the stability of the transition path and the envisioned future state; and
iii. Increase the positive contribution from the emerging/alternative technology domain towards the stability of the transition process.

Table 59. Adaptability current state and goals

		GOAL(S)
ADAPTABILITY	A_T	The adaptability of the South African electricity transition is (significantly) hindered by the lock-in to the dominant mode of electricity generation, both from a technical as well as a social perspective. The phased approach to the expansion of the electricity sector does however allow for adaptability. The risk of further lock-in is evident, in that the planned expansion entails the expansion of coal-based generation rather than the expansion of renewable energy capacity.
	A_S	The existing conflicting visions of the future system allow for adaptability, but unfortunately the lock-in of the incumbent technology domain hinders the adaptability of the system under transition.

Goals in terms of adaptability are to:

i. Guard against the (further) lock-in of coal-fired electricity generation (both from a technological and a social perspective); and
ii. Ensure future adaptive capacity of the South African electricity sector.

The goals outlined above should be considered in line with the context specificity, as this relates to the transition phase. In order to progress through the current transition phase and to move from the take-off phase to the acceleration phase, (i) tension should decrease, (ii) stress should increase, and (iii) pressure should increase. This means that, even if moving towards the acceleration phase is not an immediate reality or goal for the South African electricity sector, the goals should focus on this transition. The goals are thus geared towards moving towards these conditions for change – ultimately leading to the forces required that will 'set the stage' for these conditions. Furthermore, as we have seen, stability is very important, progress is important, and adaptability is hardly important (see Table 21) in the specific transition phase of the South African electricity sector, and this should guide the prioritisation of considerations.

9.4.3 Analytical perspective III: Progression state analysis of the South African electricity system

In the third analytical perspective, which comprises Phases 3 and 4, the identification and evaluation of the changes required in the South African electricity system is looked at in order to identify and evaluate the forces that are required to bring about the desired change, and to identify the relevant technology management considerations.

9.4.3.1 Phase 3: Analysis of the requirements for system performance, transition progress and transition capability of the South African electricity system.

The first sub-phase of Phase 3 is concerned with the system performance, transition progress and transition capability requirement analysis. The second sub-phase is concerned with the identification of the required forces to support the requirements identified in Sub-phase 3.1.

9.4.3.1.1 Sub-phase 3.1: System performance, transition progress and transition capability requirements analysis for the South African electricity system

In this sub-phase, the focus is on the requirement (i.e., the required contribution) from the 12 respective perspectives to support a successful transition. In the case of the South African electricity sector, this is to progress through the take-off phase towards the acceleration phase of the transition, thus addressing the first dimension of a 'successful' transition, i.e., to progress towards an increasing level of sustainability. In addition, it must be ensured that the transition does not fail, and that the transition resilience dimensions are thus addressed accordingly. With regard to the first instance, the required contributions to support the desired change in system performance should be considered. Table 60 shows the requirements from the respective technology domains towards system performance. Table 61, Table 62, and Table 63 show the requirements (required contributions) towards the respective transition resilience dimensions.

Table 60. System performance requirements for the respective technology domains

	SYSTEM PERFORMANCE ELEMENT	TECHNOLOGY DOMAIN	REQUIREMENTS FOR THE RESPECTIVE DOMAINS
SYSTEM PERFORMANCE	Environmental sustainability	*i*	Decrease the negative contributions of the incumbent technology domain towards environmental sustainability[61].
		e/a	Increase the positive contributions of the emerging/alternative technology domain towards environmental sustainability.
	Energy access and security	*i*	Shift the dependence on the incumbent technology domain for energy access and security, and economic growth and development towards the emerging/alternative technology domain, and increase energy access and security, and economic growth and development.
		e/a	
	Economic growth and development	*i*	
		e/a	

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[61] It is important to note that this does not simply mean to reduce the amount of electricity generated via coal-fired generation as the incumbent technology domain also contributes to other system performance elements, as well as other transition resilience dimensions.

Table 61. Progress requirements set for the respective technology domains

	REQUIREMENTS FOR THE RESPECTIVE DOMAINS		
PROGRESS	P_T	P_{Ti}	The requirement in terms of the incumbent technology domain is that this system will have to be maintained, given that coal will be part of all electricity sectors for the foreseeable future and thus remain a crucial part of the energy supply, and probably even more so in South Africa. As a result, there will need to be a focus on demand side interventions, and energy efficiencies – especially within the existing systems of the incumbent system. In addition, given the above and in order to leverage the existing infrastructure that will inevitably be part of the system, a diversification of electricity generation technologies within the incumbent technology domain (i.e., the inclusion of renewables) will allow for the incumbent technology domain to contribute towards progress. Also, in order to reduce the risk of system collapse, and thus transition failure, existing systems will need to be maintained (to an extent), and subsequently (actively) phased out, as renewable energy capacity increases. Moreover, given the current (low) installed renewable energy capacity, should the incumbent technology domain fail, there is a risk of system breakdown – i.e., the societal functions not being fulfilled.
		$P_{Te/a}$	The requirements for both P_{Ti} and $P_{Te/a}$ are arguably straightforward and as can be expected; from a technical perspective, renewable energy is not significantly prevented from replacing coal-based electricity generation technologies – renewable energy generation is available, and both technically and economically feasible. A key area where this may be improved is in local capacity building – not only in respect of the manufacturing of renewable electricity technologies, but also with regard to R&D focus. Again, unsurprisingly, from a technical perspective renewable energy capacity should be increased. A key area that will facilitate the progress here is improved storage capacity at different scales across the electricity network. Additionally, the current structure of the REIPPPP programme does not allow for the full benefit of the low cost of electricity to be transferred to the system – this should be addressed.
	P_S	P_{Si}	Here, the key requirements are for reduced political support, not necessarily for Eskom, but for coal-fired electricity generation In general; this will require initiatives and efforts that reach far beyond the electricity sector. As mentioned, the political and social support for the incumbent technology domain is not due to the objections against the technology employed, but due to the social and economic effects of the transitions. These should thus be managed accordingly. Another significant requirement is to ensure that the people who are negatively affected, as a result of the decommissioning of coal-fired power plants and the phase-out of such technologies, are assisted, in terms of re-skilling and up-skilling.
		$P_{Se/a}$	In order to support progress, stable and broad political support is needed for renewable energy. The renewable energy domain should increasingly contribute towards access to electricity, and towards creating jobs (i.e., jobs related to low-carbon economies). From an institutional perspective, the legitimisation of the technology domain is important. Here specific attention has to be paid to directionality, thus managing the risk of directionality failure.

When stability is considered, the system resilience seems to be relatively high – especially due to the decreasing demand in electricity. At the same time, though, the risk of system collapse (systemic failure) is evident. It should be noted that the system resilience is regarded as high because, even despite the high levels of tension, the system has not collapsed; thus the system is not necessarily stable, but it is resilient. Ideally, the system resilience should be significantly more dependent on the renewable energy niche. Key stability requirements are thus to maintain a high level of stability. A stable transition path as well as an envisioned future state is required.

Table 62. Stability requirements set for the respective technology domains

	REQUIREMENTS FOR THE RESPECTIVE DOMAINS		
STABILITY	S_T	S_{Ti}	Given that the incumbent technology domain plays a significant role at this stage in maintaining system resilience, i.e., limiting the risk of system-level collapse, the requirement is to maintain capacity to contribute the required generation from coal-based electricity and reduce/eliminate the systemic failures within the incumbent technology domain. Another requirement is to reduce the cost of electricity across the system in order to guard against the risk of increasing energy poverty; here is an example of a clear trade-off in the system – increasing the cost of electricity increases the stress in the regime, which drives transitional change (see P_{Ti}). However, given that in this phase of the transition, stability is more important than progress (see Table 21), and the risk of system collapse (i.e., lack of system resilience) is more grave than the loss of stability of the transition process (even though this is not entirely stable) – the requirement here would be to prioritise addressing social issues that increase the stress in the regime (see S_{Si} – the requirement is set [in order to move towards the conditions for change in the acceleration phase] from a social perspective, and not from a technical perspective). Furthermore, there is a requirement to manage the risk of (further) lock-in.
		$S_{Te/a}$	Given that the system's resilience primarily relies on the incumbent technology domain, the requirement is to increase the contribution of the renewable energy technology domain towards fulfilling the societal function and to maintain functionality, while guarding against the risk of increasing the cost of the system. A key factor that could hinder this, is the demand articulation failure risk evident in the system.
	S_S	S_{Si}	Stability in terms of (i) the transition pathway, and (ii) the envisioned future state, is considered to transcend the technology domains, and the particular contributions from the respective technology domains are not as evident as the combined effect of the dynamics of the respective technology domains. Here, the important aspects are to (i) establish a common goal, and (ii) to articulate such a goal in order for it to become a guiding norm. In addition, it is important that a transition pathway is agreed upon. However, the stability of the transition process requires similar actions from both technology domains, with support for renewable energy initiatives and policy coordination across the technology domains and sectoral levels. This highlights the importance of the co-management of technology domains.
		$S_{Se/a}$	

Table 63. Adaptability requirements set for the respective technology domains

	Requirements set for respective technology domains		
ADAPTABILITY	A_T	A_{Ti}	Improved adaptability to counter the extreme lock-in will require new functioning and practices to be created, as well as a diversified and scalable electricity generation mix.
		$A_{Te/a}$	Adaptability is required – i.e., a diversified and scalable electricity generation mix.
	A_S	A_{Si}	With regard to improved adaptability to counter the extreme lock-in, there is a requirement for institutions to reflect, discuss and decide upon new developments. There needs to be capacity and willingness of system actors to monitor and re-assess the transition process constantly. Similar to stability from a social perspective, adaptability from a social perspective is considered to be a construct that transcends the respective technology domains, in that the adaptability of the system is, by definition, reliant on both technology domains. Also, similarly to the stability from a social perspective, this speaks to the importance policy coordination.
		$A_{Se/a}$	

When the conditions for change are considered, and when keeping the respective importance of the transition resilience dimensions in mind, in order to increase the stress in the incumbent technology domain (the conditions for change in the subsequent phase of the transition), and in order to allow for the expansion of the emerging/alternative technology domain, the focus should be on increasing the contributions within the incumbent technology domain from a social perspective. In order to increase the pressure, the contribution towards progress and stability of the emerging/alternative technology domain should be increased. It should be noted that these two aforementioned requirements support the stability of the transition from a system resilience perspective. Then tension has to decrease, as the conditions for change during an acceleration phase are that tension should be present rather than significant, as is the case in the take-off phase. It is argued that if the requirements outlined above are met (i.e., increased stress due to increased support from a social perspective for renewable energy in the incumbent technology domain, and an increase in the contribution towards progress and the stability of the emerging/alternative technology domain), the tension would decrease, given that this would result in less of a mismatch between landscape developments and system operations.

It is important to note that all these requirements will most likely not result in the desired ultimate changes in progress towards environmental sustainability. However, the objectives here are threefold: (i) to progress towards a higher level of environmental sustainability, (ii) to improve (other) system performance (unsustainability) elements, and (iii) to support the transition capability of the system. Should a transition fail, the societal function is no longer fulfilled, and/or the unsustainability of the system does not improve sufficiently to be deemed ‘sustainable’. At this stage, it is thus imperative to ‘set the system up’ for transition success.

9.4.3.1.2 Sub-phase 3.2: Identification of required forces to support a transition in the South African electricity sector

When considering the current system state (i.e., system performance/sustainability), the current state of the transition progress and transition capability, and the requirements to (i) improve the system performance, and (ii) support a successful transition (i.e., progress and capability), the forces that are required (i.e., required forces (RF), may be identified (see Table 64, Table 65, Table 66 and Table 67 for the respective technology domains). The forces are also summarised based on force type, which is contained in Table 79, Table 80, Table 81, and Table 82 Appendix F.

It is argued that, ideally, one does not want triggering forces – i.e., systemic failures, infrastructure inefficiencies and inadequacies – to be present in a system. However, such triggers do create windows of opportunity. Again, ideally, windows of opportunities should be created actively, for example, through the decommissioning of coal-based power plants rather than by relying on systemic failures to create such windows of opportunities, as this negatively affects the system resilience and increases uncertainty. Rather, existing triggers in a system (if feasible, as some cannot be created) should be addressed (see Table 78 in Appendix E) It is thus argued that the required forces will primarily consist of formation and supportive forces.

Table 64. Required forces to address system performance

				REQUIRED FORCES	
	REQUIREMENTS FOR THE RESPECTIVE DOMAINS			*FORMATION FORCES*	*SUPPORTIVE FORCES*
SYSTEM PERFORMANCE	*Environmental sustainability*	*Incumbent technology domain*	Decrease the negative contributions of the incumbent technology domain towards environmental sustainability	Presence of a niche: Presence of a new social movement for environmental sustainability within the incumbent technology domain (RF45) Presence of a new demand: Demand for increasingly environmentally friendly technologies (RF47) Demand for new decision-making processes (RF48) Presence of a new functioning: New market for previously locked-in organisations (RF51)	Standardisation of practices/routines: Regulation of practices based on ecosystem's threshold/limitations (global demand for coal likely to decrease environmental impact of coal-fired electricity generation) (RF56) Provision of resources: Provide resources to the development of interventions that can reduce the impact of the coal-based electricity generation on the environment (RF57) Exercise of power: Control over technology, i.e. phase out of coal-fired power plants (RF61)
		Emerging/ alternative technology domain	Increase the positive contributions of the emerging/alternative technology domain towards environmental sustainability	Presence of a niche: Increasing dependence on the renewable energy niche to fulfil societal functions (RF52)	Provision of resources: Investment into the renewable energy technologies (RF62) Exercise of power: Protection of the market by government (RF66) Increase the number of supporters for the renewable energy niche (RF67)
	Energy access and security	*Incumbent technology domain*	Shift the dependence on the incumbent technology domain for energy access and security, and economic growth and development towards the emerging/alternative technology domain	Presence of a niche: Creation of a hybrid institution to manage the shift in socio-economic dependence (RF46) (RF53) Presence of a new demand: Socio-economic demand from renewable energy niche (RF49) (RF54) Demand for new knowledge and technology to facilitate the transition (RF50) (RF55)	Provision of resources: Investment into the renewable energy technologies (R Disinvestment into the expansion of the incumbent technology domain (RF59 Invest in markets that will support the socio-economic requirements from the energy niche (RF60)
		Emerging/ alternative technology domain			
	Economic growth and development	*Incumbent technology domain*			
		Emerging/ alternative technology domain			

Table 65. Required forces to address progress

				REQUIRED FORCES	
	REQUIREMENTS FOR THE RESPECTIVE DOMAINS			*Formation forces*	*Supportive forces*
PROGRESS	P_T	P_{Ti}	The requirement in terms of the incumbent technology domain is that this system will have to be maintained as, given that coal will be part of all electricity sectors for the foreseeable future and thus a crucial part of, and probably even more so in South Africa, there thus needs to be a focus on carbon capture, demand side interventions, and energy efficiencies – especially within the existing systems of the incumbent system. In addition, given the above and in order to leverage the existing infrastructure that will inevitably be part of the system, a diversification of electricity generation technologies within the incumbent technology domain (i.e., the inclusion of renewables) will allow for the incumbent technology domain to contribute towards progress. Also, reducing the risk of system collapse, and thus transition failure, will require that existing systems are maintained (to an extent), and subsequently (actively) phased out as renewable energy capacity increases. Given the current (low) installed renewable energy capacity, should the incumbent technology domain fail, there is a risk of system breakdown – i.e., the societal functions not being fulfilled.	Presence of a new functioning: Demand side interventions, energy efficiencies, diversification of electricity generation (RF10)	Provision of resources: Maintain capacity - to the extent where he fulfilment of the societal function is dependent on the incumbent technology domain (RF26) Investment into new markets (new functioning required) (RF31) Exercise of power: Phase-out of coal-fired electricity generation technologies. (RF32) Protection of new markets (RF33)
		$P_{Te/a}$	The requirements for both P_{Ti} and $P_{Te/a}$ are arguably straightforward and as can be expected; from a technical perspective, renewable energy is not significantly prevented from replacing coal-based electricity generation technologies – they are available, and technically and economically feasible. A key area where this may be improved is in local capacity building – not only for the manufacturing of renewable electricity technologies, but also R&D focus. Again, unsurprisingly, from a technical perspective renewable energy capacity should be increased. A key area that will facilitate the progress here is improved storage capacity. Additionally, the current structure of the REIPPPP programme does not allow for the full benefit of the low cost of electricity to be transferred to the system – this should be addressed.	Presence of a niche: Expansion of RE energy niche (RF12) Storage capacity niche (RF13) Presence of a new demand: Increased effectiveness and efficiency of the structure of REIPPPP (RF15) Presence of a new functioning: R&D and manufacturing of renewable energy technologies (RF23)	Standardisation of practices/routines: Institutionalise RE technologies (RF37) Provision of resources: Provide resources to RE niche in order to expand (RF38)
	P_S	P_{Si}	Here, the key requirements are for reduced political support, not necessarily for Eskom, but for coal-fired electricity generation In general, which will require initiatives and efforts that reach far beyond the electricity sector. As mentioned, the political and social support for the incumbent technology domain is not due to the objections against the technology employed, but due to the social and economic effects of the transitions. These should thus be managed accordingly. Another significant requirement is ensuring that the people who are negatively affected as a result of decommissioning of coal-fired power plants and the phase-out of such technologies are assisted.	Presence of a niche: Presence of social demand for renewable electricity generation (RF1) Presence of a new demand: Decoupling of social and economic reliance on coal-fired electricity generation (RF3)	Provision of resources: Reduced political support for coal-fired electricity generation (RF27) Societal support for RE technology for electricity generation (RF28)
		$P_{Se/a}$	In order to support progress, stable and broad political support is needed for renewable energy. The renewable energy domain should increasingly contribute towards access to electricity, creating jobs (i.e., jobs related to low-carbon economies). From an institutional perspective, the legitimisation of the technology domain is important. Here specific attention has to be paid to directionality, thus managing the risk of directionality failure.	Presence of a new demand: Emerging/alternative technology domain to address socio-economic needs (RF16)	Provision of resources: Social and political support for emerging/alternative technology domain (RF39) Exercise of power: Legitimise institutions in the emerging/alternative technology domain (RF43)

Table 66. Required forces to address stability

				REQUIRED FORCES	
	REQUIREMENTS FOR THE RESPECTIVE DOMAINS			*Formation forces*	*Supportive forces*
STABILITY	S_T	S_{Ti}	Given that the incumbent technology domain plays a significant role at this stage in maintaining system resilience, i.e., limiting the risk of system-level collapse, the requirement is to maintain capacity to contribute the required generation from coal-based electricity and reduce/eliminate the systemic failures within the incumbent technology domain. Another requirement is to reduce the cost of electricity across the system in order to guard against the risk of increasing energy poverty; here is an example of a clear trade-off in the system – increasing cost of electricity increases the stress in the regime, which drives transitional change (see P_{Ti}), however given that in this phase of the transition, stability is more important than progress (see Table 21), and the risk of system collapse (i.e., lack of system resilience) is more grave than loss of stability of the transition process (even though this is not entirely stable) – the requirement here would be to prioritise addressing social issues that increase the stress in the regime (see S_{Si} – the requirement is rather to (in order to move towards the conditions for change in the acceleration phase) to increase stress in the regime from a social perspective, and not from a technical perspective). Furthermore, there is a requirement to manage the risk of (further) lock-in.	Presence of a new demand: Reduce cost of electricity (RF4) Guard against further lock-in (RF5)	Provision of resources: Maintain (sufficient) capacity (RF29) Exercise of power: Increase the number of supporters for the renewable energy niche / emerging/alternative technology domain (RF34)
		$S_{Te/a}$	Given that the system's resilience relies primarily on the incumbent technology domain, the requirement is to increase the contribution of the renewable energy technology domain towards fulfilling the societal function and to maintain functionality, while guarding against the risk of increasing the cost of the system. A key factor that could hinder this, is the demand articulation failure risk evident in the system.	Presence of a new demand: Guard against increases in cost (RF17) Demand of new knowledge (demand articulation) (RF18)	Provision of resources: Support and expansion of renewable energy niche (RF40)
	S_S	S_{Si}	Stability in terms of (i) the transition pathway, and (ii) the envisioned future state is considered to transcend the technology domains, and particular contributions from the respective technology domains are not as evident as the combined effect of the dynamics of the respective technology domains. Here, the important aspects are to (i) establish a common goal, and (ii) to articulate such a goal in order for it to become a guiding norm. In addition, it is important that a transition pathway is agreed upon. However, the stability of the transition process requires similar actions from both technology domains – support for renewable energy initiatives and policy coordination across the technology domains. This inevitably means that the co-management of technology, as this is a foundational construct in the ITMST framework.	Presence of a niche: Creation of a new / hybrid institutional form (RF2) (RF14) Presence of a new demand: Common (transition) stability goal (RF6) (RF19) Policy coordination across technology domains (RF7) (RF20)	Provision of resources: Legitimise new (hybrid) institution (RF30) (RF41) Exercise of power: Increase support for cross-domain activities (RF34) (RF44)
		$S_{Se/a}$			

Table 67. Required forces to address adaptability

				REQUIRED FORCES	
	REQUIREMENTS FOR THE RESPECTIVE DOMAINS			*Formation forces*	*Supportive forces*
ADAPTABILITY	A_T	A_{Ti}	Improved adaptability to counter the extreme lock-in, which will require new functioning and practices to be created as well as diversified and a scalable electricity generation mix to be created.	Presence of a new demand: Diversification and scalable electricity generation mix in the incumbent technology domain (RF8) Presence of a new functioning: Increased adaptability in system (RF11)	Standardisation of practices/routines: Regulation of practices based on ecosystem's thresholds/limitations (RF25) Provision of resources: Investment in new markets and infrastructure within the incumbent technology domain (RF31) Exercise of power: Control over the use of resources by government (RF35)
		$A_{Te/a}$	Adaptability required – i.e., a diversified and scalable electricity generation mix.	Presence of a new demand: Diversification and scalable electricity generation mix in the renewable energy niche (RF21) Presence of a new functioning: Increased adaptability in system (RF24)	Provision of resources: Investment in new markets and infrastructure within the renewable energy niche (RF42)
	A_S	A_{Si}	Improved adaptability to counter the extreme lock-in is needed, and for this there is a requirement for institutions to reflect, discuss and decide upon new developments. There needs to be capacity and the willingness of system actors to monitor and re-assess the transition process constantly. Similar to stability from a social perspective, adaptability from a social perspective is considered to be a construct that transcends the respective technology domains, in that the adaptability of the system is, by definition, reliant on both technology domains. Also, similarly to the stability from a social perspective, this speaks to the importance of policy coordination.	Presence of a niche: Creation of a new / hybrid institutional form (RF2) Presence of a new demand: Common adaptability goal (RF9) (RF22) Policy coordination across technology domains (RF7) (RF19)	Exercise of power: Increase support for cross-domain activities (RF36)
		$A_{Se/a}$			

9.4.3.1.3 Sub-phase 3.3: Evaluation of present and required forces within the South African electricity system and transition

Given the conditions for change present in the South African electricity sector, various forces are present in the system or should ideally be present (hence they are referred to as the required forces). In order to provide guidance for the development of technology management considerations, these forces have to be evaluated to gain insight into whether they will drive or resist progress, or positively or negatively contribute towards transition progress, transition capability and system performance, as well as to identify forces that are required, but not present. The matrices presented in Figure 48 are used to evaluate and characterise the present and required forces. Firstly, the required forces identified in Sub-phase 3.2 (which are all deemed forces that contribute positively towards transition progress, transition capability and/or system performance by nature of the requirements) are evaluated to determine whether or not they are present in the South African electricity system (seeTable 83, Table 84, and Table 85 in Appendix G) for an evaluation of the present and required forces in terms of whether they are present or absent, whether they drive or resist transition progress, and whether they contribute positively or negatively towards stability, adaptability and the system performance elements).

9.4.3.2 Phase 4: Identification of technology management considerations

As discussed in Section 8.2.3.2, Phase 4 is concerned with the identification and definition of technology management considerations based on the ***contribution*** of the respective technology domains within the South African electricity system to (i) ***transition progress***, (ii) ***transition capability***, and (iii) ***system performance***; as well as the ***requirements*** from the respective technology domains to bring about the desired change in terms of (i***) transition progress***, (ii) ***transition capability***, and (iii) ***system performance***. These insights may then be translated into risks and opportunities for the (i) respective technology domains, (ii) transition (i.e., transition progress and transition capability), and (iii) system performance.

Technology management considerations from the perspective of the South African electricity system technology domain contributions

Table 55 and Table 56 show the contributions of the respective technology domains towards transition progress, transition capability, and system performance. Given that the incumbent technology domain contributes positively towards transition progress, technology management actions may be geared towards the long-term sustainability and existence of the technology domain (or the element of the technology domain that contributes towards transition progress). Furthermore, the incumbent technology domain contributes positively towards progress from both a technical and a social perspective; this may be translated into technology management considerations that are geared towards exploiting these technologies to facilitate the growth of the technology domain and to protect such technologies with approaches such as strategic niche management. In terms of the positive contribution towards progress, from a social perspective, the incumbent technology domain also drives progress, and the technology management considerations in this regard are to ensure that the social requirements and support are continually satisfied. The challenge here lies in the resistance that is faced from the incumbent technology domain from a social perspective; technology co-management activities should thus be geared towards aligning the acquisition, identification of learning and selection of technologies towards addressing the factors that provide for resistance to progress from a social perspective in the incumbent technology domain.

Considering the contribution of the incumbent technology domain of the South African electricity sector towards progress, it is evident that, from both a technical as well as a social perspective, there is a negative contribution towards progress. Even though the net contribution of the incumbent technology domain is negative, however, it does still add value to the transition, in that it contributes towards stability from a technical perspective, and it also contributes towards system performance (i.e., energy access and security and economic growth and development). The risks are evident nonetheless, given that, if a technology domain does contribute negatively towards progress, it also contributes negatively towards environmental sustainability; there is thus a need to move away from coal-fired electricity generation. Technology management considerations for the incumbent technology domain should thus be geared towards understanding how the role of the technology is creating value for the transition and the system performance in the short and medium term, thus exploiting technologies for the short and medium term, while also decommissioning and phasing out coal-fired electricity generating technologies. Furthermore, an opportunity exists for the incumbent technology domain to exploit, grow and expand the currently limited technologies that drive progress. Here, the management of technology clearly needs technology management initiatives that stretch across both technology domains. The resistance to progress from a social perspective calls for technology management that allows for a decoupling of social and economic dependence on the supply chains and processes surrounding a specific technology.

The risks for the transition, given the respective contributions towards transition progress, are that the system's transition capability is hampered by the resistance to progress of the incumbent technology domain (lock-in), and that the contribution from the renewable energy technology domain is still relatively small, which puts the system resilience at risk. The risks for system performance are that the technology management considerations of decommissioning and phasing out of coal-fired electricity generation technologies pose risks for energy access and security, and economic growth and development, given that these system performance elements depend on the incumbent technology domain to a significant extent.

The renewable energy niche contributes positively towards stability, from both a social and technical perspective. However, it is important to note that these contributions are considered 'slight' contributions (see Section 9.4.1.3), because the contribution towards stability in terms of the system functioning of the renewable energy niche is small, relative to the incumbent technology domain. The technology management considerations in terms of stability from a technical perspective are thus similar to the considerations for the renewable energy technology domain in terms of progress, in that the technologies that contribute towards stability should be exploited, in this case primarily for two reasons: (i) to increase the contribution of the renewable energy niche towards system resilience, and (ii) to reduce the dependence on the incumbent technology domain to provide for system resilience. From a social perspective, i.e., the stability of the sustainability transition process, the technology management considerations should be geared towards identifying the technology elements that could contribute towards addressing the social needs, as well as the technologies and/or technology elements that align with the sustainability and transition goals. This then extends to identifying the unmet social needs, as well as the social needs that are met by the incumbent technology domain.

The incumbent technology domain, as mentioned above, contributes positively towards stability from a technical perspective (i.e., system resilience), but it contributes negatively towards stability (i.e., the stability of the sustainability transition process). Again, here the technology management considerations should be viewed together with the contributions towards transition progress and the related technology management considerations. Given that the incumbent technology domain does not contribute positively towards progress (and thus also not towards environmental sustainability), the technology management considerations should include the exploitation of the technologies in the incumbent technology domain, but only to the extent that the renewable energy niche cannot provide for system resilience.

Given that the renewable technology domain contributes towards the adaptive capacity from a technical perspective, primarily due to the array of technologies employed, the technology management considerations are that multiple technologies have to operate across a number of technologies. Technology management considerations should furthermore be geared towards the identification of technologies that will counter lock-in, and the identification of early onset lock-in risks. Learning is also a critical part of technology management activity here, as there is a need to reflect critically on the technology projects in order to identify alternative means of increasing the adaptive capacity, especially given that adaptability becomes increasingly important during the transition phase after take-off.

The incumbent technology domain significantly hinders adaptability, given the extreme lock-in with regard to coal-fired electricity generation. Technology management considerations should be geared towards learning how these dependencies on the specific technology could potentially be decoupled, and to identify technologies that could address (i) the environmental sustainability, and (ii) the social needs currently addressed by the specific technology. Furthermore, the long-term negative effects (from a system performance perspective as well as from a transitions perspective) should be identified and articulated, and the misalignment with system performance elements should be identified and highlighted.

The contributions from the respective technology domains towards the system performance elements of the South African electricity system are shown in Table 55. When considering these contributions, it is clear that both technology domains contribute positively towards all system performance elements, with the exception of the incumbent technology domain, which has a significant negative contribution towards environmental sustainability. Given that the renewable energy niche has a positive contribution, albeit only slightly, it is unsurprising that the technology management considerations should be geared towards exploiting the technologies in order to increase the contribution of this technology domain towards the system performance elements. However, for the incumbent technology domain, technology management considerations should be geared towards identifying alternative technologies that can contribute towards other system performance elements (i.e., fulfil societal functions), but also contribute towards improving the system performance elements that is linked to progress.

Technology management considerations from the perspective of the South African electricity system technology domain requirements

Technology management considerations based on the requirements from the respective technology domains in the South African electricity system are inferred from the evaluation of the present and required forces. The forces that are not present, have to be created (generated), and are indicated as such in Table 84 in Appendix G (with regard to transition progress and transition capability) and Table 85 in Appendix G (with regard to system performance). The quality of the forces that are present is evaluated thereafter in order to determine whether the respective forces have to be developed (i.e., they exist, but are not sufficient to contribute effectively towards transitional change) or exploited (i.e., they are present and sufficient to drive transitional change). They are also shown in Table 84 in Appendix G (with regard to transition progress and transition capability) and Table 85 in Appendix G (with regard to system performance). Similarly, the forces present in the South African electricity system that are present but not required – thus resisting transitional change – have to be evaluated to determine whether such forces should be managed or monitored. The forces that are present in the South African electricity system are evaluated and shown in Table 83 in Appendix G

The majority of the forces that have to be created/generated to support transition progress and transition capability are forces that are concerned with the social perspective (see Table 84 in Appendix G). This clearly indicates that technology management considerations should extend into technology management actions, interventions and activities that address social requirements. Technology management considerations in this context, as can be deduced from the forces shown in Table 84 in Appendix G, should be geared towards learning, selecting, and identifying technologies, as well as technological capabilities, that will facilitate and support the creation and generation of forces to create value for the transition, and to translate social and institutional requirements into technical specification, and vice versa. Interestingly, the majority of the forces that are not present in the South African electricity sector to support the creation of value for the transition, are social in nature.

The technology management considerations necessary to create/generate forces require more 'traditional' technology management considerations, such as technology development, assessment, etc. However, even though forces that are required, such as 'reduce the cost of electricity' and 'development of a storage capacity niche', which may easily be linked to system performance elements (and thus 'traditional value creation elements for electricity systems'), there are forces that are geared towards transition value creation, such as the need for 'demand articulation' and 'guarding against further lock-in', which require technology management considerations that go beyond the commercial and technological perspective but need to be seen from the transition perspective.

The forces that are present, but not sufficient, call for technology management considerations that see such forces being developed, and that are thus geared towards expanding these forces and/or the effect of these forces on the electricity system and/or on the capability of the system to transition. The forces that are identified here require both transitional technology management considerations, i.e., actions, activities, initiatives and interventions that result in the creation of value that is measured by means of the system performance elements, as well as organisations (i.e., from a commercial and technological perspective). An example may be the 'expansion of the renewable energy niche' or the 'provision of resources towards the renewable energy niche'. However, a number of forces are also identified that require technology management considerations that will result in value being created for the transition – an example of this is the need for 'increased adaptability in the system'.

Interesting, but arguably unsurprising, is the limited number of forces that are present and sufficient that have to be exploited. Technology management considerations should thus be geared towards exploiting such forces. These forces are all from a technical perspective, which is as expected – again clearly highlighting that the transition capability is primarily supported from a technical perspective. Again, here forces are identified that call for technology management to be also geared towards the creation of value for the transition and not only for the system (i.e., system performance elements) and/or for organisations from a technical and/or technological perspectives; an example is the need for 'increased adaptability in the electricity system'.

When considering the forces that are present in the South African electricity that are not required, i.e., the forces that resist transitional change (see Table 83 in Appendix G), the actions, activities and initiatives that are required from a technology management perspective are to a large extent encapsulated within the considerations outlined above, as the requirements also incorporate the resistance and risks within the South African electricity system.

In addition, there are also risks that may be identified and that should be monitored; for example, there is a risk of system backlash in the event that the renewable energy niche gains power and popularity, but fails to stabilise and become the incumbent regime. Or the demand for renewable energy may expand too quickly (should, for example the political and social support for renewable energy increase), and unforeseen risks or problems may become apparent (i.e., directionality failure), in response to which the niche is abandoned.

Furthermore, it is important to take note of forces that may be categorised as a force that resists transitional progress – for example, supportive forces provided to the incumbent technology domain – but that nonetheless contribute towards the capability of the system to transition, in that they contribute towards system resilience.

Finally, the impact of the required actions (exploit, develop, create/generate), which guide the technology management considerations, across the transition progress, transition capability and system performance elements, should be evaluated in order to identify risks. This evaluation is shown in Table 86 and Table 87 in Appendix H, and highlights the importance of considering the required actions across transition progress, transition capability and system performance elements. The requirements to facilitate and support stability of the transition highlighted a need to reduce the cost of electricity in the incumbent technology domain (RF4 in Table 86 in Appendix H). However, even though this is a requirement for stability, it will negatively affect the transition progress, in that the high electricity prices currently contribute towards the 'window of opportunity' for renewable energy technologies. Similarly, the need to 'maintain sufficient capacity' (RF28 in Table 86 in Appendix H) in the incumbent technology domain will resist progress; in order to drive progress, the coal-fired electricity generation should ideally be reduced. The need to 'maintain sufficient capacity' (RF28 in Table 86 in Appendix H) in the incumbent technology domain may also have a negative effect on the transition capability in terms of adaptability. Here, it becomes important to take into account the relative importance of the transition capability elements (see Table 21). In this scenario, stability is very important, and adaptability is hardly important. Furthermore, FR4 and FR28 discussed above may also have a negative influence on the environmental sustainability of the system. This should be highlighted as a risk, especially given that adaptability in the next transition phase is very important. The technology management considerations should all take such risks into account.

Another example, where negative impacts may be seen on the stability of the transition, is the case where the phasing out of coal-fired electricity generation technologies (RF32 in Table 86 in Appendix H) is identified as a requirement to support and facilitate transition progress. However, this will likely have a negative effect on stability in terms of system resilience, as well as on energy access and security, and economic growth and development, should the renewable energy technology domain, or the alternative environmentally friendly technologies not have sufficient capacity to meet the demand for electricity. Stability is very important in the phase within which the South African electricity sector currently is, i.e., during the take-off phase. However, the risks of system collapse and lock-in (which may require a contradictory set of actions), should be considered alongside the technology management considerations outlined above.

There are other examples of risks that should be considered; these may be found in Table 86 and Table 87 in Appendix H, but for the sake of brevity, not all examples are discussed in detail.

9.5 Discussion

The key outcomes in terms of the validation of the ITMST framework and methodology, as mentioned in Section 9.2, are the applicability, practicability and usability of the ITMST framework and methodology, and are defined as follows:.

i. Applicability to real-world cases, i.e. to illustrate that the conceptual framings presented in the ITMST framework and methodology are representative of real-world phenomena;
ii. The practicability of the developed framework and methodology; i.e. to assess whether the framework and methodology can be put into action; and
iii. The usability of the ITMST framework and methodology; i.e. whether it is easy to use or the degree to which it is easy to use.

Given that the ITMST methodology is the operationalisation of the ITMST framework, the practicability and usability of the ITMST framework is evaluated in the practicability and the usability of the ITMST methodology.

Applicability

The ITMST methodology systematically proceeds through four phases, providing sufficient information and insight into the transition progress, transition capability, and system performance contributions and requirements from the respective technology domains, in order to facilitate the definition and identification of technology management considerations. The case study, of the South African electricity system, is a system in transition, and the applicability of the ITMST methodology to a system under transition is thus also evidenced. The applicability of the features formulated as part of the ITMST framework, and which manifests in the ITMST methodology are, as discussed in Table 68.

Practicability

A key priority of this research was to, as mentioned in Chapter 1, propose not only a theoretical construct that provides a premise for the integration between technology management and socio-technical transitions, but also a practical one. The ITMST framework, as is the case with most theoretical and/or conceptual constructs, although valuable lacks immediate practicability. This was also highlighted as a key drawback of the ITMST framework during SME consultations (see Section 9.1.2). The ITMST methodology, however, holds a high degree of practicability in that it provides clear and concise steps, information requirements, and support frameworks and constructs to support the practical utility thereof.

Usability

Although the ITMST methodology does hold a necessary level of complicatedness, the developed methodology allows for a structured and systematic gathering of data and information, evaluation of elements (transition progress, transition capability and system performance contributions and requirements), and definition and identification of technology management considerations.

Table 68. Evaluation of key framework features based on case study findings

FRAMEWORK FEATURE	APPLICABILITY AND VALIDITY OF ITMST FRAMEWORK FEATURES BASED ON CASE STUDY FINDINGS
Transition value creation	It is evident that the system performance elements used in the context of electricity systems (i.e. environmental sustainability, security and access, and economic development and growth) are (i) primarily geared towards metrics that considers the creation of value for the system (i.e. the environment within which it exists as well as for its users), and (ii) outcome focussed (as opposed to focussed on the transition process). Furthermore, technology management is geared towards the development and implementation of technological capabilities to support firms to achieve their strategic and operational objectives (Cetindamar, Phaal and Probert, 2010), and thus to create value for such organisations. The transition value creation feature of the framework highlights this necessary and complementary focus on the transition process in addition to the focus on value creation for the system in transition and for technology management domains or organisations. It is evident, given that technology domains contribute towards transition progress, transition capability and system performance, that technology domains should then also be manged to satisfy the required contributions to support a transition and thus to create value for a transition. Furthermore, when considering a premise for the integration between technology management and socio-technical transitions, the introduction of the idea of 'transition value creation' allows for a transcending concept between technology management and socio-technical transitions as a common measure that may be translated into transition and technology management objectives. The transition value creation feature manifests in the ITMST methodology across all three analytical perspectives in that the contributions and required contributions towards transition progress and transition capability, in addition to system performance elements, are considered.
Collective and individual consideration of transition progress, transition capability and system performance	From the case study it is evident that it is not only possible to individually and collectively consider transition progress, transition capability and system performance, but also that it is necessary for this individual and collective consideration. Also, this feature is strongly linked to, and supports, transition value creation in that it is not only focused on the individual and collective consideration of transition progress, transition capability and system performance, but also that all three these perspectives have to be taken into account in order to support the transition. Individual consideration is necessary to elucidate the specific and nuanced contributions and requirements from the respective technology domains (shown in Phases 1 to 3 of the ITSMT methodology and related sections in the case study), as well as to define and identify technology management considerations (i.e. Phase 4 of the ITMST methodology and related sections of the case study). Specifically considering transition progress, transition capability and system performance allows for the necessary common objectives that transcends technology domain objectives (and therefore also technology management objectives), transition objectives, and system objectives – in turn again supporting the premise for integration between technology management and socio-technical transitions. Collective considerations, as shown in the case study, is necessary given that a specific technology domains may have contradicting effects on transition progress, transition capability and/or the various system performance elements – as shown in Section 9.4.1.3. The collective consideration of transition progress, transition capability and system performance elements further support the identification of technology management considerations and supports a holistic view of the three different value creation perspectives. This then also supports and contributes towards a premise for the integration between technology management and socio-technical transitions.

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Co-management of incumbent and emerging/alternative technology domains	From a theoretical perspective, it is evident that both technology domains contribute toward a socio-technical system's performance as well as its capability to transition. It is clear that for a system to maintain functionality throughout a transition, as well as for the transition not to fail, both technology domains should be considered, and thus should the technology domains be manged holistically. The co-management of incumbent and emerging/alternative technology domains therefor support the premise for integration between technology management and socio-technical transitions in that highlights the importance and necessity for management practices across technology domains.
Contextual specificity	The importance and relevance of the context specific indicators in terms of the socio-technical system and its environment, as well as the transition phase is evident in the case study presented above. The South African electricity system holds specific unique characteristics that are (i) specific to the context of electricity systems (for example, the system performance elements), and (ii) specific to the South African context (for example the extreme lock-in of the coal-fired electricity generation, and the specific performance of the electricity system across the three system performance elements). These context specific characteristics, as can be seen from the case study, influences the technology management considerations both in terms of how these are identified (through the evaluation of the contributions of, and requirements from the respective technology domains towards transition progress, transition capability and system performance), as well as in terms of understanding the impact and/or prioritising of actions based on the effect such actions may have across system performance and transition capability elements. Furthermore, as shown in Section 9.4.2.1.2, the context specificity in terms of the transition phase that the socio-technical system is in, also guides the definition of system performance, transition progress and transition capability goals. Transition phases holds certain conditions for change, which in turn influences the necessary forces that are, or may become, necessary to support the transition.
Contribution-requirement view	From the case study it is evident that the contributions from the respective technology domains towards transition progress, transition capability and system performance results in a unique set of technology management considerations compared to when the requirements from the respective technology domains are evaluated. This highlights the value and necessity of considering both the contributions as well as requirements when aiming to infer technology management contributions that will support the transition as well as the performance of the system. Furthermore, and complementary to the identification of the technology management considerations, the contribution-requirement view allows for not only a short-term view of the technology management considerations, but also allows for (together with the context specificity considerations in term of transition phases) a futures perspective in that what is required to support the transition (i.e. the required forces) may be identified. In addition to this, the contribution-requirement view facilitates the identification of risks and opportunities for the technology domains, the transitions as well as for system performance. The contribution-requirement view thus further facilitates and supports the premise for the integration between technology management and socio-technical transition as it provides for nuanced and temporal perspectives from which technology management considerations may be derived.

Ultimately, the evaluation approach looked to address whether (i) the ITMST framework provides for a premise for the integration of technology management, and (ii) provides the basis for the definition and identification of technology management considerations within the context of socio-technical transitions. These were addressed through the literature review, theoretical verification, the operationalisation of the framework, and the case study. The case study addressed whether the framework and methodology are implementable. The case study findings showcased that the ITMST methodology provide a basis for the definition and identification of technology management considerations within the context of sustainability transitions. And, the evaluation of the validity and applicability of the ITMST framework, along with the theoretical verification, highlights that the ITMST framework provides a premise for the integration between technology management and socio-technical transitions.

9.6 Conclusion: Chapter 9

The aim of this chapter was to evaluate the developed framework and methodology through verification and validation processes. The verification included the evaluation of the requirement specifications and theoretical verification through subject matter expert consultations. A case study, which focussed on transitions in the South African electricity system, was conducted to evaluate the applicability, practicability and usability of the ITMST methodology, and to infer the applicability and validity of the ITMST framework.

Chapter 10.

Summary and conclusions

In this chapter, a summary of the study is provided, the attainment of the research objectives stated in Chapter 1 is evaluated, and meta-insights are discussed. Subsequently, the contributions evidenced through this research study are highlighted, and the chapter concludes by highlighting opportunities for future research.

10.1 Research summary

In this dissertation the problem of the disconnection that exists between the conceptual, theoretical and practical framings of technology management and socio-technical transitions was addressed. Both technology management and socio-technical transitions approaches are perspectives that give rise to only a partial understanding of the management of technology within the context of socio-technical or sustainability transitions. The value of an integrative approaches that combine (or link) these different approaches take advantage of the strengths of the different approaches in order to generate an increasingly robust, informed and nuanced approaches for the evaluation of transitions and the management of technology within such transitions. This argument, along with evidenced disconnection that exists between technology management and socio-technical transitions, served as motivation for this research.

The research products (i.e., the ITMST framework and methodology) that is put forward in this dissertation suggests a refined view of how technology may be managed within the context of socio-technical transitions. The research outputs thus also contributes towards the development of increasingly complete and flexible analysis of transitions that are useful to decision-makers and practitioners, in addition to contributing towards the theoretical debate surrounding how we could govern socio-technical transitions more effectively and efficiently.

In Chapter 1, an introduction to and overview of the research is provided. This includes an outline of the problem that is addressed in this study, as well as the research aim and objectives. Four research objectives (ROs) and a number of sub-research objectives are defined. Figure 53 shows the relationship between the dissertation chapters and the stated research objectives, and Table 69 provides an overview of the research objectives and how they were addressed in this study. Moreover, Table 69 also provides an overview of the research progression.

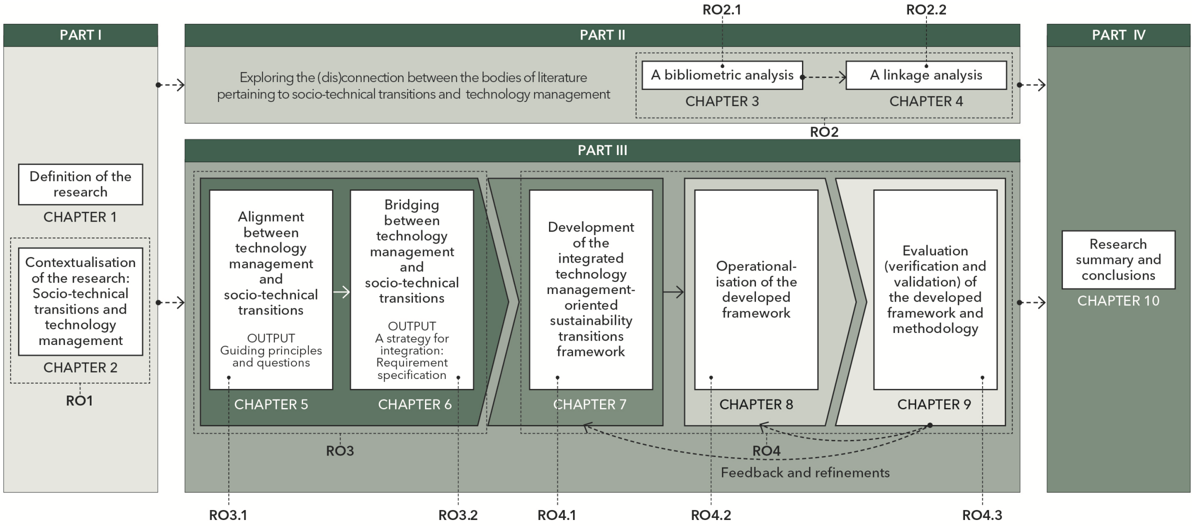

Figure 53. Dissertation chapters and research objectives

Table 69. Evaluation of the attainment of research objectives

SUB-RESEARCH OBJECTIVES	CHAPTER	CHAPTER SUMMARY AND EVALUATION OF THE OBJECTIVES ATTAINED
Research objective 1: To contextualise technology management and socio-technical transitions, as well as the challenges that face these two fields of research, from a theoretical and practical perspective in order to support the rationale of this research.		
N/A	2	In order to address RO1, a review of literature pertaining to the field of technology management and the field of socio-technical transitions was performed. The challenges faced by the respective fields were also reviewed and discussed to support the rationale for this research. The insights gained from the review of literature, and the consideration of the challenges faced by the respective fields in light of sustainability, highlighted the potential and value that an integrative framework may contribute towards addressing the need for increasingly effective and efficient management practices within the context of socio-technical transitions.
Research objective 2: To establish the extent of either integration or disconnection between the concepts of technology management and socio-technical transitions to elucidate the level of and extent to which these bodies of literature have been integrated.		
RO2.1: To investigate and compare the structures of the scientific networks in the technology management and socio-technical transitions literature through a bibliometric analysis in order to explore the interfacial layer between the two bodies of literature.	3	A bibliometric analysis was conducted to refute or confirm the seeming disconnect that exists between the literature pertaining to socio-technical transitions and technology management respectively. A number of areas of overlap were identified. However, the only key areas of overlap that emerged from the bibliometric analysis was that of innovation, and to a lesser extent sustainability and the focus on technology. Yet, no concrete evidence of integration or significant similarity in foundational concepts used in both bodies of literature was evident. Furthermore, the bibliometric analysis served as motivation for further analysis to elucidate the extent to which these bodies of literature have been integrated.

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SUB-RESEARCH OBJECTIVES	CHAPTER	CHAPTER SUMMARY AND EVALUATION OF THE OBJECTIVES ATTAINED
RO2.2: To explore existing linkages between technology management and socio-technical transitions through a linkage analysis in order to elucidate the extent to which there exists an overlap, and to what extent these two bodies of literature share intellectual roots.	4	Subsequent to the bibliometric analysis, a linkage analysis was performed. The linkage analysis highlighted the most prominent areas of overlap between the technology management and socio-technical transitions' bodies of literature based on the references that the documents in these bodies of literature cite. However, from the linkage analysis is was concluded that the level of integration between the fields of technology management and that of socio-technical transitions is diminutive and that there does not exist overlaps in terms of conceptual framings fundamental to either technology management or socio-technical transitions.
Research objective 3: To develop a proposition in the form of an integration strategy that transcends technology management and the concept of socio-technical transitions in order to articulate the conceptual notions from which to develop a premise for the integration between technology management and socio-technical transitions.		
RO3.1: To identify and define the elements around which an integrated meta-perspective can be articulated – this will inform the objective to establish and elaborate on a common understanding and rationality about a transcending phenomena to inform a strategy for integration between technology management and socio-technical transitions.	5	In Chapter 5, the key epistemic and methodological grounds of socio-technical transitions and technology management are explored. This, along with the views from the respective bodies of literature that could assist in addressing the challenges faced by technology management and socio-technical transitions respectively, informed the elements around which a 'meta-perspective' was developed. Thus, it emerged that a premise for integration between technology management and socio-technical transitions should: (i) go beyond the ordering of either technology management or socio-technical transitions; (ii) facilitate in dealing with complexity; (iii) support the development of strategic, tactical and operational goals that will enable/facilitate the transitioning of socio-technical systems; (iv) contribute towards the operationalising and institutionalising of the concept of transitions; (v) support the idea of a set of core rationales and/or activities; and (iv) develop and exploit (the required) capabilities within a socio-technical system that will support transitioning towards increasingly sustainable futures. Any concept that transcends technology management and socio-technical transitions was thus conceived as the development and exploitation of the capability of a system to transition. Such a concept should be purposefully oriented towards improving our understanding of decision-making that will develop and exploit the capability of a socio-technical system to transition, and for the transition to progress and hence not fail. Two key questions that must be addressed when further conceptualising the aforementioned are: (i) what are the appropriate perspectives and/or unit of analysis that will allow for linkages to be established between socio-technical transitions and technology management?; and (ii) how does one identify the technology management considerations required that will contribute towards socio-technical transitions? The guiding principles and guiding questions briefly outlined above (and discussed in Section 5.2.3) provided the elements around which an integrated meta-perspective may be articulated.

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SUB-RESEARCH OBJECTIVES	CHAPTER	CHAPTER SUMMARY AND EVALUATION OF THE OBJECTIVES ATTAINED
RO3.2: To formulate an integration strategy that transcends technology management and socio-technical transitions.	6	In Chapter 6 an integration strategy in the form of a set of requirement specifications that any construct that aims to provide a premise for the integration between technology management and socio-technical transitions should adhere to, was developed. The requirement specification consists of 11 functional requirements, four user requirements, four design restrictions, four attention points and three boundary conditions. The integration strategy proposed in this chapter is primarily intended to act as a vehicle for bridging between technology management and socio-technical transitions as it is argued to be interpretively flexible enough for the mobilisation of different kinds of information offered by the various approaches to be incorporated into a framework, yet specific enough to enable systematic analysis and cumulative knowledge development. On a more practical level, the integration strategy (i.e. requirement specification) facilitates the capturing of the rich multiplicity of socio-technical transitions, and selectively identifies and evaluates opportunities to elucidate the role that technology management can play in structuring and moderating the dynamics of transitions.
Research objective 4: To develop and evaluate a conceptual framework and methodology that transcends technology management and socio-technical transitions in order to contribute towards increasingly effective and efficient management practices within the context of socio-technical transitions.		
RO4.1: To develop a conceptual framework that provides the conceptual framings of a premise for the integration of technology management and socio-technical transitions.	7	The ITMST framework is proposed as the designed result of the requirement analysis presented in Chapters 5 and 6. The framework consists of five key features, namely: (i) transition value creation, (ii) collective and individual consideration of transition progress, transition capability and system performance, (iii) co-management of incumbent and emerging/alternative technology domains, (iv) context-specificity, and (v) contribution-requirement view that collectively provide the premise for the integration between technology management and socio-technical transitions.
RO4.2: To operationalise the developed conceptual framework through the development of a methodology that outlines the practicability of the framework.	8	The focus of Chapter 8 is on the ITMST framework as a methodology, in contrast with the presented constructs in Chapter 7 focussing on the conceptual framing of a premise for the integration between technology management and socio-technical transitions. The ITMST methodology outlines the practicability of the framework and provides a basis for the definition and identification of technology management considerations within the context of socio-technical transitions.

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SUB-RESEARCH OBJECTIVES	CHAPTER	CHAPTER SUMMARY AND EVALUATION OF THE OBJECTIVES ATTAINED
RO 4.3: To verify and validate the developed framework and methodology in order to evaluate whether the developed framework and methodology are fit for their intended purpose and are practicable.	9	The evaluation (i.e., verification and validation) of the developed framework and methodology was done in Chapter 9. The verification of the framework was based on the set of requirements that was developed in Chapter 6, as well as on the theoretical verification of the framework. For validation purposes, a case study was subsequently performed to provide confidence in the applicability and practicability of the developed framework and methodology. Through the theoretical verification a number of framework refinements emerged that was incorporated into the framework and methodology presented in Chapters 7 and 8. Ultimately, the evaluation approach looked to address whether the ITMST framework and methodology (i) provide a premise for the integration between technology management and socio-technical transitions, and (ii) provide the basis for the definition and identification of technology management considerations within the context of socio-technical transitions. These were addressed through the literature, theoretical verification, the operationalisation of the framework and the case study. The case study findings showcased that the ITMST methodology provide a basis for the definition and identification of technology management considerations within the context of sustainability transitions. And, the evaluation of the validity and applicability of the ITMST framework, along with the theoretical verification, highlighted that the ITMST framework provide a premise for the integration between technology management and socio-technical transitions.

10.2 Meta-insights

The following meta-insights emerged from retrospective reflection on the research process and the research outputs, and specifically also on the ITMST framework and methodology.

The ITMST framework and methodology were developed through a combination of mutually exclusive literature reviews, and subsequent synthesising of the literature. The framework and methodology underwent an evaluation process to confirm theoretical consistency of the framework, as well as the applicability and validity of the developed framework and methodology. Feedback from the evaluation process resulted in refinements and updates being made to the research products. The evaluation process further provided valuable insights into the strengths and limitations of the ITMST framework and methodology.

The utility of the developed framework and methodology is derived from the integrative nature and comprehensiveness of the research products. It is argued that the value of the framework is brought to light through these characteristics. As mentioned in Chapter 9, the framework and methodology is as simple as possible, without being simplistic and one-dimensional, and is clear about on what basis simplifications are made to ensure that one may substantiate any conclusions that are drawn from it. The framework provides an integrated perspective on technology management within the context of socio-technical transitions, as well as the necessary complementary perspectives from which to analyse and understand the requirements form the management of technology when aiming to support and/or facilitate a socio-technical transition. The framework further also guides and moderates the different perspectives of technology management and socio-technical transitions. The applicability of the framework and methodology has already been proven in the application of the framework and methodology to the South African electricity system. The framework and methodology not only provides for an integrative perspective between technology management and socio-technical transitions, but also provides for complementary and nuanced analysis of the interaction between regimes and emerging or alternative niches, as well as the interactions between the (process of a) transition and the regime and emerging/alternative niches respectively. The framework links familiar concepts in such a manner that clarifies the relationships between socio-technical system elements, technology management elements and a larger context.

As discussed in Chapter 1, a constructivist philosophical perspective is embraced in this study. In addition, practical utility is highlighted as a key objective. Given this constructivist perspective alongside practice-oriented focus, the research products had to attain two goals: (i) an appropriate way to integrate technology management and socio-technical transitions that is more informed and more sophisticated than what previously existed had to be developed to satisfy the constructivist perspective; and, (ii) the developed research product(s) had to have practical value. Given the comprehensive investigation into the extent to which technology management and socio-technical transitions have been integrated, and the conclusion that no concrete evidence of integration or significant similarity in foundational concepts used in both bodies of literature exist, it is evident that the IMTST framework represents, by nature of novelty, more informed and more sophisticated than what previously existed. However, the theoretical validation that saw the framework being scrutinised by SMEs, and the validation process further confirmed the ITMST framework and methodology to be a nuance and sophisticated way to present a premise for the integration between technology management and socio-technical transitions.

In terms of practical utility, by means of the case study it was showcased that the ITMST methodology (which encompasses the key features of the ITMST framework) can guide and facilitate the process of adequately evaluating a socio-technical system in transition and that the foundational concepts used guides the definition and identification of technology management considerations within the context of socio-technical transitions.

The limitations outlined in Section 1.6.2 also embodies the limitations of the ITMST framework and methodology, and is again reflected on here. Even though the ITMST framework and methodology does hold practical utility, it does not provide explicit management practices, tools and techniques. Even though the development of such tools and techniques does not fall within the scope of this research study, nor is the absence of such tools considered to subtract from the value of the developed framework and methodology in terms of the stated research aim and objectives. However, elaborating on the work presented in this dissertation to extend to such explicit management tools and techniques will further the practical utility of the ITMST framework and methodology. This is also highlighted in Section 10.4 as an opportunity for future research.

The application of the developed framework and methodology at (i) a lower and/or increasingly aggregate levels of analysis (i.e., at sub-systems level and/or at, for example, across multiple systems), and (ii) in a developed and/or Western county contexts have not been evaluated. Such evaluations will be valuable in order to develop further nuanced understandings of the transferability of the ITMST framework and methodology.

10.3 Contributions

The primary contribution of this dissertation is the ITMST framework presented in Chapter 7. This framework provides a premise for the integration between technology management and socio-technical transitions. As evidenced in Chapters 3 and 4, the integration of socio-technical transitions approaches, concepts, and frameworks with that of technology management theories and practices, and vice versa, are not adequately addressed in literature, and the framework presented in this research thus addresses this knowledge gap.

The ITMST framework goes beyond the general arguments within technology management and socio-technical transitions respectively to outline a set of key features to provide novel guidance on how technology management and socio-technical transitions may be conceptualised in relation to one another. The ITMST framework further provide guidance on how socio-technical transitions and technology management research can advance in a way that addresses critical issues regarding epistemological tensions, problem identification and definition, selection of system boundaries, unit and level of analysis, and the role of technology management research in relation to socio-technical transitions research, and vice versa. Furthermore, even though not within the scope of this research, the ITMST framework and methodology may also provide foundational ideas in relation to governance and policies related to management of technology within the context of socio-technical transitions. The ITMST framework and methodology contribute important insights regarding the potential of taking a nuance view on the management of technology within the contexts on socio-technical transitions for innovative and less destructive practices to emerge due to a more comprehensive and cross-domain, cross-actor understanding of contributions and requirements from regimes and emerging or alternative niches towards transition progress, transition capability, and system performance

The operationalisation of the ITMST framework – presented as the ITMST methodology in Chapter 8 – provides a basis for the definition and identification of technology management considerations within the context of socio-technical transitions. This structured and systematic approach to the analysis of socio-technical systems in transitions that incorporates the foundational features that are required to elucidate the necessary technology management considerations builds on the unique contribution of the ITMST framework by providing a practical perspective to the conceptual nature of the developed framework.

Moreover, the development of the ITMST methodology showcases how a framework within the context of socio-technical transitions may be operationalised. Although the importance of the operationalisation of transitions concepts is highlighted in literature, there exists a lack of operationalised concepts in this field. The ITMST methodology is clear on the particular activities and actions that are required to analyse a system in transition, and results in explicated and concrete action contexts.

The identification that the fields of technology management and socio-technical transitions have not been adequately integrated at a conceptual or theoretical level in itself presents another contribution from this research. As mentioned in Chapter 1, a preliminary investigation indicated that there exists a disconnect in literature between these two fields; however, this was not explicated nor quantified in literature. The bibliometric analysis (Chapter 3) and linkage analysis (Chapter 4) thus provide for contributions towards the fields of technology management and socio-technical transitions as the extent to which (albeit limited) these two fields overlap and share intellectual roots are identified and described.

The research contributes towards the field of technology management in that it positions the field in relation to the field of socio-technical transitions and proposes an approach that draws the wider context of socio-technical systems and transitions closer to the concept of technology management. A specific contribution that is highlighted is the proposition that, in addition to the technological and the commercial perspective, technology management approaches should also include a transitions perspective in order to manage technology, not only towards the attainment of the objectives of an organisation and/or to support the performance of a system within which such technologies are employed, but to also contribute towards the capability of a socio-technical system to transition, and thus to create value for the transition.

The conceptualisation of ‘transition value creation’ specifically contributes an alternative, yet complementary perspective, to existing socio-technical transitions approaches, frameworks and concepts in that it purposefully places the transition in relation to other, more traditional views of value creation. Furthermore, a noteworthy observation from the case study, whilst acknowledging the shortcoming to yet make a generalisation, is that value creation is primarily measured for either the system (i.e. system performance), the environment within which the system exists, or then from an economic point of view (i.e. the creation of value for organisations). The addition of value creation from the perspective of the transitions draws the focus towards the process of transitioning which hereinto has been lacking.

As mentioned in the dissertation, a number of researchers have raised concerns about the lack of non-western representation in the research on issues such as socio-technical transitions, and the applicability of developed concepts to non-western contexts is subsequently questioned. A noteworthy contribution of the research presented in this dissertation is the application of the developed framework and methodology to the South African electricity system, highlighting the applicability to a developing country context.

10.4 Opportunities for future research

This research provided the foundational building blocks for the integration between technology management and socio-technical transitions, but leaves room for additional and complementary research to further the integration, with three paths for further work identified: (i) an empirical path, (ii) a quantitative modelling path, and (iii) further integration between, and with technology management and socio-technical transitions concepts.

This type of multi-dimensional framework is complex by nature. As a qualitative approach, it guides thinking, analysis and understanding of socio-technical transitions and the management of technology within such transitions. Even though an empirical application was done, with more empirical research across different contexts, the identification of some general patterns of technology management considerations and a (possibly limited) set of typical consideration may potentially be theorised. This will further reduce complexity, and guide policy and governance considerations. Furthermore, the application of the ITMST framework and methodology across a number of different contexts will allow for additional insights into the breadth of the applicability of the framework and methodology, as well as facilitate the development of context-specific and/or unique contributions that may be incorporated into the ITMST framework and methodology.

Quantitative modelling (such as system dynamics), will capture the dynamic interactions between the technology domains and transition progress, transition capability and system performance in order to quantify the impact of such considerations across the various elements, and to evaluate different consideration scenarios, especially from a futures perspective (i.e. to inform longer-term planning). Such a modelling approach would result in models that could potentially be used to quantitatively evaluate various parameters that may further identify plausible transition pathways, as well as to quantify risks and opportunities for technology domains, for the system under consideration, and for the transition.

An important area for future research would be further integration across technology management and socio-technical transitions concepts. For example, the various modes of interaction that have been defined between technologies (Pistorius and Utterback, 1997; Sandén and Hillman, 2011) could provide for further clarification on technology management considerations. It is commonly accepted that the mode of interaction between technologies can shift from one mode to another, and it is suggested that specific technology management strategies must be developed for each mode of interaction (Pistorius and Utterback, 1997). It is also important to note that multi-mode interactions between technologies are possible, and technologies can thus interact according to a number of interaction modes. By incorporating these theoretical notions into the ITMST framework and methodology will add further value to the debate about how technology should be managed within the context of transitions.

Also, the ITMST framework may be extended to how organisational strategies may be developed given the insights gained from the incorporation of a transitions perspective and transition value creation. This perspective will also extend to business case development research as traditional value creation will have to be put into relation to transition value creation.

Extending and elaborating on the ITMST framework, to explicitly link to transitions concepts like strategic niche management, innovation systems approaches, and so forth, will enhance the absorption opportunities of the ITMST framework and methodology amongst transitions scholars, as well as to increase the application opportunities of the developed framework and methodology, but also to understand how these existing frameworks and concepts may further contribute towards the debate on technology management and socio-technical transitions.

10.5 Final reflection

The research presented in this dissertation provides a premise for the integration between technology management and socio-technical transitions, and serves as bases on which future studies that are concerned with the management of technology within the context of socio-technical transitions may build. Furthermore, the research presented in this dissertation contributes towards a (much) larger conversation relating to sustainability (i.e., sustainable socio-technical systems), the attainment of sustainability (i.e., socio-technical transitions), and the role of technology within the quest for sustainability.

Bibliography

Ahlborg, H., Ruiz-Mercade, I., Molander, S., and Masera, O. (2019) 'Bringing technology into social-ecological systems research-Motivations for a socio-technical-ecological systems approach', *Sustainability (Switzerland)*, 11(7), pp. 1–23.

Van Aken, J. E., Berends, H. and Van der Bij, H. (2006) *Problem Solving in Organizations: A Methodological Handbook for Business Students*. Cambridge: Cambridge University Press.

Alkemade, F., Frenken, K., Hekkert, M., and Schwoon*, M.* (2009) 'A complex systems methodology to transition management', *Journal of Evolutionary Economics*, 19(4), pp. 527–543.

Baker, L. (2015) 'Renewable energy in South Africa's minerals-energy complex: a "low carbon" transition?', *Review of African Political Economy*, 42(144), pp. 245–261.

Baker, L., Burton, J., Godinho, C., Trollip, H. (2015) 'The political economy of decarbonisation: Exploring the dynamics of South Africa's electricity sector', Energy Research Centre, University of Cape Town.

Ballew, B. S. (2009) 'Elsevier 's Scopus ® Database', Journal of Electronic Resources in Medical Libraries, 6(3), pp.245-252.

Berg, D*.,* Mani, H.S, Marinakis, Y., Tierney, R., and Walsh, S. (2015) 'An introduction to Management of Technology pedagogy (andragogy)', *Technological Forecasting and Social Change*. Elsevier Inc., 100, pp. 1–4.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., and Rincke, A. (2008) 'Analyzing the functional dynamics of technological innovation systems: A scheme of analysis', *Research Policy*, 37(3), pp. 407–429.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., and Truffer, B. (2015) 'Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics', *Environmental Innovation and Societal Transitions*. Elsevier B.V., 16, pp. 51–64.

Bergman, N., Haxeltine, L., Whitmarch, L., Kohler, J., Schilperoord, M. and Rotmans, J. (2008) 'Modelling Socio-Technical Transition Patterns and Pathways', *Journal of Artificial Societies and Social Simulation*, 11(3).

Berkhout, F., Smith, A. and Stirling, A. (2004) 'Socio-technological regime and transition contexts', in Elzen, B., Geels, F. W., and Green, K. (eds) *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*. Cheltenham: Edward Elgar, pp. 48–75.

Bijker, W. E., Hughes, T. P. and Pinch, T. (1989) 'The Social Construction of Technological Systems, Social Studies of Science', *Social tudies of Science, 19(1).*

Binder, C., Mühlemeier, S. and Wyss, R. (2017) 'An Indicator-Based Approach for Analyzing the Resilience of Transitions for Energy Regions. Part I: Theoretical and Conceptual Considerations', *Energies*, 10(1), p. 36.

Bocken, N. M. P., Short, S., Rana, P. and Evans, S. (2014) ‘A literature and practice review to develop sustainable business model archetypes’, *Journal of Cleaner Production*. Elsevier Ltd, 65, pp. 42–56.

Boehm, B. (1984) ‘Verifying and validating software requirements and design specifications’, *IEEE Software*, 1(1).

Brent, A. C. and Pretorius, M. W. (2008) ‘Sustainable development: A conseltual framework for the technology management field of knowledge and a departure for further research, *South African Journal of Industrial Engineering*, 19(June), pp. 31–52.

Brundtland, G. H. (1987) *Report of the World Commission on Environment and Development: Our Common Future. World Commission on Environment and Development.* NewYork: United Nations.

Brynjolfsson, E. and McAffee, A. (2014) *The Second Machine Age*. New York: Norton.

Carlsson, B., Jacobsson, S., Holmén, M., Rinke, A.(2002) ‘Innovation systems: analytical and methodological issues’, *Research Policy*, 31, pp. 233–245.

Casper, S. (2013) ‘New-technology clusters and public policy: Three perspectives’, *Social Science Information*, 52(4), pp. 628–652.

Centidamar, D., Phaal, R. and Probert, D. (2010) *Technology Management Activities and Tools*. London: Palgrave MacMillan.

Centobelli, P., Cerchione, R. and Esposito, E. (2018) ‘Environmental sustainability and energy-efficient supply chain management: A review of research trends and proposed guidelines’, *Energies*, 11(275).

Cetindamar, D., Phaal, R. and Probert, D. (2009) ‘Understanding technology management as a dynamic capability: A framework for technology management activities’, *Technovation*, 29(4), pp. 237–246.

Cetindamar, D., Phaal, R. and Probert, D. (2010) *Technology Management, Activities and Tools*. Basingstoke, UK: Palgrave MacMillan.

Cetindamar, D., Phaal, R. and Probert, D. R. (2016) ‘Technology management as a profession and the challenges ahead’, *Journal of Engineering and Technology Management - JET-M*. Elsevier B.V., 41(June 2011), pp. 1–13.

Chappin, E. J. L. and Ligtvoet, A. (2014) ‘Transition and transformation: A bibliometric analysis of two scientific networks researching socio-technical change’, *Renewable and Sustainable Energy Reviews*, 30, pp. 715–723.

Chorn N (1998) ‘The Alignment Theory: Creating Strategic Fit’, *Management Descisions*, 29(1), pp. 1–5.

Cock, J. and Fraser, D. (2019) ‘Who will make the energy transition just?’, *Daily Maverick*, pp. 1–10.

Coenen, L. and Díaz López, F. J. (2010) ‘Comparing systems approaches to innovation and technological change for sustainable and competitive economies: An explorative study into conceptual commonalities, differences and complementarities’, *Journal of Cleaner Production*. Elsevier Ltd, 18(12), pp. 1149–1160.

Cohen, M. J. (2012) ‘The future of automobile society: a socio-technical transitions perspective’, *Technology Analysis & Strategic Management*, 24(4), pp. 377–390.

Crabtree, B. and Miller, W. (1999) *Doing qualitative research*. Second. Newbury Park, CA: SAGE.

Daim, T. U., Rueda, G., Martin, H., Gerdsri, P. (2006) ‘Forecasting emerging technologies: Use of bibliometrics and patent analysis’, *Technological Forecasting and Social Change*, 73, pp. 981–1012.

Department of Energy (2018) *Draft Integrated Resource Plan 2018*. Available at: http://www.energy.gov.za/IRP/irp-update-draft-report2018/IRP-Update-2018-Draft-for-Comments.pdf.

Department of Energy (2019) ‘Draft IRP 2018 Update for NEDLAC Energy Task Team’, (March 2018).

Department of Environmental Affairs (2012) *National climate change response White Paper*.

De Haan, F. J., Ferguson, B., Adamowicz, R., Johnstone, P., Brown, R. R., and Wong, T.H.F. (2014) 'The needs of society : A new understanding of transitions , sustainability and liveability’, *Technological Forecasting & Social Change*. Elsevier Inc., 85, pp. 121–132.

De Haan, F. J. and Rogers, B. C. (2019) ‘The Multi-Pattern Approach for systematic analysis of transition pathways’, *Sustainability (Switzerland)*, 11(2), pp. 1–30.

De Haan, J. (2010) 'Towards Transition Theory Towards Transition Theory', Duch Research Institution for Transitions, Erasmus Universiteit Rotterdam.

De Haan, J. and Rotmans, J. (2011) ‘Patterns in transitions: Understanding complex chains of change’, *Technological Forecasting and Social Change*. Elsevier Inc., 78(1), pp. 90–102.

De Kock, I. H. and Brent, A. C. (2017a) ‘New insights into socio-technical transitions: A technology management perspective’, in *2017 IEEE Technology and Engineering Management Society Conference, TEMSCON 2017*. Palo Alto, pp. 329–334.

De Kock, I. H. and Brent, A. C. (2017b) ‘Technology management from a socio-technical transitions perspective’, in *International Association for the Management of Technology (IAMOT)*. Vienna.

De Wet, G. (2001) ‘Technology space maps fot technology management and audits’, *The University of Pretoria, Faculty of Engineering, South Africa*.

Dewulf, A., Termeer, C.J.A.M, Werkman, R., Beerman, G. (2009) *Transition management for sustainability: towards a multiple theory approach*, *Transitions towards sustainable agriculture and food chains in peri-urban areas*.

Doci, G., Vasileiadou, E. and Petersen, A. C. (2015) ‘Exploring the transition potential of renewable energy communities’, 66, pp. 85–95.

Dolata, U. (2008) ‘The Transformative Capacity of New Technologies. How Innovations Affect Sectoral Change: Conceptual Considerations’.

Dolata, U. (2013) *The Transformative Capacity of New Technologies*. New York: Routledge.

Dym, B. and Hutson, H. (2012) ‘Theoretical Alignment’, in *Leadership in Nonprofit Organizations*. SAGE Publications, pp. 35–46.

Eberhard, A. and Naude, R. (2017) *The South African renewable energy IPP procurement programme*.

Edquist, C. (2005) ‘Systems of innovation: Perspectives and challenges’, in Fagerberg, J., Mowery, D. C., and Nelson, R. R. (eds) *The Oxford Handbook of Innovation*. Oxford: Oxford University Press, pp. 181–208.

Ehnert, F., Frantzeskaki, N., Barnes, J., Borgstörm, S., Gorissen, L., Kern, F., Strenchock, L., and Egermann, M. (2018) ‘The acceleration of urban sustainability transitions: A comparison of Brighton, Budapest, Dresden, Genk, and Stockholm’, *Sustainability (Switzerland)*, 10(3), pp. 1–25.

Elkington (1994) ‘Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development’, *iness Strategies for Sustainable Development,"*, 36(2), pp. 90–100.

Elkington, J. (1998) ‘Partnerships from cannibals with forks: The triple bottom line of 21st-century business’, *Environmental quality management*, 8(1).

Elzen, B., Geels, F. W. and Green, K. (2004) *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy,*. Cheltenham: UK: Edward Elgar.

Energy Transition Commission (2016) 'Shaping energy transitions', *Position Paper of the Energy Transition Comission,* April 2016.

Energy Transitions Commission (2017) *Achievable pathways to low-carbon energy systems*. Available at: www.energy-transition.org.

Enkel, E., Gassmann, O. and Chesbrough, H. (2009) ‘Open R&D and open innovation: Exploring the phenomenon’, *R and D Management*, 39(4), pp. 311–316.

ERC, CSIR and IFPRI (2017) *The developing energy landscape in South Africa : Technical Report*.

Farrington, T. and Crews, C. (2013) ‘The IRI 2038 scenarios. Research Technology Management 56 (6), 23–32’, *Research Technology Management*, pp. 23–32.

Fleck, J. (2008) ‘Technology and the business school world’, *Journal of Management Development*, 27(4), pp. 415–424.

Fleck, J. and Howells, J. (2001) ‘Technology, the Technology Complex and the Paradox of Technological Determinism’, *Technology Analysis & Strategic Management*, 13(4), pp. 523–531.

Foxon, T. and Pearson, P. (2008) ‘Overcoming barriers to innovation and diffusion of cleaner technologies: Some features of a sustainable innovation policy regime’, *Journal of Cleaner Production*, 16, pp. 148–161.

Frantzeskaki, N. and de Haan, H. (2009) ‘Transitions: Two steps from theory to policy’, *Futures*, 41(9), pp. 593–606.

Fuenfschilling, L. and Truffer, B. (2013) ‘The structuration of socio-technical regimes-Conceptual foundations from institutional theory’, *Research Policy*. Elsevier B.V., 43(4), pp. 772–791.

Gann, D. M. and Salter, A. J. (2000) ‘Innovation in project-based, service-enhanced firms: the construction of complex products and systems’, *Research Policy*, 29(7–8), pp. 955–972.

Garud, R., Gehman, J. and Karnoe, P. (2010) ‘Categorization by association: nuclear technology and emission-free electricity’, in Sine, W. D. and David, R. (eds) *Research in the Sociology of Work*. Bingley, UK: Emerald Group Publishing Ltd., pp. 51–93.

Gay, B. and Weaver, S. (2011) ‘Theory Building and Paradigms: A Primer on the Nuances of Theory Construction’, *American International Journal of Contemporary Research*, 1(2), pp. 24–32.

Geels, F., Hekkert, M. and Jacobsson, S. (2008) ‘The dynamics of sustainable innovation journeys: Introduction to the special issue’, *Technology Analysis & Strategic Management*, 20, pp. 521–536.

Geels, F. and Raven, R. (2006) ‘Non-linearity and expectations in niche-development trajectories: Ups and downs in Dutch biogas development (1973-2003)’, *Technology Analysis & Strategic Management*, 18(3–4), pp. 375–392.

Geels, F. W. (2002) 'Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study', 31, pp. 1257–1274.

Geels, F. W. (2004) 'From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory', *Research Policy*, 33(6–7), pp. 897–920.

Geels, F.W. (2005) *Technological Transitions and System Innovations: a Co- evolutionary and Socio-technical Analysis*. Cheltenham, UK: Edward Elgar Publishing Ltd.

Geels, F. W. (2005) 'The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930)', *Technology Analysis & Strategic Management*, 17(4), pp. 445–476.

Geels, F. W. (2006) 'Co-evolutionary and multi-level dynamics in transitions : The transformation of aviation systems and the shift from propeller to turbojet (1930 – 1970)', 26, pp. 999–1016.

Geels, F. W. (2011) 'The multi-level perspective on sustainability transitions: Responses to seven criticisms', *Environmental Innovation and Societal Transitions*, 1(1), pp. 24–40.

Geels, F. W. (2012) 'A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies', *Journal of Transport Geography*. Elsevier Ltd, 24, pp. 471–482.

Geels, F. W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M., and Wasserman, S. (2016) 'The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014)', *Research Policy*. Elsevier B.V., 45(4), pp. 896–913.

Geels, F. W. (2018) 'Energy Research & Social Science Disruption and low-carbon system transformation : Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective', *Energy Research & Social Science*. Elsevier, 37(September 2017), pp. 224–231.

Geels, F. W. and Schot, J. (2007) 'Typology of sociotechnical transition pathways', *Research Policy*, 36(3), pp. 399–417.

Genus, A. and Coles, A.M. (2007) 'A critique of Geels' multi-level perspective of technological transition', in *International Summer Academy on Technology Studies, 27-31 August 2007, Deutschlandsberg*.

Gregory, M. J. (1995) 'Technology management: a process approach', in *Proceedings of the Institution of Mechanical Engineers, Part B*, pp. 347–356.

Grin, J., Rotmans, J. and Schot, J. (2010) 'Transitions to sustainable development: new directions in the study of long term transformative change', (1).

Groen, A. J. and Walsh, S. T. (2013) 'Introduction to the Field of Emerging Technology Management', *Creativity and Innovation Management*, 22(1), pp. 1–5.

Grübler, A. (2003) *Technology and Global Change*. Cambridge University Press.

Haines, J. D. and Sharif, N. M. (2006) 'A framework for managing the sophistication of the components of technology for global competition', *Competitiveness Review: An International Business Journal incorporating Journal of Global Competitiveness*, 16(2), pp. 106–121.

Halsey, R. (2018) 'Job-figures fantasies drain the power form national electricity plan hearings', *Daily Maverick*.

Hamilton, W. F. (1997) ‘Managing technology as a strategic asset’, *International Journal of Technology Management (IJTM)*, 14(2/3/4).

Hang, C., Chen, J. and Subramian, A. M. (2010) ‘Developing Disruptive Products For Emerging Economies : Lessons From Asian Cases’, *Research Technology Management*, 53(4), pp. 21–26.

Hansen, T. and Coenen, L. (2014) ‘The geography of sustainability transitions: Review , synthesis and reflections on an emergent research field Environmental Innovation and Societal Transitions The geography of sustainability transitions Elsevier B.V., (January).

Hara, K., Uwasu, M., Kobayashi, H., Kurimoto, S., Shimoda, Y. and Umeda, Y. (2012) ‘Enhancing meso level research in sustainability science-challenges and research needs’, *Sustainability*, 4(8), pp. 1833–1847.

Hecher, M., Vilsmaier, U., Akhavan, R., and Binder, C.R. (2016) ‘An integrative analysis of energy transitions in energy regions: A case study of ökoEnergieland in Austria’, *Ecological Economics*, 121, pp. 40–53.

Hekkert, M. P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M. (2007) ‘Functions of innovation systems: A new approach for analysing technological change’, *Technological Forecasting and Social Change*, 74(4), pp. 413–432. doi: 10.1016/j.techfore.2006.03.002.

Hekkert, M. P., Negro, S., Heimmeriks, G., and Harmsen, R. (2011) ‘Technological Innovation System Analysis: a manual for analysts’, *Utrecht University*, (November).

Hekkert, M. P. and Negro, S. O. (2011) *Understanding technological change: explanation of different perspectives on innovation and technological change*. Utrecht. Available at: http://www.innovation-system.net/wp-content/uploads/2013/03/UU_01rapport_uUnderstanding_Technological_Change.pdf.

Hillman, K., Nilsson, M., Rickne, A., and Magnusson, T. (2011) ‘Fostering sustainable technologies: A framework for analysing the governance of innovation systems’, *Science and Public Policy*, 38(5), pp. 403–415.

Horwitch, M. and Stohr, E. (2008) ‘Transforming technology management education: Value creation-learning in the early twenty-first century’, *Journal of Engineering and Technology Management*, 29(4), pp. 2015–2026.

Howells, J. (2005) *The Management of Innovation & Technology*, *The Shaping of Technology and Institutions of the Market Economy*. SAGE Publications.

Hughes, T. (1987) ‘The evolution of large technological systems’, in *The Social Construction of Technological Systems*. Cambridge: The MIT Press, pp. 51–82.

Huxham, M., Muhammed, A. and Nelson, D. (2019) ‘Understanding the impact of a low carbon transition on South Africa’, (March).

Ireland, G. and Burton, J. (2018) *An assessment of new coal plants in So uth Africa ’ s electricity future programme*. Cape Town, South Africa.

Ittipanuvat, V., Fujita, K. Sakata, I., and Kajikawa, Y. (2014) ‘Finding linkage between technology and social issue: A Literature Based Discovery approach’, *Journal of Engineering and Technology Management - JET-M*. Elsevier B.V., 32, pp. 160–184.

Jabareen, Y. (2009) ‘Building a Conceptual Framework : Philosophy , Definitions , and Procedure’, pp. 49–62.

Jacobsson, S. and Bergek, A. (2010) ‘Innovation system analyses and sustainability transitions: contributions and suggestions for research.’, *Environmental Innovation and Societal Transitions*, 1(1), pp. 41–57.

Jacobsson, S. and Bergek, A. (2011) ‘Innovation system analyses and sustainability transitions: Contributions and suggestions for research’, *Environmental Innovation and Societal Transitions*. Elsevier B.V., 1(1), pp. 41–57.

Jacobsson, S. and Johnson, A. (2000) ‘The diffusion of renewable energy technology: An analytical framework and key issues for research’, *Energy Policy*, 28(9), pp. 625–640.

Jin, J. and von Zedtwitz, M. (2008) ‘Technological capability development in China’s mobile phone industry’, *Technovation*, 28(6), pp. 327–334.

Jorgenson, D., Goettle, R., Sing Hoc, M., and Wilcoxen, P. (2009) ‘Cap and trade climate policy and U.S. economic adjustments’, *Journal of Policy Modeling*, 31, pp. 362–381.

Jovanovic, M., Rakicevic, J., Jaksic, M., Petkovic, J., and Marinkovic, S. (2019) ‘Composite Indices in Technology Management’, in *Disruptive Technology*. Hershey PA, USA: IGI Global, pp. 1860–1893.

Kasser, J., John, P. and Weng, Y. (2008) ‘Systems Engineering a 21st Century Introductory Course on Systems Engineering: The Saraswati Project.’, in *Asia Pacific Conference on Systems Engineering*.

Kemp, R., Loorbach, D. and Rotmans, J. (2007) ‘Transition management as a model for managing processes of co-evolution towards sustainable development’, *International Journal of Sustainable Development and World Ecology*, 14(1), pp. 78–91.

Kemp, R., Schot, J. and Hoogma, R. (1998) ‘Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management’, *Technology Analysis & Strategic Management*, 10(2), pp. 175–198.

Kennon, D. (2017) *Towards an Antifragile South African SME*. Stellenbosch University.

Kerr, C., Farrukh, C., Phaal, R., and Probert, D.. (2013) ‘Key principles for developing industrially relevant strategic technology management toolkits’, *Technological Forecasting and Social Change*. Elsevier Inc., 80(6), pp. 1050–1070.

Kim, S. K. (2013) ‘General framework for management of technology evolution’, *Journal of High Technology Management Research*. Elsevier Inc., 24(2), pp. 130–137.

Kim, W. (2015) ‘The current transition in management of technology education: The case of Korea’, *Technological Forecasting and Social Change*. Elsevier Inc., 100(December), pp. 5–20.

Kivimaa, P., Boon, W., Hyysalo, S., Klerkx, L. (2018) ‘Towards a typology of intermediaries in sustainability transitions: A systematic review and a research agenda’, *Research Policy*. Elsevier, 48(4), pp. 1062–1075.

Kivimaa, P., Hyysalo, S., Boon, W., Klerkx, L., Martiskainen, M., and Schot, J. (2019) ‘Passing the baton: How intermediaries advance sustainability transitions in different phases’, *Environmental Innovation and Societal Transitions*. Elsevier, (November 2018), pp. 1–16.

Klavans, R. and Boyack, K. W. (2006) ‘Identifying a better measure of relatedness for mapping science’, *Journal of the American Society for Information Science and Technology*, 52(2), pp. 251–263.

Klein Woolthuis, R., Lankhuizen, M. and Gilsing, V. (2005) ‘A system failure framework for innovation policy design’, *Technovation*, 25(6), pp. 609–619.

Köhler, J. *et al.* (2019) ‘An agenda for sustainability transitions research: State of the art and future directions’, *Environmental Innovation and Societal Transitions*, 31, pp. 1–66.

Kungl, G. and Geels, F. W. (2018) ‘Sequence and alignment of external pressures in industry destabilisation: Understanding the downfall of incumbent utilities in the German energy transition (1998–2015)’, *Environmental Innovation and Societal Transitions*. Elsevier, 26(January 2017), pp. 78–100.

Lachman, D. A. (2013) ‘A survey and review of approaches to study transitions’, *Energy Policy*. Elsevier, 58, pp. 269–276.

Lachman, D. A. (2014) ‘A combination of existing concepts and approaches to take on energy system transitions - The Republic of Panama as a case-study’, *Sustainable Energy Technologies and Assessments*, 5, pp. 84–94.

La Nauze, R. and Shodde, R. . (2004) *Managing Technology Development in a Changing Business Environment, Improving and Optimizing Operations:Things That Acutall Work! Plant Operators Forum*.

Lee, H., Kim, N., Kwak, K., Kom, W., Soh, H., and Park, K. (2016) ‘Diffusion Patterns in convergence among high-technology industries: A co-occurrence-based analysis of newspaper article data’, *Sustainability (Switzerland)*, 8(10).

Leedy, P. D. and Ormrod, J. E. (2013) *Practical Research*. Tenth. Pearson Education, Inc.

Li-Hua, R. and Khalil, T. (2006) ‘Technology Management in China: A Global Perspective and Challenging Issues’, *Journal of Technology Management in China*, 1(1), pp. 9–26.

Linton, J. D. and Thongpapanl, N. (2004) ‘Perpective: Ranking the Technology Innovation Management Journals’, *Journal of Product Innovation Management*, 21(2), pp. 123–139.

Liu, X. and White, S. (2001) ‘Comparing innovation systems: A framework and application to China’s transitional context’, *Research Policy*, 30, pp. 1091–1114.

Loorbach, D. (2004) ‘Governance and Transitions: A multi-level policy-framework based on complex systems thinking Paper’, *Conference on Human Dimensions of Global Environmental Change*, pp. 1–19.

Loorbach, D. (2010) ‘Transition management for sustainable development: A prescriptive, complexity-based governance framework’, *Governance*, 23(1), pp. 161–183.

Loorbach, D. (2014) *To Transition! Governance Panarchy in the New Transformation*.

Loorbach, D., Frantzeskaki, N. and Avelino, F. (2017) ‘Sustainability Transitions Research: Transforming Science and Practice for Societal Change’, *Annual Review of Environment and Resources*, 42(1), pp. 599–626.

Loorbach, D. and Wijsman, K. (2013) ‘Business transition management: exploring a new role for business in sustainability transitions’, *Journal of Cleaner Production*, 45, pp. 20–28.

Lopolito, A., Morone, P. and Sisto, R. (2011) ‘Innovation niches and socio-technical transition: A case study of bio-refinery production’, *Futures*. Elsevier Ltd, 43(1), pp. 27–38.

Markard, J., Raven, R. and Truffer, B. (2012) ‘Sustainability transitions: An emerging field of research and its prospects’, *Research Policy*. Elsevier B.V., 41(6), pp. 955–967.

Markard, J., Suter, M. and Ingold, K. (2016) ‘Socio-technical transitions and policy change - Advocacy coalitions in Swiss energy policy’, *Environmental Innovation and Societal Transitions*. Elsevier B.V., 18, pp. 215–237.

Markard, J. and Truffer, B. (2008) ‘Actor-oriented analysis of innovation systems: exploring micro–meso level linkages in the case of stationary fuel cells’, *Technology Analysis & Strategic Management*, 20(4), pp. 443–464.

Meelen, T. and Farla, J. (2013) ‘Towards an integrated framework for analysing sustainable innovation policy’, *Technology Analysis and Strategic Management*, 25(8), pp. 957–970.

Meredith, J. (1993) ‘Theory Building through Conceptual Methods’, *International Journal of Operations & Production Management*, 13(5), pp. 3–11.

Moldan, B., Janoušková, S. and Hák, T. (2012) ‘How to understand and measure environmental sustainability: Indicators and targets’, *Ecological Indicators*, 17, pp. 4–13.

Mouton, J. (2013) *How to succeed in your Master’s & Doctoral Studies*. 18th edn. Edited by M. Hittge and A. Thorne. Van Schaik Publishers.

Mühlemeier, S., Binder, C. R. and Wyss, R. (2017) ‘No Title’, *GAIA: Ecological Perspectives for Science and Societ*, 26, pp. 161–224.

Murmann, J. P. and Frenken, K. (2006) ‘Toward a systematic framework for research on dominant designs, technological innovations, and industrial change’, *Research Policy*, 35(7), pp. 925–952.

Musango, J. K. and Brent, A. C. (2011) ‘A conceptual framework for energy technology sustainability assessment’, *Energy for Sustainable Development*. International Energy Initiative, 15(1), pp. 84–91.

National Research Council (1987) *Management of Technology: The Hidden Competitive Advantage*. Washington, DC: National Academy Press.

OECD (2005) *Oslo Manual Guidelines for Collecting and Interpreting Innovation Data, 3rd edition*. Paris.

Pacey, A. (1983) *The Culture of Technology*. Cambridge, Massachusetts: The MIT Press.

Panetti, E., Parmentola, A., Wallis, S. E., and Feretti, M. (2018) ‘What drives technology transitions? An integration of different approaches within transition studies’, *Technology Analysis and Strategic Management*. Taylor & Francis, 30(9), pp. 993–1014.

Papachristos, G. (2014) ‘Towards multi-system sociotechnical transitions: why simulate’, *Technology Analysis & Strategic Management*, 26(9), pp. 1037–1055.

Papachristos, G., Sofianos, A. and Adamides, E. (2013) ‘System interactions in socio-technical transitions: Extending the multi-level perspective’, *Environmental Innovation and Societal Transitions*. Elsevier B.V., 7, pp. 53–69.

Paredis, E. (2011) ‘Sustainability transitions and the nature of technology’, *Foundations of Science*, 16(2–3), pp. 195–225.

Patton, M. . (2002) *Qualitative research and evaluation methods*. Third. Thousand Oaks, CA: SAGE.

Phaal, R, O'Sullivan, E., Routley, M., Ford, S., and Probert, D. *et al.* (2011) ‘A framework for mapping industrial emergence’, *Technological Forecasting and Social Change*. Elsevier Inc., 78(2), pp. 217–230.

Phaal, R, Farrukh, C. J. P. and Probert, D. R. (2004) ‘No Title’, *Journal of Technology Management*, 27(1), pp. 1–15.

Phaal, R., Farrukh, C. J. P. and Probert, D. R. (2006) ‘Technology management tools: Concept, development and application’, *Technovation*, 26(3), pp. 336–344.

Phaal, R., Farrukh, C. J. and Probert, D. R. (2004) ‘A framework for supporting the management of technological knowledge', *Journal of Technology Management*, 27(1), pp. 1–15.

Philbin, S. P. (2013) 'Emerging requirements for technology management: A sector-based scenario planning approach', *Journal of Technology Management and Innovation*, 8(3), pp. 34–44.

Pilkington, A. (2014) 'Technology management: A comprehensive bibliometric analysis', in *IEEE International Technology Management Conference*. Chicago, IL, USA: IEEE.

Pilkington, A. and Teichert, T. (2006) 'Management of technology: themes, concepts and relationships', *Technovation*, 26(3), pp. 288–299.

Pistorius, C. W. I. and Utterback, J. M. (1997) 'Multi-mode interaction among technologies', *Research Policy*, 26, pp. 67–84.

Pittaway, L., Robertson, M., Munir, K., Denyer, D., and Neely, A. (2004) *Networking and innovation: a systematic review of the evidence*, *International Journal of Management Reviews*. London: Advanced Institute of Management Research.

Popp, D. (2001) 'The effect of new technology on energy consumption', *Resource and Energy Economics*, 23, pp. 215–239.

Porter, A. L. and Rafols, I. (2009) 'Is science becoming more interdisciplinary? Measuring and mapping six research fields over time', *Scientometrics*, 81(3), pp. 719–745.

Raven, R. P. J. M. and Geels, F. W. (2010) 'Socio-cognitive evolution in niche development: Comparative analysis of biogas development in Denmark and the Netherlands (1973-2004)', *Technovation*, 30(2), pp. 87–99.

Raven, R. and Walrave, B. (2018) 'Overcoming transformational failures through policy mixes in the dynamics of technological innovation systems', *Technological Forecasting and Social Change*. Elsevier, (May).

Rip, A and Kemp, R. (1998) 'Technological Change', *Human Choice and Climate Change*, pp. 327–399.

Roberts, D. (2019) *The global transition to clean energy*, *Vox*. Available at: https://www.vox.com/energy-and-environment/2019/6/18/18681591/renewable-energy-china-solar-pv-jobs.

Roberts, J. C. D. (2017) 'Discursive destabilisation of socio-technical regimes: Negative storylines and the discursive vulnerability of historical American railroads', *Energy Research and Social Science*. Elsevier, 31(October 2016), pp. 86–99.

Roberts, K. H. and Grabowski, M. (1996) 'Organizations, Technology and Structuring', in Clegg, S. R., Hardy, C., and Nord, W. R. (eds) *Managing Organizations, Current Issues*. SAGE Publications, pp. 159–172.

Rotmans, J., Kemp, R. and Van Asselt, M. (2001) 'More evolution than revolution: transition management in public policy', *Foresight*, 3(1).

Safarzyńska, K., Frenken, K. and Van Den Bergh, J. C. J. M. (2012) 'Evolutionary theorizing and modeling of sustainability transitions', *Research Policy*, 41(6), pp. 1011–1024.

Sakata, I., Sasaki, H., Akiyama, M., Yuriko, S., Shibata, N., Kajikawa, Y. (2013) 'Bibliometric analysis of service innovation research: Identifying knowledge domain and global network of knowledge', *Technological Forecasting and Social Change*. Elsevier Inc., 80(6), pp. 1085–1093.

Sandén, B. A. and Hillman, K. M. (2011) 'A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden', *Research Policy*, 40(3), pp.

403–414.

Sarin, S., Haon, C. and Belkhouja, M. (2018) ‘Guest Editorial A Bibliometric Analysis of the Knowledge Exchange Patterns Between Major Technology and Innovation Management Journals (1999–2013), 35(1), pp. 2–8.

Savaget, P., Geissdoerfer, M., Kharrazi, A., and Evans, S. (2019) ‘The theoretical foundations of sociotechnical systems change for sustainability: A systematic literature review’, *Journal of Cleaner Production*. Elsevier Ltd, 206(November), pp. 878–892.

Schiederig, T., Tietze, F. and Herstatt, C. (2012) ‘Green innovation in technology and innovation management - an exploratory literature review’, *R&D Management*, 42(2), pp. 180–192.

Schilling, T., Wyss, R. and Binder, C. R. (2018) ‘The resilience of sustainability transitions’, *Sustainability (Switzerland)*, 10(12).

Schot, J. (2016) ‘Confronting the second deep transition through the historical imagination’, *Technology and Culture*, 2(445–456).

Schot, J. and Geels, F. W. (2008) ‘Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy’, (September 2015).

Schot, J., Kanger, L. and Verbong, G. (2016) ‘The roles of users in shaping transitions to new energy systems’, *Nature Energy*, 1.

Schreuer, A., Ornetzeder, M. and Rohracher, H. (2010) ‘Negotiating the local embedding of socio-technical experiments: a case study in fuel cell technology’, *Technology Analysis & Strategic Management*, 22(6), pp. 729–743.

Shove, E. and Walker, G. (2007) ‘CAUTION! Transitions Ahead: Politics, Practice, and Sustainable Transition Management.’, *Environment and Planning*, 39, pp. 763–770.

Smith, A. (2009) ‘The multi-level perspective on socio-technical transitions: some reflections on concepts, spaces and scales in sustainable energy transitions’, in *Seminar 1: Energy Transition: From Histories to Geographies University of Leicester*.

Smith, A. and Stirling, A. (2007) ‘Moving Outside or Inside? Objectification and Reflexivity in the Governance of Socio-Technical Systems’, (June 2015), pp. 37–41.

Smith, A. and Stirling, A. (2008) ‘Social-ecological resilience and socio-technical transitions: critical issues for sustainability governance’, *Brighton STEPS centre working paper*, 8(8), pp. 1–25.

Smith, A. and Stirling, A. (2010) ‘The politics of social-ecological resilience and sustainable socio-technical transitions’, *Ecology and Society*, 15(1).

Smith, A., Stirling, A. and Berkhout, F. (2005) ‘The governance of sustainable socio-technical transitions’, *Research Policy*, 34(10), pp. 1491–1510.

Smith, A., Voß, J.-P. and Grin, J. (2010) ‘Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges’, *Research Policy*, 39(4), pp. 435–448.

Snyder, H. (2019) ‘Literature review as a research methodology: An overview and guidelines’, *Journal of Business Research*, 104, pp. 333–339.

South African Government (2012) *National Development Plan 2030. Our Future - make it work*.

Späth, P. and Rohracher, H. (2010) 'Energy regions: The transformative power of regional discources on socio-technical futures.', *Research Policy*, 39, pp. 449–458.

Spoerri, A., Lank, D.J., Staeubli, B., Scholz, R.. (2010) 'Technological change in Swiss thermal waste treatment: An expert-based socio-technical analysis', *Waste Management*. Elsevier Ltd, 30(7), pp. 1382–1394.

Star, S. L. and Griesemer, J. R. (1989) 'Institutional ecology, "Translations" and boundary objects: amateurs and professionals in Berkeley's museum of vertebrate zoology', *Social Studies of Science*, 1907(39), pp. 387–420.

Syryamkin, V. I. and Syryamkina, E. G. (2015) 'Technology Management as a Tool of Innovative Strategy of Education and Cognitive Management', *Procedia - Social and Behavioral Sciences*. Elsevier B.V., 166, pp. 468–471. d

Takeo, Y. (2019) 'Government moving Eskom towards renewable energy', *Business Day*.

Taylor, M. and Taylor, A. (2012) 'The technology life cycle: Conceptualization and managerial implications', *International Journal of Production Economics*. Elsevier, 140(1), pp. 541–553.

Teece, D. J., Pisano, G. and Shuen, A. (1997) 'Dynamic capabilities and strategic management', *Strategic Management Journal*, 18(7), pp. 509–533.

The World Bank Group (2019) *Annual Report 2019: Ending Poverty. Investigating Opportunity*. Available at: https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS.

Thongpapanl, N. (2012) 'The changing landscape of technology and innovation management: An updated ranking of journals in the field', *Technovation*. Elsevier, 32(5), pp. 257–271.

Tidd, J. and Bessant, J. (2013) *Managing Innovation: Integrating Technological, Market and Organizational Change*. 5th editio. Chichester.: John Wiley.

Tigabu, A. D., Berkhout, F. and van Beukering, P. (2013) 'Technology innovation systems and technology diffusion: Adoption of bio-digestion in an emerging innovation system in Rwanda', *Technological Forecasting and Social Change*. Elsevier Inc., 90, pp. 318–330.

Ting, M. B. and Byrne, R. (2020) 'Eskom and the rise of renewables: Regime-resistance, crisis and the strategy of incumbency in South Africa's electricity system', *Energy Research and Social Science*. Elsevier, 60(April 2019), p. 101333. doi: 10.1016/j.erss.2019.101333.

Tran, M. (2014) 'Modeling Sustainability Transitions on Complex Networks', *Complexity*, 19(5), pp. 8–22.

Tranfield, D., Denyer, D. and Smart, P. (2003) 'Towards a methodology for developing evidence-informed management knowledge by means of systematic review', *British Journal of Management*, 14, pp. 207–222.

Turban, E. and Meredith, J. R. (1994) *Fundamentals of Management Science*. 6th edn. Richard D Irwin.

Turnheim, B., Berkhout, F., Geels, F.W., Hof, A., McMeekin, A, Nykvist, B., and Van Vuuren, D.P. (2015) 'Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges', *Global Environmental Change*. Elsevier Ltd, 35, pp. 239–253.

Turnheim, B., Berkhout, F., Geels, F.W., Hof, A., McMeekin, A., Nykvist, B., Van Vuuren, D.P. (2019) 'An agenda for sustainability transitions research: State of the art and future directions', *Environmental Innovation and Societal Transitions*. Elsevier, (February), pp. 1–32.

Turnheim, B. and Geels, F. W. (2012) ‘Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913-1997)’, *Energy Policy*. Elsevier, 50, pp. 35–49.

Turnheim, B. and Geels, F. W. (2013) ‘The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913-1967)’, *Research Policy*. Elsevier B.V., 42(10), pp. 1749–1767.

Ulli-beer, S. (2013) ‘Conceptual Grounds of Socio-Technical Transitions and Governance’, *Dynamic Governance of Energy Technology Change*, pp. 19–47.

Ungerer, G. D. (2015) ‘A Competitive Strategy Framework for E-Business Start-Ups by’, (December).

United Nations (2015) *Transforming our world: the 2030 Agenda for Sustainable Development*.

Utterback, J. M. (1995) *Mastering the Dynamics of Innovation*. Boston, MA: Harvard Business School Press.

Van Den Bergh, J.C.J.M., Truffer, B. and Kallis, G. (2011) ‘Environmental innovation and societal transitions: Introduction and overview’, *Environmental Innovation and Societal Transitions*. Elsevier B.V., 1(1), pp. 1–23.

Van Niekerk, S. (2019) ‘A different Eskom: Achieving a just energy transition for South Africa’, *Daily Maverick*, pp. 1–14.

Van der Brugge, R. and Rotmans, J. (2007) ‘Towards transition management of European water resources’, *Water Resources Management*, 21(1), pp. 249–267.

Verbong, G. and Geels, F. (2007) ‘The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004)’, *Energy Policy*, 35(2), pp. 1025–1037.

Wagner, M., Bachor, V. and Ngai, E. W. T. (2014) ‘Engineering and technology management for sustainable business development: Introductory remarks on the role of technology and regulation’, *Journal of Engineering and Technology Management*, 34, pp. 1–8.

Walker, B., Holling, C.S., Carpernter, S.R., Kinzig, A. (2004) ‘Resilience, adaptability and transformability in social-ecological systems’, *Ecology and Society*, 9(5).

Walker, S. L., Hope, A. and Bentley, E. (2014) ‘Modelling steady state performance of a local electricity distribution system under UK 2050 carbon pathway scenarios’, *Energy*. Elsevier Ltd, 78, pp. 604–621.

Walrave, B. and Raven, R. (2016) ‘Modelling the dynamics of technological innovation systems’, *Research Policy*. Elsevier B.V., 45(9), pp. 1833–1844.

Wang, L., Wei, Y. and Brown, M. A. (2017) ‘Global transition to low-carbon electricity : A bibliometric analysis’, *Applied Energy*. Elsevier, 205(January), pp. 57–68.

Weber, K. M. and Rohracher, H. (2012) ‘Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive “failures” framework’, *Research Policy*. Elsevier B.V., 41(6), pp. 1037–1047.

Wells, P. and Lin, X. (2015) ‘Spontaneous emergence versus technology management in sustainable mobility transitions: Electric bicycles in China’, *Transportation Research Part A: Policy and Practice*. Elsevier Ltd, 78, pp. 371–383.

World Economic Forum (2015) *Renewable energy is not enough: it needs to be sustainable*.

World Economic Forum (2019) *Fostering Effective Energy Transition 2019 edition*. Geneva.

WWF (2014) *Understanding South Africa's most urgent sustainability challenge*.

WWF (2017) *Renewable Energy: Facts and Futures The energy future we want*.

Zeleny, M. (1986) 'High Technology Management', *Human Systems Management*, 6, pp. 109–120.

Zeschky, M. B., Winterhalter, S. and Grassmann, O. (2014) 'From Cost to Frugal and Reverse Innovation: Mapping the Field and Implications for Global Competitiveness', *Research Technology Management*.

Appendix A - Transition pathways

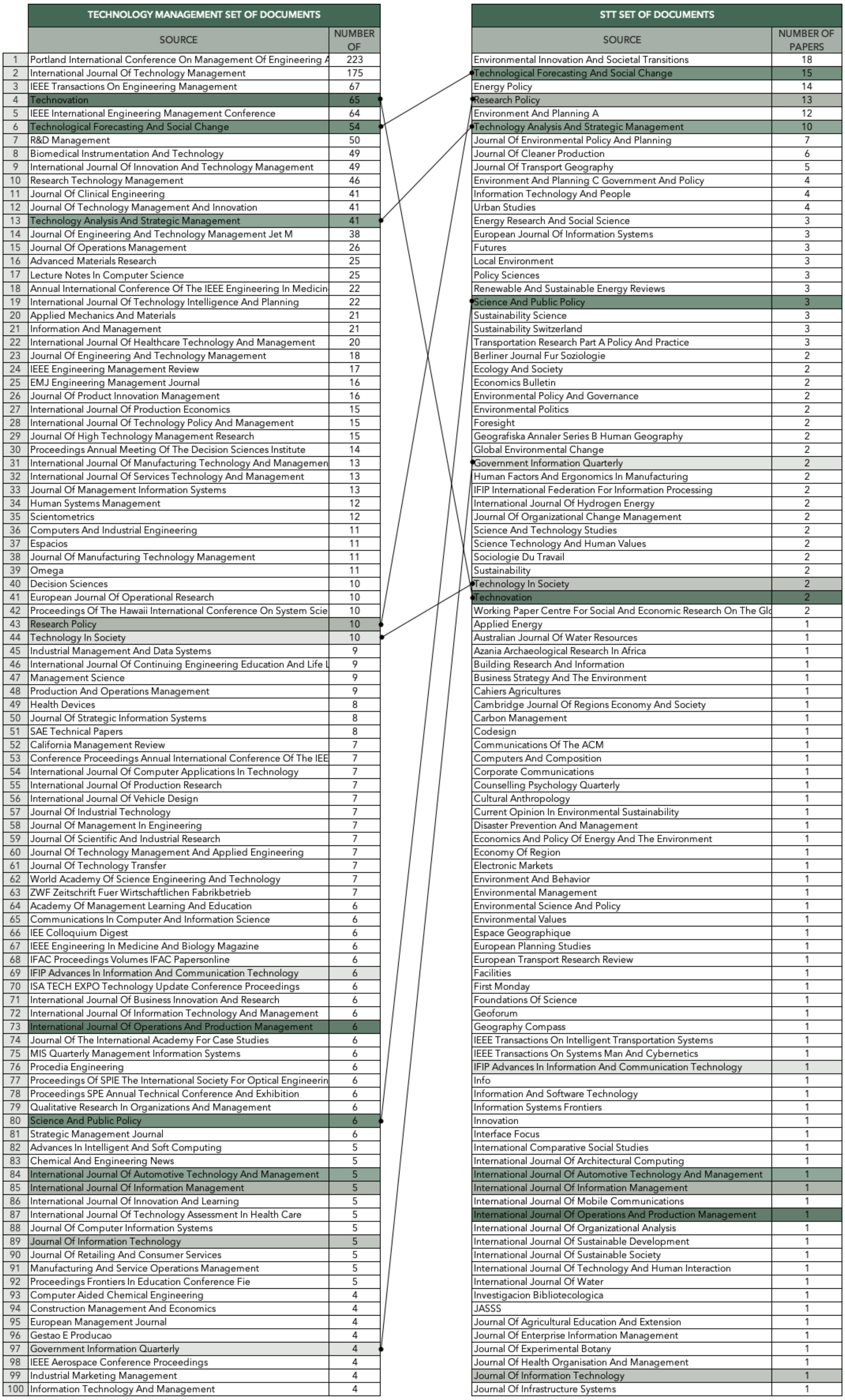
In Table 70 the different transition pathways defined as by Geels and Schot (2007) are summarised.

Table 70. Summary of the different transition pathways (compiled from Geels and Schot, 2007)

	P0	P1			P2	P3		P4
	Reproduction pathway	Transformation pathway			De-alignment and re-alignment	Technological substitution		Reconfiguration pathways
		Gradual reorientation of the existing regime through adjustments by incumbent actors in the context of landscape pressures, societal debates, and tightening institutions			Existing regime is disrupted by external shocks, which in followed by the rise of multiple niche-innovations and constituencies, ones of which gradually becomes dominant.			Niche-innovations and the existing regime combine to transform the system's architecture.
Landscape pressure	N	Y			Y	Y		Y
Niche-innovation sufficiently developed		N			N	Y		Y
Actors		Incumbents reorient incrementally by adjusting search routines and procedures		Incumbents reorient substantially to radical, new technology, or even more deeply to new beliefs, missions and business models	Incumbents collapse because of landscape pressure, creating opportunities for new entrants	New firms struggle against incumbent firms, leading to overthrow	Different kinds of 'new entrants' (e.g. citizens, communities, social movement actors, incumbents from different sectors) replace incumbents	New alliances between incumbents and new entrants
Technologies		Incremental improvements in existing technologies (leading to major performance enhancement over long time periods).	Incorporation of symbiotic niche-innovations and add-ons (competence-adding, creative accumulation)	Reorientation towards new technologies: (a) partial reorientation (diversification) with incumbents developing both old and new technologies; (b) full reorientation, leading to technological substitution	Decline of old technologies creates space for several innovations which compete with one another	Radical innovation(s) substituting existing technology		From additional add-ons to new combinations between new and existing technologies; knock-on effects and innovation cascades that change system architecture
Rules and institutions		Limited institutional change (layering)		Substantial change in institutions (conversion, displacement)	Institutions are disrupted by shocks and replaced, possibly after prolonged uncertainty (Disruption)	Limited institutional change, implying that niche innovation needs to compete in existing selection environment ('fit-and-conform'). (Incremental adjustment, layering)	Creation of new rules and institutions to sui niche-innovation ('stretch-and-transform') (Disruption, Displacement)	From limited institutional change (layering) to more substantial change, including operational principles ('drift', 'conversion')

Appendix B - Sources of publication

The leading outlets for documents published on socio-technical transitions and technology management respectively are shown in Figure 54. In addition, the overlaps in outlet sources between the technology management set of documents and the socio-technical transition set of documents are highlighted.



	TECHNOLOGY MANAGEMENT SET OF DOCUMENTS	
	SOURCE	NUMBER OF
1	Portland International Conference On Management Of Engineering A	223
2	International Journal Of Technology Management	175
3	IEEE Transactions On Engineering Management	67
4	Technovation	65
5	IEEE International Engineering Management Conference	64
6	Technological Forecasting And Social Change	54
7	R&D Management	50
8	Biomedical Instrumentation And Technology	49
9	International Journal Of Innovation And Technology Management	49
10	Research Technology Management	46
11	Journal Of Clinical Engineering	41
12	Journal Of Technology Management And Innovation	41
13	Technology Analysis And Strategic Management	41
14	Journal Of Engineering And Technology Management Jet M	38
15	Journal Of Operations Management	26
16	Advanced Materials Research	25
17	Lecture Notes In Computer Science	25
18	Annual International Conference Of The IEEE Engineering In Medicin	22
19	International Journal Of Technology Intelligence And Planning	22
20	Applied Mechanics And Materials	21
21	Information And Management	21
22	International Journal Of Healthcare Technology And Management	20
23	Journal Of Engineering And Technology Management	18
24	IEEE Engineering Management Review	17
25	EMJ Engineering Management Journal	16
26	Journal Of Product Innovation Management	16
27	International Journal Of Production Economics	15
28	International Journal Of Technology Policy And Management	15
29	Journal Of High Technology Management Research	15
30	Proceedings Annual Meeting Of The Decision Sciences Institute	14
31	International Journal Of Manufacturing Technology And Managemen	13
32	International Journal Of Services Technology And Management	13
33	Journal Of Management Information Systems	13
34	Human Systems Management	12
35	Scientometrics	12
36	Computers And Industrial Engineering	11
37	Espacios	11
38	Journal Of Manufacturing Technology Management	11
39	Omega	11
40	Decision Sciences	10
41	European Journal Of Operational Research	10
42	Proceedings Of The Hawaii International Conference On System Scie	10
43	Research Policy	10
44	Technology In Society	10
45	Industrial Management And Data Systems	9
46	International Journal Of Continuing Engineering Education And Life L	9
47	Management Science	9
48	Production And Operations Management	9
49	Health Devices	8
50	Journal Of Strategic Information Systems	8
51	SAE Technical Papers	8
52	California Management Review	7
53	Conference Proceedings Annual International Conference Of The IEE	7
54	International Journal Of Computer Applications In Technology	7
55	International Journal Of Production Research	7
56	International Journal Of Vehicle Design	7
57	Journal Of Industrial Technology	7
58	Journal Of Management In Engineering	7
59	Journal Of Scientific And Industrial Research	7
60	Journal Of Technology Management And Applied Engineering	7
61	Journal Of Technology Transfer	7
62	World Academy Of Science Engineering And Technology	7
63	ZWF Zeitschrift Fuer Wirtschaftlichen Fabrikbetrieb	7
64	Academy Of Management Learning And Education	6
65	Communications In Computer And Information Science	6
66	IEE Colloquium Digest	6
67	IEEE Engineering In Medicine And Biology Magazine	6
68	IFAC Proceedings Volumes IFAC Papersonline	6
69	IFIP Advances In Information And Communication Technology	6
70	ISA TECH EXPO Technology Update Conference Proceedings	6
71	International Journal Of Business Innovation And Research	6
72	International Journal Of Information Technology And Management	6
73	International Journal Of Operations And Production Management	6
74	Journal Of The International Academy For Case Studies	6
75	MIS Quarterly Management Information Systems	6
76	Procedia Engineering	6
77	Proceedings Of SPIE The International Society For Optical Engineerin	6
78	Proceedings SPE Annual Technical Conference And Exhibition	6
79	Qualitative Research In Organizations And Management	6
80	Science And Public Policy	6
81	Strategic Management Journal	6
82	Advances In Intelligent And Soft Computing	5
83	Chemical And Engineering News	5
84	International Journal Of Automotive Technology And Management	5
85	International Journal Of Information Management	5
86	International Journal Of Innovation And Learning	5
87	International Journal Of Technology Assessment In Health Care	5
88	Journal Of Computer Information Systems	5
89	Journal Of Information Technology	5
90	Journal Of Retailing And Consumer Services	5
91	Manufacturing And Service Operations Management	5
92	Proceedings Frontiers In Education Conference Fie	5
93	Computer Aided Chemical Engineering	4
94	Construction Management And Economics	4
95	European Management Journal	4
96	Gestao E Producao	4
97	Government Information Quarterly	4
98	IEEE Aerospace Conference Proceedings	4
99	Industrial Marketing Management	4
100	Information Technology And Management	4

STT SET OF DOCUMENTS	
SOURCE	NUMBER OF PAPERS
Environmental Innovation And Societal Transitions	18
Technological Forecasting And Social Change	15
Energy Policy	14
Research Policy	13
Environment And Planning A	12
Technology Analysis And Strategic Management	10
Journal Of Environmental Policy And Planning	7
Journal Of Cleaner Production	6
Journal Of Transport Geography	5
Environment And Planning C Government And Policy	4
Information Technology And People	4
Urban Studies	4
Energy Research And Social Science	3
European Journal Of Information Systems	3
Futures	3
Local Environment	3
Policy Sciences	3
Renewable And Sustainable Energy Reviews	3
Science And Public Policy	3
Sustainability Science	3
Sustainability Switzerland	3
Transportation Research Part A Policy And Practice	3
Berliner Journal Fur Soziologie	2
Ecology And Society	2
Economics Bulletin	2
Environmental Policy And Governance	2
Environmental Politics	2
Foresight	2
Geografiska Annaler Series B Human Geography	2
Global Environmental Change	2
Government Information Quarterly	2
Human Factors And Ergonomics In Manufacturing	2
IFIP International Federation For Information Processing	2
International Journal Of Hydrogen Energy	2
Journal Of Organizational Change Management	2
Science And Technology Studies	2
Science Technology And Human Values	2
Sociologie Du Travail	2
Sustainability	2
Technology In Society	2
Technovation	2
Working Paper Centre For Social And Economic Research On The Glo	2
Applied Energy	1
Australian Journal Of Water Resources	1
Azania Archaeological Research In Africa	1
Building Research And Information	1
Business Strategy And The Environment	1
Cahiers Agricultures	1
Cambridge Journal Of Regions Economy And Society	1
Carbon Management	1
Codesign	1
Communications Of The ACM	1
Computers And Composition	1
Corporate Communications	1
Counselling Psychology Quarterly	1
Cultural Anthropology	1
Current Opinion In Environmental Sustainability	1
Disaster Prevention And Management	1
Economics And Policy Of Energy And The Environment	1
Economy Of Region	1
Electronic Markets	1
Environment And Behavior	1
Environmental Management	1
Environmental Science And Policy	1
Environmental Values	1
Espace Geographique	1
European Planning Studies	1
European Transport Research Review	1
Facilities	1
First Monday	1
Foundations Of Science	1
Geoforum	1
Geography Compass	1
IEEE Transactions On Intelligent Transportation Systems	1
IEEE Transactions On Systems Man And Cybernetics	1
IFIP Advances In Information And Communication Technology	1
Info	1
Information And Software Technology	1
Information Systems Frontiers	1
Innovation	1
Interface Focus	1
International Comparative Social Studies	1
International Journal Of Architectural Computing	1
International Journal Of Automotive Technology And Management	1
International Journal Of Information Management	1
International Journal Of Mobile Communications	1
International Journal Of Operations And Production Management	1
International Journal Of Organizational Analysis	1
International Journal Of Sustainable Development	1
International Journal Of Sustainable Society	1
International Journal Of Technology And Human Interaction	1
International Journal Of Water	1
Investigacion Bibliotecologica	1
JASSS	1
Journal Of Agricultural Education And Extension	1
Journal Of Enterprise Information Management	1
Journal Of Experimental Botany	1
Journal Of Health Organisation And Management	1
Journal Of Information Technology	1
Journal Of Infrastructure Systems	1

Figure 54: Distribution of documents by journal for the technology management and socio-technical transitions sets of documents respectively

Appendix C - Linkage analysis results

Results from the linkage analysis presented in Chapter 4 is presented in Appendix C.

Table 71: References *used by both the technology management and socio-technical transitions' scientific networks where (significant) overlap(s) occur*

	OVERLAP GROUP					Normalised title of reference (Normalised during step i of LA Phase 1)	# of times as TM reference (thus the number of times an TMentry cites this reference)	# of times as STT reference (thus the number of times an STTentry cites this reference)
	Most prominent STT refs	Most prominent TM refs	10 each way	10 TM, 5 STT	10 STT, 5 TM			
T1		x				a critical look at technological innovation typology and innovativeness terminology a literature prod innov manag	18	3
T2		x				a dynamic theory of organizational knowledge creation organization science	50	1
T3		x		x		a national systems of innovation theory of innovation and interactive learning pinter publishers london	28	7
T4		x				a new product growth model for consumer durables manag sci	32	1
T5		x				a resource based perspective on information technology capability and firm performance an empirical investigation mis quarterly	16	2
T6		x				a resource based view of the firm strategic management	51	2
T7		x				a theoretical extension of the technology acceptance model four longitudinal field studies management science	26	1
T8		x				absorptive capacity a new perspective on learning and innovation administrative science quarterly	124	2
T9	x	x	x	x	x	an evolutionary theory of economic change harvar	83	26
T10		x		x		architectural innovation the reconfiguration of existing product technologies and the failure of existing firms administrative science quarterly	64	5
T11		x				asset stock accumulation and sustainability of competitive advantage management science	27	1
T12				x		basics of qualitative research techniques and procedures for developing grounded theory london sage	11	5
T13		x	x	x	x	building theories form case study research acad manag rev	74	10
T14		x				burns stalker the management of innovations tavistock publications london	22	1
T15		x				business cycles a theoretical historical and statistical analysis of the capitalist process mcgraw hill new yor	17	3
T16		x				business dynamics systems thinking and modeling complex world mcgraw hill new york	22	4
T17		x				business models business strategy and innovation long range plann	19	1
T18	x					can cities shape socio technical transitions and how would we know if they were res policy	1	21
T19		x		x		capitalism socialism and democracy new york harper row	52	9
T20	x	x	x	x	x	case study research design and methods sage london	129	17
T21			x	x	x	clio and the economics of qwerty am econ rev	11	12
T22	x		x	x	x	competing technologies increasing returns and lock in by historical events econ j	14	17
T23		x				competitive strategy techniques for analyzing industries and competitors fre york	60	2
T24	x					constructing transition paths through the management of niches path dependence and creation eds lawrence erlbaum mahwah nj london	3	16
T25		x				customer power strategic investment and the failure of leading firms strategic management	18	2
T26		x				customization of technology roadmaps according to roadmapping purposes overall process and detailed modules technological forecasting	16	1
T27		x				development of an instrument to measure the perceptions of adopting an	21	1
T28		x	x	x	x	diffusion of innovations fre york	145	15
T29		x				dynamic capabilities and strategic management strategic management	98	4
T30		x				dynamic capabilities what are they strategic management	36	1
T31		x		x		economic action and social structure the problem of embeddedness sociol	17	5
T32		x				emergence triple helix of university industry government relations science and public policy	28	1
T33		x				evaluating structural equation models with unobservable variables and measurement error research	33	1
T34	x					experimenting for sustainable transport the approach of strategic niche management london gbr pp ix spo	2	35
T35		x				explicating dynamic capabilities the nature and microfoundations of sustainable enterprise performance strategic management doi 10 1002	16	1
T36		x				exploration and exploitation in organizational learning organ sci	42	4
T37		x				firm resources and sustained competitive advantage	92	2
T38		x				first mover advantages strateg manage j	23	1
T39	x				x	from sectoral systems of innovation to socio technical systems insights about dynamics and change from sociology and institutional theory	6	64
T40	x				x	functions of innovation systems a new approach for analysing technological change technol forecast soc change	8	16
T41		x				h process innovation reengineering work through information technology harvard business schoo ma	26	1
T42		x				innovation mapping the winds of creative destruction res policy	36	2
T43		x				innovation the attacker s advantage macmillan london	44	1
T44		x				inside the black box technology and economics cambridg	23	2
T45				x		institutions institutional change and economic performance cambridg ma	11	5
T46		x				knowledge management and knowledge management systems conceptual foundations and research issues mis quarterly	17	1

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T47		X				leonard core capabilities and core rigidities a paradox in managing new product development strategic management	38	1
T48		x				leonard wellsprings of knowledge building and sustaining the sources of innovation harvard business schoo	32	1
T49		x				managing innovation integrating technological market and organizational change wiley chichester	47	1
T50		x				markets and hierarchies analysis and antitrust implications new york fre	23	1
T51		x				mastering the dynamics of innovation boston harvard business school	63	3
T52		x				motorola s technology roadmap process research management september october	42	1
T53		x				national innovation systems a comparative analysis new york oxfor	22	3
T54	x				x	networks of power electrification in western society 1880 1930 johns hopkin	7	25
T55	x				x	of bicycles bakelites and bulbs theory of socio technical change mi ma	6	25
T56		x				organisational learning a theory of action perspective addison wesley reading ma	21	4
T57		x				organization and environment harvar ma	26	2
T58		x				organizational culture and leadership jossey bass san francisco	16	2
T59		x				organizational innovation a meta analysis of effects of determinants and moderators academy of management	17	1
T60		x				organizational strategy structure and process mcgraw hill	39	2
T61			x	x	x	our common future world commission on environment and development oxfor	15	12
T62	x					p innovation studies and sustainability transitions the allure of the multi level perspective and its challenges research policy	1	47
T63	x					processes and patterns in transitions and system innovations refi ning the co evolutionary multi level perspective technological forecasting	1	22
T64		x				profiting from technological innovation implications for integration collaboration licensing and public policy research policy	60	1
T65				x		qualitative data analysis an expanded sourcebook sage publications thousand oaks ca	14	5
T66	x					regime shifts to sustainability through processes of niche formation the approach of strategic niche management technology analysis and	5	77
T67		x				science and technology roadmaps ieee transactions on engineering management	49	1
T68	x		x	x	x	science in action how to follow scientists and engineers through society cambridge ma harvar	13	24
T69		x				sectoral patterns of technical change taxonomy theory research policy	22	1
T70		x				sensemaking in organisations sage london	18	3
T71	x		x	x	x	shaping technology building society and eds mi ma	10	24
T72		x				smith interorganizational collaboration and the locus of innovation networks of learning in biotechnology administrative science quarterly	25	1
T73		x				social network analysis methods and applications cambridg	16	2
T74	x					socio technological regimes and transition contexts system innovation and the transition to sustainability theory evidence and geels green eds	1	21
T75		x				sources procedures and microeconomic effects of innovation literature	19	4
T76	x					spatial perspective on sustainability transitions res policy	1	17
T77	x					system innovation and the transition to sustainability theory evidence and policy cheltenham edward elgar	4	100
T78		x				systems thinking systems practice wiley chichester	25	2
T79	x	x	x	x	x	technical change and economic theory london pinter	24	17
T80	x					technological change human choice and climate change resources and technology eds battell	3	86
T81		x				technological discontinuities and dominant designs a cyclical model of technological change administrative science quarterly	37	1
T82		x		x		technological discontinuities and organizational environments adm sci q	54	7
T83	x	x	x	x	x	technological paradigms and technological trajectories research policy	51	22
T84	x					technological transitions and system innovations a co evolutionary and sociotechnical analysis cheltenham edward elgar	2	31
T85	x				x	technological transitions as evolutionary reconfiguration processes a multi level perspective case study research policy	5	122
T86		x				technology foresight using roadmaps long range planning	18	1
T87		x				technology policy and economic performance lessons from japan pinter	14	2
T88		x				technology roadmapping a planning framework for evolution and revolution technological forecasting and social change	38	1
T89		x				the age of the smart machine the future of work and power new york basic books	19	3
T90		x				the competitive advantage of nations macmillan london	62	2
T91	x	x	x	x	x	the constitution of society	24	27
T92		x				the delphi method techniques and applications reading ma	17	1
T93		x		x		the discovery of grounded theory strategies for qualitative research aldine publishing chicago il	27	6
T94		x		x		the duality of technology rethinking the concept of technology in organizations organization science	16	8
T95	x					the dynamics of transitions in socio technical systems a multi level analysis of the transition pathway from horse drawn carriages to automobiles technol anal strat manage	1	32
T96		x				the economics of industrial innovation pinter london	48	3
T97	x					the governance of sustainable socio technical transitions res policy	4	88
T98						the innovation journey oxfor	8	5
T99	x	x	x	x	x	the innovator s dilemma harvard business schoo	118	18

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T100		X				the innovator s solution creating and sustaining successful growth harvard busines	21	1
T101				x		the iron cage revisited institutional isomorphism and collective rationality in organizational fields american sociological review	15	8
T102		x				the knowledge creating company how japanese companies create the dynamics of innovation oxfor	124	2
T103		x				the machine that changed the world macmilla	43	3
T104	x					the multi level perspective on sustainability transitions responses to seven criticisms environ innov soc trans	1	28
T105		x				the myopia of learning strategic management	17	2
T106		x				the relational view cooperative strategy and sources of interorganizational competitive advantage acad manage rev	17	1
T107	x	x	x	x	x	the social construction of technological systems cambridge ma mi	20	55
T108		x				the social psychology of organizing second ed reading addison wesley	19	3
T109	x		x	x	x	the social shaping of technology ope	12	22
T110		x		x		the structure of scientific revolutions chicago university of chicag	29	7
T111		x		x		the theory of economic development harvar ma	74	6
T112		x				the theory of planned behavior organizational behavior and human decision processes	20	2
T113		x		x		theory building from cases opportunities and challenges academy of management	16	5
T114	x				x	typology of sociotechnical transition pathways research policy	5	99
T115	x					understanding carbon lock in energy policy	2	32
T116		x				user acceptance of computer technology a comparison of two theoretical models management science	36	2
T117		x				user acceptance of information technology unified view mis quarterly	29	3
T118		x				von democratizing innovation mi mass	17	1
T119		x				von the sources of innovation oxfor york	40	2

Table 72: The 'most prominent STT' and the 'most prominent TM' references

	OVERLAP GROUP					
	Most prominent STT refs	Most prominent TM refs	Key focus	Normalised title of reference (Normalised during step i of LA Phase 1)	# of times as TM reference (thus the number of times an TMentry cites this reference)	# of times as STT reference (thus the number of times an STTentry cites this reference)
T9	x	x	Economics	an evolutionary theory of economic change harvar	83	26
T20	x	x	Research methodology	case study research design and methods sage london	129	17
T79	x	x	Economics	technical change and economic theory london pinter	24	17
T83	x	x	Technological innovation	technological paradigms and technological trajectories research policy	51	22
T91	x	x	Social theory	the constitution of society	24	27
T99	x	x	Innovation / technology focussed, not socio-technical transitions	the innovator s dilemma harvard business schoo	118	18
T107	x	x	Social studies of technology.	the social construction of technological systems cambridge ma mi	20	55

Table 73: Technology management Entries cite the most prominent references that deals with socio-technical transitions from a sustainability perspective or sustainability transitions

# OF REFERENCES REFRENCED*	UNIQUE IDENTIFIERS OF TM ENTRIES	REFERENCES THAT DEALS WITH TRANSITIONS TO SUSTAINABILITY (in the 'most prominent' overlap group)**	TM ENTRY TITLE	PUBLICATION DATE	AUTHORS
6	4427	T77, T114, T97, T80, T62, T84	The transformative capacity of new technologies	2013	Dolata, U.
5	3788	T77, T114, T97, T95, T104	Spontaneous emergence versus technology management in sustainable mobility transitions: Electric bicycles in China	2015	Wells, P., Lin, X.
2	253	T80, T55	The transformation of technological regimes	2003	Poel, D.I.V.
2	3829	T114, T84	Technology, innovation and management for sustainable growth: A flexible toolkit for strategic technology management	2015	Almeida, F.L.M., Melo, A.C.M.
2	4679	T114, T34	Managing the diffusion of low emission vehicles	2012	Van Der Vooren, A., Alkemade, F.
1	3368	T77	Strategic innovation in sustainable technology: The case of fuel cells for vehicles	2006	Peters, S.R., Coles, A.M.
1	2518	T34	Strategic niche management of intelligent transport systems deployment and development in developing countries	2009	Shah, A.A.S., Mahalik, N.P., Ha, A.B.
1	2304	T115	Challenges and trade-offs in corporate innovation for climate change	2010	Pinkse, J., Kolk, A.
1	280	T55	Organizational innovations	2003	Clark, P.
1	474	T55	Social scientists: Managing identity in socio-technical networks	2002	Davidson, E., Lamb, R.
1	2283	T55	Convergence and reorientation via open innovation: The emergence of nutraceuticals	2010	Siedlok, F., Smart, P., Gupta, A.
1	3057	T55	Social exclusion and transgenic technology: The case of Brazilian agriculture	2008	Hall, J., Langford, C.H., Matos, S.
1	4299	T55	The innovation big picture: Including effectiveness dependencies, efficiency dependencies, and potential negative effects within the framing of new technologies	2013	Fox, S.
1	2317	T97	Sustainability and diversity in the global automotive industry	2010	Wells, P.
1	2869	T80	A dynamic view of technological regime concept: Toward a framework for industrial policies in developing countries	2008	Mehrizi, H.M.R., Mozafari, A.
1	3069	T34	Users as a source of learning in environmental technology management	2007	Rohracher, H.
1	4374	T144	Exploring industry dynamics and interactions	2013	Routley, M., Phaal, R., Probert, D.

* number of times the 31 references are references by each Entry
** corresponding references references by each Entry

Table 74: The most prominent references that deals with socio-technical transitions from a sustainability perspective or sustainability transitions

	Normalised title of reference (Normalised during step I of LA Phase)1	# of times as TM reference*	# of times as STT reference**	UNIQUE IDENTIFIERS OF TM ENTRIES REFERENCING THESE REFERENCES
T77	system innovation and the transition to sustainability theory evidence and policy cheltenham edward elgar	4	100	3368, 3788, 4472, 4472
T114	typology of sociotechnical transition pathways research policy	5	99	3788, 3829, 4374, 4472, 4679
T97	the governance of sustainable socio technical transitions res policy	3	88	2317, 3788, 4472
T80	technological change human choice and climate change resources and technology eds battell	3	86	253, 2869, 4472
T62	p innovation studies and sustainability transitions the allure of the multi level perspective and its challenges research policy	1	47	4472
T34	experimenting for sustainable transport the approach of strategic niche management london gbr pp ix spo	2	35	2518, 3069
T115	understanding carbon lock in energy policy	2	32	2304, 4679
T95	the dynamics of transitions in socio technical systems a multi level analysis of the transition pathway from horse drawn carriages to automobiles technol anal strat manage	1	32	3788
T84	technological transitions and system innovations a co evolutionary and sociotechnical analysis cheltenham edward elgar	2	31	3829, 4472
T104	the multi level perspective on sustainability transitions responses to seven criticisms environ innov soc trans	1	28	3788;
T55	of bicycles bakelites and bulbs theory of socio technical change mi ma	6	25	253, 280, 474, 2283, 3057, 4299

*Thus the number of times in TM entry sigts this reference
**Thus the number of times in STT entry sigts this reference

Table 75: Keywords associated with the Entries *that reference the* References *that deal with transitions to sustainability (i.e. the articles in the technology body of literature that references the references in the 'most prominent' overlap group shown in Table 73)*

KEYWORD	NUMBER OF OCCURENCES
Technology management	6
Innovation	4
Sustainability	4
Developing countries	2
Technological change	2
Beijing	1
Corporate social responsibility	1
Framing	1
Industry dynamics	1
Agent-based simulation	1
Innovation strategy	1
Capabilities	1
Automotive technology management	1
Industrial policy	1
Brazilian agriculture	1
Commercialisation	1
Niches	1
Organisational innovation	1
Communications technology	1
Technological innovations	1
China	1
Modular toolkits	1
Hype	1
Lifecycle	1
Consumer adoption	1
Knowledge management	1
Climate change	1
Business models	1
Intelligent transport systems	1
Social exclusion	1
Sustainable development	1
Fuel cells	1
Patterns of innovation	1
Identity management systems	1
Technology	1
Transport policy	1
Telephony	1
Web pages	1
World Wide Web	1
Writing	1
Electric bicycles	1
Strategic foresight	1
Negative effects	1
Technology system	1
Infrastructure development	1
New product development	1
Corporate strategy	1
Economic diversity	1
ITS	1
Socio-technical transitions	1
Radical innovation	1
Organisational change	1
Intelligent networks	1
Socio-technical transformation	1
New energy vehicles	1
Strategic technology management	1
Pharmaceutical industry	1
Industrial ecology	1
Transgenics	1
Regime transformations	1
Marine technology	1
Socio-technical change	1
Technology and innovation studies	1
Sociotechnical system	1
Path dependency	1
Technology strategy	1
Technological regimes	1
Psychology	1

Table 76. References used by both the technology management and socio-technical transitions' scientific networks where (significant) overlap(s) occur, grouped according to clusters

			OVERLAP GROUP							
			Most prominent STT refs	Most prominent TM refs	10 each way	10 TM, 5 STT	10 STT, 5 TM	NORMALISED TITLE OF REFERENCE (Normalised during step i of LA Phase 1)	# of times as TM reference (thus the number of times an TMentry cites this reference)	# of times as STT reference (thus the number of times an STTentry cites this reference)
CLUSTER 1	1	T66	x					regime shifts to sustainability through processes of niche formation the approach of strategic niche management technology analysis and strate	5	77
	1	T77	x					system innovation and the transition to sustainability theory evidence and policy cheltenham edward elgar	4	100
	1	T80	x					technological change human choice and climate change resources and technology eds battell	3	86
	1	T85	x				x	technological transitions as evolutionary reconfiguration processes a multi level perspective case study research policy	5	122
	1	T97	x					the governance of sustainable socio technical transitions res policy	4	88
	1	T114	x				x	typology of sociotechnical transition pathways research policy	5	99
CLUSTER 2	2	T12				x		basics of qualitative research techniques and procedures for developing grounded theory london sage	11	5
	2	T21			x	x	x	clio and the economics of qwerty am econ rev	11	12
	2	T22	x		x	x	x	competing technologies increasing returns and lock in by historical events econ j	14	17
	2	T31		x		x		economic action and social structure the problem of embeddedness sociol	17	5
	2	T40	x				x	functions of innovation systems a new approach for analysing technological change technol forecast soc change	8	16
	2	T45				x		institutions institutional change and economic performance cambridg ma	11	5
	2	T61			x	x	x	our common future world commission on environment and development oxfor	15	12
	2	T65				x		qualitative data analysis an expanded sourcebook sage publications thousand oaks ca	14	5
	2	T79	x	x	x	x	x	technical change and economic theory london pinter	24	17
	2	T83	x	x	x	x	x	technological paradigms and technological trajectories research policy	51	22
	2	T91	x	x	x	x	x	the constitution of society	24	27
	2	T94		x		x		the duality of technology rethinking the concept of technology in organizations organization science	16	8
	2	T98				x		the innovation journey oxfor	12	5
	2	T101				x		the iron cage revisited institutional isomorphism and collective rationality in organizational fields american sociological review	15	8
	2	T113		x		x		theory building from cases opportunities and challenges academy of management	16	5

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CLUSTER 3	3	T2		x				a dynamic theory of organizational knowledge creation organization science	50	1
	3	T4		x				a new product growth model for consumer durables manag sci	32	1
	3	T6		x				a resource based view of the firm strategic management	51	2
	3	T8		x				absorptive capacity a new perspective on learning and innovation administrative science quarterly	124	2
	3	T10		x		x		architectural innovation the reconfiguration of existing product technologies and the failure of existing firms administrative science quarterly	64	5
	3	T13		x	x	x	x	building theories form case study research acad manag rev	74	10
	3	T20	x	x	x	x	x	case study research design and methods sage london	129	17
	3	T23		x				competitive strategy techniques for analyzing industries and competitors fre york	60	2
	3	T28		x	x	x	x	diffusion of innovations fre york	145	15
	3	T29		x				dynamic capabilities and strategic management strategic management	98	4
	3	T30		x				dynamic capabilities what are they strategic management	36	1
	3	T33		x				evaluating structural equation models with unobservable variables and measurement error research	33	1
	3	T37		x				firm resources and sustained competitive advantage	92	2
	3	T42		x				innovation mapping the winds of creative destruction res policy	36	2
	3	T43		x				innovation the attacker s advantage macmillan london	44	1
	3	T47		x				leonard core capabilities and core rigidities a paradox in managing new product development strategic management	38	1
	3	T48		x				leonard wellsprings of knowledge building and sustaining the sources of innovation harvard business schoo	32	1
	3	T49		x				managing innovation integrating technological market and organizational change wiley chichester	47	1
	3	T51		x				mastering the dynamics of innovation boston harvard business school	63	3
	3	T52		x				motorola s technology roadmap process research management september october	42	1
	3	T60		x				organizational strategy structure and process mcgraw hill	39	2
	3	T64		x				profiting from technological innovation implications for integration collaboration licensing and public policy research policy	60	1
	3	T67		x				science and technology roadmaps ieee transactions on engineering management	49	1
	3	T81		x				technological discontinuities and dominant designs a cyclical model of technological change administrative science quarterly	37	1
	3	T88		x				technology roadmapping a planning framework for evolution and revolution technological forecasting and social change	38	1
	3	T90		x				the competitive advantage of nations macmillan london	62	2
	3	T96		x				the economics of industrial innovation pinter london	48	3
	3	T99	x	x	x	x	x	the innovator s dilemma harvard business schoo	118	18
	3	T102		x				the knowledge creating company how japanese companies create the dynamics of innovation oxfor	124	2
	3	T103		x				the machine that changed the world macmilla	43	3
	3	T111		x		x		the theory of economic development harvar ma	74	6
	3	T116		x				user acceptance of computer technology a comparison of two theoretical models management science	36	2
	3	T119		x				von the sources of innovation oxfor york	40	2

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CLUSTER 4	4	T1		x				a critical look at technological innovation typology and innovativeness terminology a literature prod innov manag	18	3
	4	T3		x		x		a national systems of innovation theory of innovation and interactive learning pinter publishers london	28	7
	4	T5		x				a resource based perspective on information technology capability and firm performance an empirical investigation mis quarterly	16	2
	4	T7		x				a theoretical extension of the technology acceptance model four longitudinal field studies management science	26	1
	4	T9	x	x	x	x	x	an evolutionary theory of economic change harvar	83	26
	4	T11		x				asset stock accumulation and sustainability of competitive advantage management science	27	1
	4	T14		x				burns stalker the management of innovations tavistock publications london	22	1
	4	T15		x				business cycles a theoretical historical and statistical analysis of the capitalist process mcgraw hill new yor	17	3
	4	T16		x				business dynamics systems thinking and modeling complex world mcgraw hill new york	22	4
	4	T17		x				business models business strategy and innovation long range plann	19	1
	4	T19		x		x		capitalism socialism and democracy new york harper row	52	9
	4	T25		x				customer power strategic investment and the failure of leading firms strategic management	18	2
	4	T26		x				customization of technology roadmaps according to roadmapping purposes overall process and detailed modules technological forecasting and	16	1
	4	T27		x				development of an instrument to measure the perceptions of adopting an	21	1
	4	T32		x				emergence triple helix of university industry government relations science and public policy	28	1
	4	T35		x				explicating dynamic capabilities the nature and microfoundations of sustainable enterprise performance strategic management doi 10 1002 smj	16	1
	4	T36		x				exploration and exploitation in organizational learning organ sci	42	4
	4	T38		x				first mover advantages strateg manage j	23	1
	4	T41		x				h process innovation reengineering work through information technology harvard business schoo ma	26	1
	4	T44		x				inside the black box technology and economics cambridg	23	2
	4	T46		x				knowledge management and knowledge management systems conceptual foundations and research issues mis quarterly	17	1
	4	T50		x				markets and hierarchies analysis and antitrust implications new york fre	23	1
	4	T53		x				national innovation systems a comparative analysis new york oxfor	22	3
	4	T56		x				organisational learning a theory of action perspective addison wesley reading ma	21	4
	4	T57		x				organization and environment harvar ma	26	2
	4	T58		x				organizational culture and leadership jossey bass san francisco	16	2
	4	T59		x				organizational innovation a meta analysis of effects of determinants and moderators academy of management	17	1
	4	T69		x				sectoral patterns of technical change taxonomy theory research policy	22	1
	4	T70		x				sensemaking in organisations sage london	18	3
	4	T72		x				smith interorganizational collaboration and the locus of innovation networks of learning in biotechnology administrative science quarterly	25	1
	4	T73		x				social network analysis methods and applications cambridg	16	2
	4	T75		x				sources procedures and microeconomic effects of innovation literature	19	4
	4	T78		x				systems thinking systems practice wiley chichester	25	2
	4	T82		x		x		technological discontinuities and organizational environments adm sci q	54	7
	4	T86		x				technology foresight using roadmaps long range planning	18	1
	4	T87		x				technology policy and economic performance lessons from japan pinter	16	2
	4	T89		x				the age of the smart machine the future of work and power new york basic books	19	3
	4	T92		x				the delphi method techniques and applications reading ma	17	1
	4	T93		x		x		the discovery of grounded theory strategies for qualitative research aldine publishing chicago il	27	6
	4	T100		x				the innovator s solution creating and sustaining successful growth harvard busines	21	1
	4	T105		x				the myopia of learning strategic management	17	2
	4	T106		x				the relational view cooperative strategy and sources of interorganizational competitive advantage acad manage rev	17	1
	4	T108		x				the social psychology of organizing second ed reading addison wesley	19	3
	4	T110		x		x		the structure of scientific revolutions chicago university of chicag	29	7
	4	T112		x				the theory of planned behavior organizational behavior and human decision processes	20	2
	4	T117		x				user acceptance of information technology unified view mis quarterly	29	3
	4	T118		x				von democratizing innovation mi mass	17	1

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CLUSTER 5	5	T18	x					can cities shape socio technical transitions and how would we know if they were res policy	1	21
	5	T24	x					constructing transition paths through the management of niches path dependence and creation eds lawrence erlbaum mahwah nj london	3	16
	5	T34	x					experimenting for sustainable transport the approach of strategic niche management london gbr pp ix spo	2	35
	5	T39	x				x	from sectoral systems of innovation to socio technical systems insights about dynamics and change from sociology and institutional theory rese	6	64
	5	T54	x				x	networks of power electrification in western society 1880 1930 johns hopkin	7	25
	5	T55	x				x	of bicycles bakelites and bulbs theory of socio technical change mi ma	6	25
	5	T62	x					p innovation studies and sustainability transitions the allure of the multi level perspective and its challenges research policy	1	47
	5	T63	x					processes and patterns in transitions and system innovations refining the co evolutionary multi level perspective technological forecasting soci	1	22
	5	T68	x		x	x	x	science in action how to follow scientists and engineers through society cambridge ma harvar	13	24
	5	T71	x		x	x	x	shaping technology building society and eds mi ma	10	24
	5	T74	x					socio technological regimes and transition contexts system innovation and the transition to sustainability theory evidence and geels green eds	1	21
	5	T76	x					spatial perspective on sustainability transitions res policy	1	17
	5	T84	x					technological transitions and system innovations a co evolutionary and sociotechnical analysis cheltenham edward elgar	2	31
	5	T95	x					the dynamics of transitions in socio technical systems a multi level analysis of the transition pathway from horse drawn carriages to automobiles	1	32
	5	T104	x					the multi level perspective on sustainability transitions responses to seven criticisms environ innov soc trans	1	28
	5	T107	x	x	x	x	x	the social construction of technological systems cambridge ma mi	20	55
	5	T109	x		x	x	x	the social shaping of technology ope	12	22
	5	T115	x					understanding carbon lock in energy policy	2	32

Appendix D – Drivers of transitions

Panetti *et al.* (2018) identified seven drivers of technology transitions, as well as the sub-factors that act on them. The forces driving transitional change and the drivers of technology transitions are shown in Figure 31 (in Section 8.2.1.2.1.1) and Table 77 below.

Table 77. Drivers of transitions (Panetti *et al.*, 2018)

DRIVERS OF TRANSITIONS	SUB-FACTORS
Articulation of visions and expectations and social desirability	Measures that promote and create informed debate
	Development of a common language
	Transition arena
	Knowledge development and diffusion
Market formation	Articulation of visions and expectations
	Knowledge development and diffusion
	Network building
	Direct Equity Investment in promising niche companies
	Public R&D and education and training policy
	Provision of targeted engineering and consulting support for niche
	Measures that support the niche (e.g. Public procurement and fisca
	Socio-technical alignment
	Creation of legitimacy/Counteract resistance to change
Technology diffusion in mainstream markets and ideas	Niche scaling up
	Replication of projects within the niche
	Translation of niche ideas into mainstream settings
	Network building
	Civil society engagement
	Windows of opportunity for the breakthrough of radical novelties
	Knowledge development and diffusion
	Transition arena
	Prime movers
	New technology price/performance improvement
	Socio-technical alignment
	Market formation
Availability of complementary technologies	Market formation
Changes and the landscape level and regime instability	Transition
	Existing technologies' problems
	Negative externalities on other systems
	Firms' strategic games
	Measures to harness landscape changes to sustainability ends
Socio-technical alignment	Market formation
Lack of adaptive capabilities in the system	Does not appear to mediate the effect of any specific sub-factors*

* Panetti et al. 2018 states that this indicates an area for further investigation

Appendix E – Forces present in the South African electricity system

A systematic inquiry[62] into the forces present in the South African electricity sector yielded the forces shown in Table 78. These forces are also discussed in Section 9.4.1.2.1.

Table 78. Forces present in the South African electricity system

	FORMATION FORCES
PF1	Presence of renewable energy niche
PF2	Demand clean / renewable energy
PF3	Growing demand for affordable energy
PF4	Growing (change in) demand for energy
PF5	(Limited) proposed demand side interventions
PF6	Distributed (as per IRP) / private electricity generation
PF7	Energy storage (new functioning)

	SUPPORTIVE FORCES
PF7	Climate change mitigation requirements
PF8	International commitments to carbon targets
PF9	Natural endowment of coal
PF10	Investment into renewable energy niche
PF11	Increasing ease of implementation of RE technologies
PF12	Investment into coal-fired power plants
PF13	Political support for coal value chain
PF14	Beneficial regulations (incentives) to encourage investment into mines, refineries, etc.
PF15	Disinvestment in coal-fired operations (decommissioning of power plants)
PF16	Constrained policy environment for renewable energy
PF17	R&D into renewables, albeit at a slower pace than needed
PF18	Limited R&D into coal-based electricity generation
PF19	Limited focus on gas and nuclear (however, this is shifting)
PF20	Carbon capture and storage research insufficient
PF21	Carbon tax
PF22	Protection power over incumbent (Eskom) (jobs, vested interest)
PF23	Protection power over RE
PF24	Decreasing cost of RE (PV) technologies
PF25	Decommissioning of power plants
PF26	Uncertainty in both technology domains
PF27	Embedded interest in technology domains

	TRIGGERS
PF28	Supply side crises (load shedding) / deteriorating reliability of the reliability of supply
PF29	Financial deterioration of Eskom
PF30	REIPPPP failures
PF31	Increasing cost of electricity
PF32	Strikes / social unrest
PF33	Natural disasters (drought in Cape Town and other parts of SA)
PF34	Sudden changes in tariffs structures

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[62] Literature and interviews with sector experts.

Appendix F – Analysis of required forces

The definition and identification of the required forces is presented in Section 9.4.3.1.2. When considering the current system state (i.e., system performance/sustainability), the current state of the transition progress and transition capability of the South African electricity system, and the requirements to (i) improve the system performance, and (ii) support a successful transition (i.e., progress and capability), the forces that are required (i.e., required forces (RF), may be identified (see Table 64, Table 65, Table 66 and Table 67 for the respective technology domains). The forces are also summarised based on force type, shown in Table 79, Table 80, Table 81 and Table 82.

Table 79. Required formation forces per technology domain to address transition capability requirements sorted by force type (formation forces)

FORMATION FORCES					
INCUMBENT TECHNOLOGY DOMAIN			EMERGING/ALTERNATIVE TECHNOLOGY DOMAIN		
Presence of a niche	Presence of a new demand	Presence of a new functioning	Presence of a niche	Presence of a new demand	Presence of a new functioning
Presence of social demand for renewable electricity generation (RF1)	Decoupling of social and economic reliance on coal-fired electricity generation (RF3)	Carbon capture, demand side interventions, energy efficiencies, diversification of electricity generation (RF10)	Expansion of RE energy niche (RF12)	Increased effectiveness and efficiency of the structure of REIPPPP (RF15)	R&D and manufacturing of renewable energy technologies (RF23)
Creation of a new / hybrid institutional form** (RF2)	Reduce cost of electricity (RF4)	Increased adaptability in system (RF11)	Storage capacity niche (RF13)	Emerging/alternative technology domain to address socio-economic needs (RF16)	Increased adaptability in system (RF24)
	Guard against further lock-in (RF5)		Creation of a new / hybrid institutional form** (RF14)	Guard against increases in cost (RF17)	
	Common (transition) stability goal* (RF6)			Demand of new knowledge (demand articulation) (RF18)	
	Policy coordination across technology domains** (RF7)			Common (transition) stability goal* (RF19)	
	Diversification and scalable electricity generation mix in the incumbent technology domain (RF8)			Policy coordination across technology domains** (RF20)	
	Common adaptability goal (RF9)			Diversification and scalable electricity generation mix in the renewable energy niche (RF21)	
				Common adaptability goal (RF22)	

Table 80. Required supportive forces per technology domain to address transition capability requirements sorted by force type (supportive forces)

SUPPORTIVE FORCES					
INCUMBENT TECHNOLOGY DOMAIN			EMERGING/ALTERNATIVE TECHNOLOGY DOMAIN		
Standardisation of practices	Provision of resources	Exercise of power	Standardisation of practices	Provision of resources	Exercise of power
Regulation of practices based on ecosystem's thresholds/limitations (RF25)	Maintain capacity - to the extent where he fulfilment of the societal function is dependent on the incumbent technology domain (RF26)	Phase-out of coal-fired electricity generation technologies (RF32)	Institutionalise RE technologies (standardisation of practices (i.e. ensuring that electricity generation via renewable energy enjoys universal status) (RF37)	Provide resources to RE niche in order to expand (RF38)	Legitimise institutions in the emerging/alternative technology domain (RF43)
	Reduced political support for coal-fired electricity generation (RF27)	Protection of new markets (RF33)		Social and political support for emerging/ alternative technology domain (RF39)	Increase support for cross-domain activities** (RF44)
	Societal support for RE technology for electricity generation (RF28)	Increase the number of supporters for the renewable energy niche / emerging/alternative technology domain (RF34)		Support and expansion of renewable energy niche (RF40)	
	Maintain (sufficient) capacity (RF29)	Control over the use of resources by government (RF35)		Legitimise new (hybrid) institution** (RF41)	
	Legitimise new (hybrid) institution** (RF30)	Increase support for cross-domain activities* (RF36)		Investment in new markets and infrastructure within the renewable energy niche (RF42)	
	Investment in new markets and infrastructure within the incumbent technology domain (RF31)				

Table 81. Required formation forces per technology domain to address system performance

FORMATION FORCES					
INCUMBENT TECHNOLOGY DOMAIN			EMERGING/ALTERNATIVE TECHNOLOGY DOMAIN		
Presence of a niche	Presence of a new demand	Presence of a new functioning	Presence of a niche	Presence of a new demand	Presence of a new functioning
Presence of a new social movement for environmental sustainability within the incumbent technology domain (RF45)	Demand for increasingly environmentally friendly technologies (RF47)	New market for previously locked-in organisations (RF51)	Increasing dependence on the renewable energy niche to fulfil societal functions (RF52)	Socio-economic demand from renewable energy niche* (RF54)	-
Creation of hybrid institutions to manage the shift in socio-economic dependence* (RF46)	Demand for new decision-making processes (RF48)		Creation of hybrid institutions to manage the shift in socio-economic dependence* (RF53)	Demand for new knowledge and technology to facilitate the transition* (RF55)	
	Socio-economic demand from renewable energy niche* (RF49)				
	Demand for new knowledge and technology to facilitate the transition* (RF50)				

Table 82. Required supportive forces per technology domain to address system performance sorted by force type (supportive forces)

SUPPORTIVE FORCES					
INCUMBENT TECHNOLOGY DOMAIN			EMERGING/ALTERNATIVE TECHNOLOGY DOMAIN		
Standardisation of practices	Provision of resources	Exercise of power	Standardisation of practices	Provision of resources	Exercise of power
Regulation of practices based on ecosystem's threshold/limitations (global demand for coal likely to decrease & environmental impact of coal-fired electricity generation) (RF56)	Provide resources to the development of interventions that can reduce the impact of the coal-based electricity generation on the environment* (RF57)	Control over technology, i.e. phase out of coal-fired power plants (RF61)	-	Investment into the renewable energy niche (RF62)	Protection of the market by government (RF66)
	Investment into the renewable energy technologies* (RF58)			Investment into the renewable energy technologies* (RF63)	Increase the number of supporters for the renewable energy niche (RF67)
	Disinvestment into the expansion of the incumbent technology domain* (RF59)			Disinvestment into the expansion of the incumbent technology domain* (RF64)	
	Invest in markets that will support the socio-economic requirements from the renewable energy niche* (RF60)			Invest in markets that will support the socio-economic requirements from the renewable energy niche* (RF65)	

Appendix G – Evaluation of present and required forces

The required forces identified in Sub-phase 3.2 (see Section 9.4.3.1.2), are evaluated inTable 83, Table 84, and Table 85 to determine whether the forces are present or absent, whether they drive or resist transition progress, and whether they contribute positively or negatively towards stability, adaptability and the system performance elements.

Table 83. Evaluation of present forces in the South African electricity system

			DRIVE	RESIST	EMERGING / WEAK	STRONG
FORMATION FORCES	PF1	Presence of renewable energy niche	X			
	PF2	Demand clean / renewable energy	X			
	PF3	Growing demand for affordable energy	X			
	PF4	Growing (change in) demand for energy	X			
	PF5	(Limited) proposed demand side interventions	X			
	PF6	Distributed (as per IRP) / private electricity generation	X			
	PF7	Energy storage (new functioning)	X			
SUPPORTIVE FORCES	PF8	Climate change mitigation requirements	X			
	PF9	International commitments to carbon targets	X			
	PF10	Natural endowment of coal		X		X
	PF11	Investment into renewable energy niche	X			
	PF12	Increasing ease of implementation of RE technologies	X			
	PF13	Investment into coal-fired power plants		X		X
	PF14	Political support for coal value chain		X		X
	PF15	Beneficial regulations (incentives) to encourage investment into mines, refineries, etc.		X	X	
	PF16	Disinvestment in coal-fired operations (decommissioning of power plants)	X			
	PF17	Constrained policy environment for renewable energy		X	X	
	PF18	R&D into renewables, albeit at a lower pace than needed	X			
	PF19	Limited R&D into coal-based electricity generation	X			
	PF20	Limited focus on gas and nuclear (however, this is shifting)	X			
	PF21	Carbon capture and storage research insufficient	X			
	PF22	Carbon tax	X			
	PF23	Protection power over incumbent (Eskom) (jobs, vested interest)		X		X
	PF24	Protection power over RE	X			
	PF25	Decreasing cost of RE (PV) technologies	X			
	PF26	Decommissioning of power plants	X			
	PF27	Uncertainty in both technology domains		X	X	
	PF28	Embedded interest in technology domains		X		X
FORMATION FORCES	PF29	Supply side crises (load shedding) / deteriorating reliability of the reliability of supply	X			
	PF30	Financial deterioration of Eskom	X			
	PF31	REIPPPP failures		X	X	
	PF32	Increasing cost of electricity	X			
	PF33	Strikes / social unrest		X	X	
	PF34	Sudden changes in tariffs structures		X	X	

Table 84. Evaluation of required forces for transition progress and transition capability in the South African electricity system

				PROGRESS				STABILITY				ADAPTABILITY										QUALITY PROPERTIES		ACTION REQUIRED		
PROGRESS (P), STABILITY (S) OR ADAPTABILITY (A)	FOMATION / SUPPORTIVE FORCES	TYPE OF FORCE	TECHNOLOGY DOMAIN	PTi	PTe/a	PSi	PSe/a	STi	STe/a	SSi	SSe/a	ATi	ATe/a	ASi	ASe/a	S	T	FORCE	FORCE REFERENCE	PRESENT	ABSENT	INSUFFICIENT	SUFFICIENT	CREATE / GENERATE	DEVELOP	EXPLOIT
P	FORMATION FORCES	PoN	INCUMBENT TECHNOLOGY DOMAIN			x										x		Presence of social demand for renewable electricity generation (RF1)	RF1	X		X			X	
S & A		PoN								x				x		x		Creation of a new / hybrid institutional form** (RF2)	RF2**		X			X		
P		PoND				x										x	x	Decoupling of social and economic reliance on coal-fired electricity generation (RF3)	RF3	X		X			X	
S		PoND						x									x	Reduce cost of electricity (RF4)	RF4		X			X		
S		PoND						x								x	x	Guard against further lock-in (RF5)	RF5		X			X		
S		PoND								x						x		Common (transition) stability goal* (RF6)	RF6*		X			X		
A		PoND												x		x		Policy coordination across technology domains** (RF7)	RF7**		X			X		
A		PoND										x					x	Diversification and scalable electricity generation mix in the incumbent technology domain (RF8)	RF8	X		X			X	
A		PoND												x		x		Common adaptability goal (RF9)	RF9*		X			X		
P		PoNF		x													x	Carbon capture, demand side interventions, energy efficiencies, diversification of electricity generation (RF10)	RF10	X		X			X	
A		PoNF										x				x	x	Increased adaptability in system (RF11)	RF11*	X		X			X	
P		PoN	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN		x												x	Expansion of RE energy niche (RF12)	RF12	X		X			X	
P		PoN			x												x	Storage capacity niche (RF13)	RF13		X			X		
S		PoN									x					x		Creation of a new / hybrid institutional form** (RF14)	RF14**		X			X		
P		PoND			x												x	Increased effectiveness and efficiency of the structure of REIPPPP (RF15)	RF15	X		X			X	
P		PoND					x										x	Emerging/alternative technology domain to address socio-economic needs (RF16)	RF16	X		X			X	
S		PoND							x								x	Guard against increases in cost (RF17)	RF17	X			X			X
S		PoND							x								x	Demand of new knowledge (demand articulation) (RF18)	RF18		X			X		
S		PoND									x					x		Common (transition) stability goal* (RF19)	RF19*		X			X		
S		PoND									x					x		Policy coordination across technology domains** (RF20)	RF20		X			X		
A		PoND											x				x	Diversification and scalable electricity generation mix in the renewable energy niche (RF21)	RF21	X			X			X
A		PoND													x	x		Common adaptability goal (RF22)	RF22*		X			X		
P		PoNF			x												x	R&D and manufacturing of renewable energy technologies (RF23)	RF23	X		X			X	
A		PoNF											x				x	Increased adaptability in system (RF24)	RF24*	X			X			X

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A	SUPPORTIVE FORCES	SoP	INCUMBENT TECHNOLOGY DOMAIN									x			x		Regulation of practices based on ecosystem's thresholds/limitations (RF25)	RF25		X			X		
P		PoR		x												x	Maintain capacity - to the extent where he fulfilment of the societal function is dependent on the incumbent technology domain (RF26)	RF26	X			X			X
P		PoR				x									x		Reduced political support for coal-fired electricity generation (RF27)	RF27	X		X			X	
P		PoR				x									x		Societal support for RE technology for electricity generation (RF28)	RF28	X		X			X	
S		PoR						x								x	Maintain (sufficient) capacity (RF29)	RF29	X			X			X
S		PoR								x					x		Legitimise new (hybrid) institution** (RF30)	RF30**		X			X		
P		PoR		x												x	Investment in new markets and infrastructure within the incumbent technology domain (RF31)	RF31	X		X			X	
P		EoP		x												x	Phase-out of coal-fired electricity generation technologies (RF32)	RF32	X		X			X	
P		EoP		x											x		Protection of new markets (RF33)	RF33		X			X		
S		EoP							x						x		Increase the number of supporters for the renewable energy niche/emerging/alternative technology domain (RF34)	RF34	X		X			X	
A		EoP										x			x		Control over the use of resources by government (RF35)	RF35	X		X			X	
A		EoP												x	x		Increase support for cross-domain activities* (RF36)	RF36*		X			X		
P		SoP	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN		x										x		Institutionalise RE technologies (standardisation of practices (i.e. ensuring that electricity generation via renewable energy enjoys universal status) (RF37)	RF37	X		X			X	
P		PoR			x											x	Provide resources to RE niche in order to expand (RF38)	RF38	X		X			X	
P		PoR					x								x		Social and political support for emerging/ alternative technology domain (RF39)	RF39	X		X			X	
S		PoR							x						x	x	Support and expansion of renewable energy niche (RF40)	RF40	X		X			X	
S		PoR									x				x		Legitimise new (hybrid) institution** (RF41)	RF41**		X			X		
A		PoR											x			x	Investment in new markets and infrastructure within the renewable energy niche (RF42)	RF42	X		X			X	
P		EoP					x								x		Legitimize institutions in the emerging/alternative technology domain (RF43)	RF43	X		X			X	
S		EoP									x				x		Increase support for cross-domain activities** (RF44)	RF44		X			X		

Table 85. Evaluation of required forces for system performance in the South African electricity system

			SYSTEM PERFORMANCE ELEMENTS									QUALITY PROPERTIES		ACTION REQUIRED		
FOMATION / SUPPORTIVE FORCES	TYPE OF FORCE	TECHNOLOGY DOMAIN	ENVIRONMENTAL SYSTAINABILITY	ENERGY ACCESS AND SECURITY	ECONOMIC GROWTH AND DEVELOPMENT	S	T	FORCE	FORCE REFERENCE	PRESENT	ABSENT	INSUFFICIENT	SUFFICIENT	CREATE / GENERATE	DEVELOP	EXPLOIT
FORMATION FORCES	PoN	INCUMBENT TECHNOLOGY DOMAIN	X			X		Presence of a new social movement for environmental sustainability within the incumbent technology domain (RF45)	RF45	X		X			X	
	PoN			X	X	X		Creation of hybrid institutions to manage the shift in socio-economic dependence* (RF46)	RF46*		X			X		
	PoND		X				X	Demand for increasingly environmentally friendly technologies (RF47)	RF47	X		X			X	
	PoND		X			X		Demand for new decision-making processes (RF48)	RF48*	X		X			X	
	PoND			X	X	X	X	Socio-economic demand from renewable energy niche (RF49)	RF49	X			X			X
	PoND			X	X	X	X	Demand for new knowledge and technology to facilitate the transition* (RF50)	RF50*	X		X			X	
	PoNF		X				X	New market for previously locked-in organisations (RF51)	RF51	X		X			X	
	PoN	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN	X				X	Increasing dependence on the renewable energy niche to fulfil societal functions (RF52)	RF52	X		X			X	
	PoN			X	X	X		Creation of hybrid institutions to manage the shift in socio-economic dependence* (RF53)	RF53*		X			X		
	PoND			X	X	X	X	Socio-economic demand from renewable energy niche* (RF54)	RF54	X		X			X	
	PoND			X	X	X		Demand for new knowledge and technology to facilitate the transition* (RF55)	RF55	X		X			X	
SUPPORTIVE FORCES	SoP	INCUMBENT TECHNOLOGY DOMAIN	X			X		Regulation of practices based on ecosystem's threshold/limitations (global demand for coal likely to decrease & environmental impact of coal-fired electricity generation) (RF56)	RF56	X		X			X	
	PoR		X			X	X	Provide resources to the development of interventions that can reduce the impact of the coal-based electricity generation on the environment* (RF57)	RF57*	X		X			X	
	PoR			X	X		X	Investment into the renewable energy technologies* (RF58)	RF58*	X		X			X	
	PoR			X	X		X	Disinvestment into the expansion of the incumbent technology domain* (RF59)	RF59*	X		X			X	
	PoR			X	X		X	Invest in markets that will support the socio-economic requirements from the renewable energy niche* (RF60)	RF60*		X			X		
	EoP		X			X		Control over technology, i.e. phase out of coal-fired power plants (RF61)	RF61	X		X			X	
	PoR	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN	X				X	Investment into the renewable energy niche (RF62)	RF62	X		X			X	
	PoR			X	X		X	Investment into the renewable energy technologies* (RF63)	RF63*	X		X			X	
	PoR			X	X		X	Disinvestment into the expansion of the incumbent technology domain* (RF64)	RF64*	X		X			X	
	PoR			X	X		X	Invest in markets that will support the socio-economic requirements from the renewable energy niche* (RF65)	RF65*		X			X		
	EoP		X			X		Protection of the market by government (RF66)	RF66	X		X			X	
	EoP		X			X		Increase the number of supporters for the renewable energy niche (RF67)	RF67	X		X			X	

Appendix H – Evaluation of the impact of present and required forces

The impact of the required actions (exploit, develop, create/generate), which guide the technology management considerations, across the transition progress, transition capability and system performance elements, should be evaluated in order to identify risks. This evaluation is shown in Table 86 and Table 87, and highlights the importance of considering the required actions across transition progress, transition capability and system performance elements.

Table 86. Evaluation of the impact of the required forces for transition progress and transition capability in the South African electricity system

				PROGRESS				STABILITY				ADAPTABILITY										QUALITY PROPERTIES		ACTION REQUIRED		
PROGRESS (P), STABILITY (S) OR ADAPTABILITY (A)	FOMATION / SUPPORTIVE FORCES	TYPE OF FORCE	TECHNOLOGY DOMAIN	PTi	PTe/a	PSi	PSe/a	STi	STe/a	SSi	SSe/a	ATi	ATe/a	ASi	ASe/a	S	T	FORCE	FORCE REFERENCE	PRESENT	ABSENT	INSUFFICIENT	SUFFICIENT	CREATE / GENERATE	DEVELOP	EXPLOIT
P	FORMATION FORCES	PoN	INCUMBENT TECHNOLOGY DOMAIN			x										x		Presence of social demand for renewable electricity generation (RF1)	RF1	X		X			X	
S & A		PoN								x				x		x		Creation of a new / hybrid institutional form** (RF2)	RF2**		X			X		
P		PoND				x										x	x	Decoupling of social and economic reliance on coal-fired electricity generation (RF3)	RF3	X		X			X	
S		PoND						x									x	Reduce cost of electricity (RF4)	RF4		X			X		
S		PoND						x								x	x	Guard against further lock-in (RF5)	RF5		X			X		
S		PoND								x						x		Common (transition) stability goal* (RF6)	RF6*		X			X		
A		PoND												x		x		Policy coordination across technology domains** (RF7)	RF7**		X			X		
A		PoND										x					x	Diversification and scalable electricity generation mix in the incumbent technology domain (RF8)	RF8	X		X			X	
A		PoND												x		x		Common adaptability goal (RF9)	RF9*		X			X		
P		PoNF		x													x	Carbon capture, demand side interventions, energy efficiencies, diversification of electricity generation (RF10)	RF10	X		X			X	
A		PoNF										x				x	x	Increased adaptability in system (RF11)	RF11*	X		X			X	
P		PoN	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN		x												x	Expansion of RE energy niche (RF12)	RF12	X		X			X	
P		PoN			x												x	Storage capacity niche (RF13)	RF13		X			X		
S		PoN									x					x		Creation of a new / hybrid institutional form** (RF14)	RF14**		X			X		
P		PoND			x												x	Increased effectiveness and efficiency of the structure of REIPPPP (RF15)	RF15	X		X			X	
P		PoND					x										x	Emerging/alternative technology domain to address socio-economic needs (RF16)	RF16	X		X			X	
S		PoND							x								x	Guard against increases in cost (RF17)	RF17	X			X			X
S		PoND							x								x	Demand of new knowledge (demand articulation) (RF18)	RF18		X			X		
S		PoND									x					x		Common (transition) stability goal* (RF19)	RF19*		X			X		
S		PoND									x					x		Policy coordination across technology domains** (RF20)	RF20		X			X		
A		PoND											x				x	Diversification and scalable electricity generation mix in the renewable energy niche (RF21)	RF21	X			X			X
A		PoND													x	x		Common adaptability goal (RF22)	RF22*		X			X		
P		PoNF			x												x	R&D and manufacturing of renewable energy technologies (RF23)	RF23	X		X			X	
A		PoNF											x				x	Increased adaptability in system (RF24)	RF24*	X			X			X
A	SUPPORTIVE FORCES	SoP	INCUMBENT TECHNOLOGY DOMAIN									x				x		Regulation of practices based on ecosystem's thresholds/limitations (RF25)	RF25		X			X		
P		PoR		x													x	Maintain capacity - to the extent where he fulfilment of the societal function is dependent on the incumbent technology domain (RF26)	RF26	X			X			X
P		PoR				x										x		Reduced political support for coal-fired electricity generation (RF27)	RF27	X		X			X	
P		PoR				x										x		Societal support for RE technology for electricity generation (RF28)	RF28	X		X			X	
S		PoR						x									x	Maintain (sufficient) capacity (RF29)	RF29	X			X			X
S		PoR								x						x		Legitimise new (hybrid) institution** (RF30)	RF30**		X			X		
P		PoR		x													x	Investment in new markets and infrastructure within the incumbent technology domain (RF31)	RF31	X		X			X	
P		EoP		x													x	Phase-out of coal-fired electricity generation technologies (RF32)	RF32	X		X			X	
P		EoP		x												x		Protection of new markets (RF33)	RF33		X			X		
S		EoP							x							x		Increase the number of supporters for the renewable energy niche/emerging/alternative technology domain (RF34)	RF34	X		X			X	
A		EoP										x				x		Control over the use of resources by government (RF35)	RF35	X		X			X	
A		EoP												x		x		Increase support for cross-domain activities* (RF36)	RF36*		X			X		
P		SoP	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN		x											x		Institutionalise RE technologies (standardisation of practices (i.e. ensuring that electricity generation via renewable energy enjoys universal status) (RF37)	RF37	X		X			X	
P		PoR			x												x	Provide resources to RE niche in order to expand (RF38)	RF38	X		X			X	
P		PoR					x									x		Social and political support for emerging/ alternative technology domain (RF39)	RF39	X		X			X	
S		PoR							x							x	x	Support and expansion of renewable energy niche (RF40)	RF40	X		X			X	
S		PoR									x					x		Legitimise new (hybrid) institution** (RF41)	RF41**		X			X		
A		PoR											x				x	Investment in new markets and infrastructure within the renewable energy niche (RF42)	RF42	X		X			X	
P		EoP					x									x		Legitimize institutions in the emerging/alternative technology domain (RF43)	RF43	X		X			X	
S		EoP									x					x		Increase support for cross-domain activities** (RF44)	RF44		X			X		

	PROGRESS			STABILITY			ADAPTABILITY			ENVIRONMENTAL SUSTAINABILITY			ENERGY ACCESS AND SECURITY			ECONOMIC GROWTH AND DEVELOPMENT		
FORCE REFERENCE	DRIVE	RESIST	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	N/A	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR
RF1	-	-	-	RF1	-	-	RF1	-	-	RF1	-	-	-	-	RF1	-	-	RF1
RF2**	-	-	RF2	RF2	-	-	RF2	-	-	-	-	RF2	RF2	-	-	RF2	-	-
RF3	RF3	-	-	-	RF3	-	RF3	-	-	RF3	-	-	-	-	RF3	RF3	-	-
RF4	-	RF4	-	-	-	-	-	-	RF4	-	-	RF4	RF4	-	-	RF4	-	-
RF5	RF5	-	-	-	-	-	RF5	-	-	RF5	-	-	-	-	RF5	-	-	RF5
RF6*	RF6	-	-	-	-	-	RF6	-	-	RF6	-	-	-	-	RF6	-	-	RF6
RF7**	RF7	-	-	RF7	-	-	-	-	-	RF7	-	-	RF7	-	-	RF7	-	-
RF8	-	-	RF8	RF8	-	-	-	-	-	-	-	RF8	-	-	RF8	-	-	RF8
RF9*	-	-	RF9	RF9		-	-	-	-	-	-	RF9	-	-	RF9	-	-	RF9
RF10	-	-	-	RF10		-	RF10	-	-	RF10	-	-	RF10	-	-	RF10	-	-
RF11*	-	-	RF11	RF11		-	-	-	-	-	-	RF11	-	-	RF11	-	-	RF11
RF12	-	-	-	RF12	-	-	RF12	-	-	RF12	-	-	RF12	-	-	RF12		-
RF13	-	-	-	RF13	-	-	RF13	-	-	RF13	-	-	RF13	-	-	-	-	RF13
RF14**	RF14	-	-	-	-	-	RF14	-	-	RF14	-	-	-	-	RF14	-	-	RF14
RF15	-	-	-	RF15	-	-	-	-	RF15	RF15	-	-	RF15	-	-	RF15	-	-
RF16	-	-	-	RF16	-	-	-	-	RF16	-	-	RF16	RF16	-	-	RF16	-	-
RF17	RF17	-	-	-	-	-	RF17	-	-	RF17	-	-	RF17	-	-	RF17	-	-
RF18	RF18	-	-	-	-	-	RF18	-	-	RF18	-	-	RF18	-	-	RF18	-	-
RF19*	RF19	-	-	-	-	-	RF19	-	-	RF19	-	-	-	-	RF19	-	-	RF19
RF20	RF20	-	-	-	-	-	RF20	-	-	RF20	-	-	-	-	RF20	-	-	RF20
RF21	RF21	-	-	RF21	-	-	-	-	-	RF21	-		RF21	-	-	RF21	-	-
RF22*	-	-	RF22	RF22		-	-	-	-	-	-	RF22	-	-	RF22	-	-	RF22
RF23	-	-	-	RF23	-	-	RF23	-	-	RF23	-	-	RF23	-	-	RF23	-	-
RF24*	-	-	RF24	RF24		-	-	-	-	-	-	RF24	-	-	RF24	-	-	RF24
RF25	RF25	-	-			RF25	-	-	-	RF25	-	-	-	-	RF25	-	-	RF25
RF26	-	-	-	RF26	-	-	-	RF26	-	-	RF26	-	RF26	-	-	RF26	-	-
RF27	R&27	-	-	-	RF27	-	RF27	-	-	RF27	-	-	-	-	RF27	-	-	RF27
RF28	-	-	-	RF28	-	-	RF28	-	-	RF28	-	-	-	-	RF28	-	-	RF28
RF29	-	RF29	-	-	-	-	-	RF29	-	-	RF29	-	RF29	-	-	RF29	-	-
RF30**	RF30	-	-	-	-	-	RF30	-	-	RF30	-	-	-	-	RF30	-	-	RF30
RF31	-	-	-	RF31	-	-	RF31	-	-	RF31	-	-	RF31	-	-	RF31	-	-
RF32	RF32	-	-	-	RF32	-	RF32	-	-	RF32	-	-	-	RF32	-	-	RF32	-
RF33	-	-	-	RF33	-	-	RF33	-	-	RF33	-	-	RF33	-	-	RF33	-	-
RF34	RF34	-	-	-	-	-	RF34	-	-	RF34	-	-	-	-	RF34	-	-	RF34
RF35	-	-	RF35	-	-	RF35	-	-	-	-	-	RF35	-	-	RF35	-	-	RF35
RF36*	RF36	-	-	RF36	-	-	-	-	-	RF36	-	-	RF36	-	-	RF36	-	-
RF37	-	-	-	RF37	-	-	RF37	-	-	RF37	-	-	RF37	-	-	RF37	-	-
RF38	-	-	-	RF38	-	-	RF38	-	-	RF38	-	-	RF38	-	-	RF38	-	-
RF39	-	-	-	RF39		-	RF39	-	-	RF39	-	-	RF39	-	-	RF39	-	-
RF40	RF40	-	-	-	-	-	RF40	-	-	RF40	-	-	RF40	-	-	RF40	-	-
RF41**	RF41	-	-	-	-	-	RF41	-	-	RF41	-	-	-	-	RF41	-	-	RF41
RF42	RF36	-	-	RF36	-	-	-	-	-	RF36	-	-	RF36	-	-	RF36	-	-
RF43	-	-	-	RF43	-	-	RF43	-	-	RF43	-	-	RF43	-	-	RF43	-	-
RF44	-	-	RF44	-	-	-	RF44	-	-	-	-	RF44	RF44	-	-	RF44	-	-

Table 87. Evaluation of the impact of the required forces for system performance in the South African electricity system

FOMATION / SUPPORTIVE FORCES	TYPE OF FORCE	TECHNOLOGY DOMAIN	SYSTEM PERFORMANCE ELEMENTS			S	T	FORCE	FORCE REFERENCE	PRESENT	ABSENT	QUALITY PROPERTIES		ACTION REQUIRED		
			ENVIRONMENTAL SYSTAINABILITY	ENERGY ACCESS AND SECURITY	ECONOMIC GROWTH AND DEVELOPMENT							INSUFFICIENT	SUFFICIENT	CREATE / GENERATE	DEVELOP	EXPLOIT
FORMATION FORCES	PoN	INCUMBENT TECHNOLOGY DOMAIN	X			X		Presence of a new social movement for environmental sustainability within the incumbent technology domain (RF45)	RF45	X		X			X	
	PoN			X	X	X		Creation of hybrid institutions to manage the shift in socio-economic dependence* (RF46)	RF46*		X			X		
	PoND		X				X	Demand for increasingly environmentally friendly technologies (RF47)	RF47	X		X			X	
	PoND		X			X		Demand for new decision-making processes (RF48)	RF48*	X		X			X	
	PoND			X	X	X	X	Socio-economic demand from renewable energy niche (RF49)	RF49	X			X			X
	PoND			X	X	X	X	Demand for new knowledge and technology to facilitate the transition* (RF50)	RF50*	X		X			X	
	PoNF		X				X	New market for previously locked-in organisations (RF51)	RF51	X		X			X	
	PoN	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN	X				X	Increasing dependence on the renewable energy niche to fulfil societal functions (RF52)	RF52	X		X			X	
	PoN			X	X	X		Creation of hybrid institutions to manage the shift in socio-economic dependence* (RF53)	RF53*		X			X		
	PoND			X	X	X	X	Socio-economic demand from renewable energy niche* (RF54)	RF54	X		X			X	
	PoND			X	X	X		Demand for new knowledge and technology to facilitate the transition* (RF55)	RF55	X		X			X	
SUPPORTIVE FORCES	SoP	INCUMBENT TECHNOLOGY DOMAIN	X			X		Regulation of practices based on ecosystem's threshold/limitations (global demand for coal likely to decrease & environmental impact of coal-fired electricity generation) (RF56)	RF56	X		X			X	
	PoR		X			X	X	Provide resources to the development of interventions that can reduce the impact of the coal-based electricity generation on the environment* (RF57)	RF57*	X		X			X	
	PoR			X	X		X	Investment into the renewable energy technologies* (RF58)	RF58*	X		X			X	
	PoR			X	X		X	Disinvestment into the expansion of the incumbent technology domain* (RF59)	RF59*	X		X			X	
	PoR			X	X		X	Invest in markets that will support the socio-economic requirements from the renewable energy niche* (RF60)	RF60*		X			X		
	EoP		X			X		Control over technology, i.e. phase out of coal-fired power plants (RF61)	RF61	X		X			X	
	PoR	EMERGING/ ALTERNATIVE TECHNOLOGY DOMAIN	X				X	Investment into the renewable energy niche (RF62)	RF62	X		X			X	
	PoR			X	X		X	Investment into the renewable energy technologies* (RF63)	RF63*	X		X			X	
	PoR			X	X		X	Disinvestment into the expansion of the incumbent technology domain* (RF64)	RF64*	X		X			X	
	PoR			X	X		X	Invest in markets that will support the socio-economic requirements from the renewable energy niche* (RF65)	RF65*		X			X		
	EoP		X			X		Protection of the market by government (RF66)	RF66	X		X			X	
	EoP		X			X		Increase the number of supporters for the renewable energy niche (RF67)	RF67	X		X			X	

FORCE REFERENCE	PROGRESS			STABILITY			ADAPTABILITY			ENVIRONMENTAL SUSTAINABILITY			ENERGY ACCESS AND SECURITY			ECONOMIC GROWTH AND DEVELOPMENT		
	DRIVE	RESIST	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	N/A	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR	POSITIVE CONTRIBUTION	NEGATIVE CONTRIBUTION	CORRELATION NOT CLEAR
RF45	RF45	-	-	-	-	RF45	RF45	-	-	-	-	-	-	-	RF45	-		RF45
RF46*	RF47	-	-	-	-	RF47	-	-	RF47	-	-	RF47	RF47	-	-	RF47	-	-
RF47	RF47	-	-	-	-	RF47	RF47	-	-	-	-	-	-	-	RF47	-	-	RF47
RF48*	RF48	-	-	-	-	RF48	-	-	RF48	-	-	-	-	-	RF48	-	-	RF48
RF49	RF49	-	-	-	RF49	-	RF49	-	-	RF49	-	-	RF49		-	RF49		-
RF50*	RF50	-	-	RF50	-	-	RF50	-	-	RF50	-	-	RF50	-	-	RF50	-	-
RF51	-	-	RF51	RF51	-	-	RF51	-	-	-	-	-	-	-	RF51	-	-	RF51
RF52	RF52	-	-	RF52	-	-	RF52	-	-	-	-	-	RF52	-	-	-	-	RF52
RF53*	RF53	-	-	-	-	RF53	-	-	RF53	RF53	-	-	RF53	-	-	RF53	-	-
RF54	RF54	-	-	RF54	-	-	RF54	-	-	RF54	-	-	RF54	-	-	RF54	-	-
RF55	RF55	-	-	RF55	-	-	RF55	-	-	RF55	-	-	RF55	-	-	RF55	-	-
RF56	RF56	-	-	-	RF56	-	-	-	RF56	-	-	-	-	RF56	-			
RF57*	RF57	-	-	RF57	-	-	-	-	RF57	-	-	-	-	-	RF57	-	-	RF57
RF58*	RF58	-	-	RF58	-	-	RF58	-	-	RF58	-	-	RF58	-	-	RF58	-	-
RF59*	RF59	-	-	RF59		-	RF59	-	-	RF59	-	-	RF59		-	RF59		-
RF60*	RF60	-	-	RF60	-	-	RF60	-	-	RF60	-	-	RF60	-	-	RF60	-	-
RF61	RF61	-	-	-	RF61	-	-	-	RF61	-	-	-	-	RF61	-	-	RF61	-
RF62	RF62	-	-	RF62	-	-	RF62	-	-	-	-	-	RF62	-	-	RF62	-	-
RF63*	RF63	-	-	RF63	-	-	RF63	-	-	RF63	-	-	RF63	-	-	RF63	-	-
RF64*	RF64	-	-	RF64		-	RF64	-	-	RF64	-	-	-	RF64	-	-	RF64	-
RF65*	RF65	-	-	RF65	-	-	RF65	-	-	RF65	-	-	RF65	-	-	RF65	-	-
RF66	RF66	-	-	RF66	-	-	RF66	-	-	-	-	-	RF66	-	-	RF66	-	-
RF67	RF67	-	-	RF67	-	-	RF67	-	-	-	-	-	RF67	-	-	RF67	-	-