The Blockchain-Energy Nexus

An exploration of the potential for blockchain in a transition to a low-carbon energy system in South Africa

By

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Declaration

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Abstract

South Africa needs to transition away from a fossil fuel-intensive energy system if it is to reduce its carbon emissions. There is both a need for the development of renewable energy technologies, and for systems to manage electricity flows in municipal distribution networks which increasingly comprise buildings with private generation such as roof-mounted solar panels. Blockchain has the potential to address both needs. How blockchain applications can form part of the dominant South African energy regime are largely unknown, as are the implications of doing so. Research has shown that blockchain can be used to crowd-finance renewable energy projects and to manage electricity trading between small-scale producers and consumers of electricity. This study aims to understand how an existing Sun Exchange solar project finance blockchain application has been developed and integrated into the South African energy system and what its impacts are. It further aims to determine the viability and prospects of blockchain-based electricity trading in South Africa. Contributing to the research on the applicability of blockchain in the South African energy system, the research asks: How is the project finance innovation developing and integrating into the South African energy system, and is there potential for it to form part of a new dominant regime? Is also asks: Is there potential for blockchain-based electricity trading in South Africa, how can it be developed, and how might it affect the energy system?

To answer the research questions a review of the literature on energy transitions, the South African energy system, blockchain technology, and theories of multi-level perspective and strategic niche management which explore sociotechnical regime transitions, was conducted. A participative case study was used to research the Sun Exchange organisation and its blockchain-based solar project finance innovation. Interviews were conducted to research the viability and prospects of blockchain-based electricity trading in South Africa.

The case study revealed that Sun Exchange uses many developmental best practices proposed by the strategic niche management theory for its project finance innovation. It also identified that it would be beneficial for the organisation to

constantly question underlying assumptions regarding which type of blockchain it uses due to the evolving nature of the technology. The case study further revealed it is unlikely that the project finance innovation will form part of the dominant energy regime in South Africa if the barrier which currently limits Sun Exchange projects to a maximum size of 10 Megawatts (MW), is not overcome.

The interviews revealed that there is potential for the development of a blockchain-based electricity trade application and that the most viable way for it to be incorporated into the energy system would be if it were implemented by municipalities that own their distribution networks for managing electricity trading. Such an application seems to have many positive implications, particularly for municipalities, consumers, and developers of renewable energy technologies, and for reducing the country's carbon emissions. Barriers to the integration of the application were identified as primarily relating to legislation. It is recommended that a public-private partnership be initiated for the development of the application and that further research be conducted to establish exactly which organisations could contribute to this collaboration and how it could be financed, developed, and integrated into the dominant energy regime.

Opsomming

Suid-Afrika moet van 'n fossielbrandstofintensiewe energiestelsel oorgaan om die koolstofvrystellings te verminder. Daar is beide 'n behoefte aan die ontwikkeling van tegnologieë vir hernubare energie, sowel as vir stelsels om elektrisiteitsvloei te bestuur in munisipale verspreidingsnetwerke wat toenemend geboue met private opwekking soos sonkragpanele op die dak behels. Blokkeketting (Blockchain) het die potensiaal om in albei behoeftes te voorsien. Hoe Blokkeketting -toepassings deel kan vorm van die dominante Suid-Afrikaanse energie-netwerk is grootliks onbekend, en ook die implikasies daarvan. Navorsing het getoon dat Blokkeketting gebruik kan word om projekte vir hernubare energie te finansier en om handel te dryf tussen kleinskaalse produsente en elektrisiteitsverbruikers. Hierdie studie het ten doel om te verstaan hoe 'n bestaande Sun Exchange-sonkrag-projekfinansiering Blokkeketting-toepassing ontwikkel en geïntegreer kan word in die Suid-Afrikaanse energiestelsel en wat die gevolge daarvan sal wees. Dit het verder ten doel om die lewensvatbaarheid en vooruitsigte van Blokkeketting-gebaseerde elektrisiteitshandel in Suid-Afrika te bepaal. Die navorsing dra by tot die navorsing oor die toepaslikheid van Blokkeketting in die Suid-Afrikaanse energiestelsel en vra die vraag: Hoe kan die projekfinansiering in die Suid-Afrikaanse energiestelsel ontwikkel en innovasie en integrasie bevorder word, en is die potensiaal daar om deel te vorm van 'n nuwe dominante netwerk? Voorts word ook die volgende bekyk: Is daar potensiaal vir Blokkeketting-gebaseerde elektrisiteitshandel in Suid-Afrika, hoe kan dit ontwikkel word, en hoe kan dit die energiestelsel beïnvloed?

Om die navorsingsvrae te beantwoord, is 'n oorsig van die literatuur oor energieoorgange, die Suid-Afrikaanse energiestelsel, Blokkeketting-tegnologie, en teorieë oor meervlakkige perspektiewe en strategiese nisbestuur wat sosio-tegniese regime-oorgange ondersoek, gedoen. 'n Deelnemende gevallestudie is gebruik om die Sun Exchange-organisasie en sy innovasie op die sonkragprojekfinansiering op Blokkeketting te ondersoek. Onderhoude is gevoer om die lewensvatbaarheid en vooruitsigte van Blokkeketting-gebaseerde elektrisiteitshandel in Suid-Afrika te ondersoek.

Die gevallestudie het aan die lig gebring dat Sun Exchange baie ontwikkelingspraktyke gebruik wat deur die strategiese nisbestuursteorie voorgestel word vir sy innovasie in projekfinansiering. Dit het ook geïdentifiseer dat dit voordelig sou wees vir die organisasie om die onderliggende aannames voortdurend te bevraagteken rakende die soort Blokkeketting wat hy gebruik as gevolg van die veranderende aard van die tegnologie. Die gevallestudie het verder getoon dat dit onwaarskynlik is dat die projekfinansieringsinnovasie deel sal vorm van die oorheersende energienetwerk in Suid-Afrika indien die hindernis wat tans Sun Exchange-projekte tot 'n maksimum grootte van 10 Megawatt (MW) beperk, nie oorbrug word nie.

Die onderhoude het aan die lig gebring dat die potensiaal bestaan vir die ontwikkeling van 'n Blokkeketting-gebaseerde elektrisiteitshandelsaansoek, en dat die lewensvatbaarste manier om dit in die energiestelsel in te sluit, sou wees as dit geïmplementeer word deur munisipaliteite wat hul verspreidingsnetwerke besit om elektrisiteitshandel te bestuur. So 'n toepassing blyk baie positiewe implikasies te hê, veral vir munisipaliteite, verbruikers en ontwikkelaars van hernubare energietegnologieë, en om die land se koolstofvrystellings te verminder. Hindernisse vir die integrasie van die aansoek is geïdentifiseer en het hoofsaaklik betrekking op die huidige wetgewing. Dit word aanbeveel dat 'n publiek-private vennootskap van stapel gestuur word vir die ontwikkeling van die aansoek en dat verdere navorsing onderneem word om vas te stel presies watter organisasies kan bydra tot hierdie samewerking en hoe dit gefinansier, ontwikkel en geïntegreer kan word in die dominante energienetwerk.

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List of Acronyms and Abbreviations

BC	Blockchain
DAG	Directed Acylctic Graph
CER	Certified Emission Reduction
DAG	Directed Acyclic Graph
DAO	Decentralised Autonomous Organisation
DER	Distributed Energy Resources
DER	Distributed Energy Resources
DES	Decentralised Energy System
DLT	Distributed Ledger Technology
EV	Electric Vehicles
GHG	Greenhouse Gas
GO	Guarantees of Origin
ICO	Initial Coin Offering
INDC's	Intended Nationally Determined Contributions
IOT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IPP's	Independent Power Producers
Maas	Microgrids as a Service
NDC	Nationally Determined Contributions
NERSA	National Energy Regulator of South Africa
p2p	Peer-to-peer
PPA	Power Purchasing Agreement
PV	Photovoltaic
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RET	Renewable Energy Technology
TREC	Tradeable Renewable Energy Certificates
UNFCCC	United Nations Framework Convention on Climate Change
Dapp	Decentralised Application

PoW	Proof-of-Work
PBFT	Practical Byzantine Fault Tolerance
DPOS	Delegated Proof of Stake
AI	Artificial Intelligence
IPO	Initial Public Offering
UN	United Nations
CSP	Concentrated Solar Power
DoE	Department of Energy
REFIT	Renewable Energy Feed-In-Tarriffs
Gg	Gigagrams
AC	Alternating Current
g/kWh	grams per kilowatt hour
DEA	Department of Environmental Affairs
NCCRPWP	Climate Change Response Policy White Paper
RED's	Regional Electricity Distributors
NMBMM	Nelson Mandela Bay Metropolitan Municipality
MLP	Multi-Level Perspective
SNM	Strategic Niche Management

Chapter 1
Introduction

The current global energy transition is influencing the ways in which electricity is produced, distributed, and consumed. Some of the causes of these transitions are technological advancements, changes in the costs associated with renewable energy (RE) technologies, and a need to transition away from the use of fossil fuels to reduce levels of greenhouse-gas (GHG) emissions (Foxon, Hammond & Pearson, 2010; Facchinetti, 2018; Hojckova, 2018).

This research uses multilevel perspective (MLP) and strategic niche management (SNM) frameworks as theoretical starting points which are useful for analysing sociotechnical transitions. The MLP dissects transitions into three different levels, one of which is the sociotechnical niche level, further understood through the supportive SNM theory. The research focuses on windows of opportunity created by regime shifts resulting from energy transitions. The thesis argues that these windows lead to the introduction of novel business models and technological innovations which aim to create value in changing energy systems. The MLP and SNM frameworks are used to analyse blockchain technology and niche innovations, enabled by the technology, in energy systems to understand what role blockchain might play in the South African energy transition.

The research explores arguably two of the most influential blockchain-based applications in the energy sector. These are: using blockchain to crowd-fund renewable energy projects and managing electricity trading. Crowd-sourcing funds for renewable energy projects using blockchain was selected for this study because at the time of writing, it was the only blockchain-based energy application in use in South Africa making it suitable for a case study research. Electricity trading using blockchain was selected because South Africa is experiencing significant growth in small-scale private electricity generation which provides opportunities for excess private generation to be traded and sold to electricity consumers (Montmasson-Clair, G *et al.*, 2017; SALGA, 2018). This can be achieved in a variety of ways which fall under the umbrella term ‘energy trading’, and which is explored in detail in this thesis. While blockchain could arguably be used for managing energy trading on a large scale, such as within the South African and Southern African power-pools, and may indeed have significant implications for the South African energy transition, reviewing its potential for these applications is beyond the scope of this research.

Energy transition is relevant for South Africa because the country has signed the 2015 Paris Agreement which commits to emission reduction targets. To reduce the country's reliance on fossil-fuels, the government has implemented various strategies aimed at increasing the country's share of renewable energy (DOE, 2010; Fourie, Niekerk & Nel, 2015). Despite making significant progress in developing renewable energy infrastructures, South Africa remains heavily reliant on coal for electricity production (Montmasson-Clair *et al.*, 2017). In addition, the existing electricity generation, transmission, and distribution regime is under pressure because of electricity price increases and the rise of private electricity generation which threatens existing energy provision business models, particularly for distribution system operates (DSOs), which in many cases are municipalities which need revenue for service delivery (River *et al.*, 2018; SALGA, 2017; SALGA, 2018).

Blockchain is increasingly recognised as a tool to be used in energy systems. Some of the ways are: energy infrastructure financing, energy trade management, grid balancing, electric vehicle (EV) charge management, and carbon tracking and trading (Orlov & Bjørndal, 2017; Chitchyan & Murkin, 2018)

Sun Exchange is an organisation in South Africa that uses blockchain to crowd-finance solar energy projects and distribute asset ownership amongst owners situated in different countries around the world (The Sun Exchange, 2017). Project investors can purchase individual photovoltaic cells from anywhere and earn revenue from the electricity which the cells produce. Blockchain has enabled this innovative model because of its ability to facilitate automated micro-transactions between Sun Exchange and project investors without the need for centralised banks (Cambridge, 2018). Using a conventional banking system, this model would not be financially and administratively viable (Cambridge, 2018).

Research into the impacts of blockchain as a disruptive technology plus the applications it enables in the South African energy sector, is limited. This thesis aims to contribute to the research which explores how blockchain might influence the South African energy system and energy transition. The research demonstrates that, while still in its infancy, blockchain has a role to play in advancing a transition to a low-carbon energy system in South Africa since its applications are already being used to finance solar energy infrastructures in the country. There are also international examples of blockchain being used to facilitate low-carbon electricity trade between small-scale producers and consumers which is a model that several research organisations encourage South African distribution system operators to adopt, but which remains largely underdeveloped as a model (Montmasson-Clair *et al.*, 2017; Zeller *et al.*, 2017; River *et al.*, 2018 ; SALGA, 2018). Furthermore, electricity trading has the capacity to stimulate the uptake of renewable energy technologies, contribute to more efficient energy systems, provide cheaper electricity, and assist with peak load shifting among other things (Hoa Nguyen *et al.*, 2018).

1.1 Energy Transitions

Sociotechnical regimes are systems which comprise interrelations between societal functions and technologies (Kern & Smith, 2008). An energy system is an example of a sociotechnical regime because many societal functions are enabled by energy generating technologies. Energy system sociotechnical regimes therefore comprise economic, social, organisational and institutional structures (Hughes, 1987; Hojckova, 2018).

System transitions can be described as the restructuring of sociotechnical regimes (Geels & Schot, 2007). Energy system regimes undergo transitions for various reasons, but are commonly attributable to existing systems no longer being able to accommodate existing elements within the system (du Pllooy, Brent, de Kock & Musango, 2017). For example, modern energy systems are becoming less able to accommodate carbon intensive energy generation technologies because renewable energy technologies are often cheaper than fossil fuel-based technologies, and because these are increasing global pressure to use energy generation methodologies with low-carbon emissions (Swilling, 2018).

One of the major sustainability related challenges of the 21st century is the race to transition existing energy systems away from carbon-emitting technologies such as coal-fired power stations, to renewable energy technologies to avoid the negative effects that are expected to result from climate change (Bridge *et al.*, 2012). There have been dramatic reductions in the costs of renewable energy technologies, and investments into renewable energy have exceeded investments into fossil fuel-based generation each year since 2009 (REN21, 2018).

Coupled with the challenge of decarbonising existing energy systems is the challenge of meeting global energy demands in a way that provides reliable, modern, and affordable energy for all people by 2030, as encouraged by the United Nations (UN) through its Sustainable Development Goals (SDGs) (United Nations, 2018). Bridge *et al.et al.* (2012) argue that energy access has considerable influence on the economic prosperity of individuals, making it an important factor in the eradication of poverty, which is another SDG (United Nations, 2018). The International Energy Agency (IEA) (2018) estimate that 1.1 billion people globally lack access to electricity which is an indication of the scale of the task set by the UN. An underlying motivation to make use of renewable energy is the global drive to decarbonise human activities in an effort to reduce anthropogenically induced greenhouse-gases (GHGs) emissions (Facchinetti, 2018). Other factors influencing the energy transition include technological advancements and decreasing prices in renewable energy technologies (Facchinetti, 2018).

1.2 The South African Energy Transition

The South African electricity system is experiencing pressures which have opened windows of opportunity for niche innovations and system restructuring. Should the industry continue its current trajectory of a failing national power utility, Eskom, in R440 billion debt (Gokoluk, 2019), plus municipal utilities which face financial insecurity as consumers install private generation (SALGA, 2018a), then potential system failures may result in restructuring via niche innovations which are gaining momentum and contributing to new system stability. Existing system pressures seem to already be presenting windows of opportunity which blockchain-based applications have the potential to take advantage of. One such innovation is Sun Exchange's solar energy project crowd-financing platform. Another innovation which this research explores, is blockchain-based electricity trading since there seems to be an opportunity for its implementation in the wake of private generation in South Africa.

The South African electricity market is both highly monopolised and heavily reliant on coal for electricity production. Eskom supplies most of the country's electricity needs and 85.7% of its electricity production is generated using fossil fuels (Republic of South Africa, 2019). South African electricity costs have increased by 408% between 2003 and 2016 (River *et al.*, 2018), putting significant pressure on end-users and on municipalities who buy electricity from Eskom and sell it to end-users to generate profits which are used for service delivery (SALGA, 2018a).

Increases in the prices of primarily fossil fuel-based electricity is resulting in a new trend in South Africa where municipalities and consumers are starting to generate their own, often renewable resource-based electricity (SALGA, 2018a). A considerable portion of municipalities' income comes from purchasing electricity from Eskom which is then sold for a profit to end-users (SALGA, 2018a). The problem is that as Eskom electricity prices increase, end-users are increasingly installing their own generation capacity which results in fewer sales for municipalities who then increase the price of electricity to make up for profit losses (National Treasury, 2011; (SALGA, 2018a). This escalates the number of private generation installations which further perpetuates the problem (SALGA, 2018a). The South African local government association (SALGA) (2018), notes that there are opportunities for municipalities to avoid this issue by implementing new business models, some of which involve using private generation in their distribution networks (SALGA, 2018a). While there are opportunities for municipalities to transition away from buying electricity from Eskom for resale to consumers, there are challenges associated with designing appropriate municipal legislation and with setting up new technologies and systems able to manage these energy grids which are becoming increasingly complex because of the integration of variable, distributed renewable energy technologies (River *et al.*, 2018). This thesis examines the potential for a blockchain-based electricity trading innovation to take advantage of the window of opportunity presented by the uptake of small-scale private generation and to assist with enabling electricity trading to occur between producers and consumers.

1.3 Blockchain and Energy Systems

Blockchain, a type of distributed ledger technology, is a relatively new technology, as is its application to energy systems (Nakamoto, 2009). A blockchain is a database of records distributed amongst a network of participants, and contains a history of all the transactions and digital events that occur within the network (Crosby, 2016). This database is commonly referred to as a distributed ledger, and every transaction that occurs is permanently stored and commonly verified by the majority of the participants in the network. This removes the need for trusted third party intermediaries to manage network interactions (Crosby, 2016). Transactions are also commonly viewable by all participants as is the case with the Bitcoin blockchain (Nakamoto, 2009). The use of blockchain technology for Bitcoin enables peer-to-peer transactions to occur directly between participants in the network (Nakamoto, 2009). Depending on the type of digital transaction, different types of intermediaries can be made redundant.

Blockchains are commonly decentralised in that they generally follow a peer-to-peer system design which relies on a collective to function rather than on central management authorities (Crosby, 2016). Renewable energy technologies too can be decentralised in that technologies such as solar panels and wind turbines are modular and can be constructed independent of centralised energy grids and without the need for centralised organisations to manage and facilitate energy provision (Bull, 2001). There is thus a commonality between blockchains and renewable energy technologies; both share decentralisation and distribution as characteristics. Blockchains are distributed insofar as system management is distributed among participants. RETs (renewable energy technologies) can be distributed which means that there can be many renewable energy resources dispersed within an energy system.

Modern energy systems, electricity grids in particular, have conventionally been centralised, monopolistic, highly regulated, and exclusive (Orlov & Bjørndal, 2017). Energy transitions in many cases result in electricity systems which are increasingly decentralised, distributed, and intermittent, due to an increase in the number of variable renewable energy technologies feeding energy into electricity grids (Yaqoot *et al.*, 2016; SALGA, 2018). Challenges however arise from this transition due to increased complexities relating to the management of variable energy systems with bi-directional electricity flows. Blockchain is recognised as a technology with significant potential for managing and automating processes and interactions within these complex electrical systems (Gustafsson, 2017). Blockchains are also being used in various other ways to deliver value within energy systems. Some of these include energy project finance, production guarantees of origin, electric vehicle charge management, energy storage management, carbon asset tracking and trade management, and the incentivisation of clean energy production (Orlov & Bjørndal, 2017).

Research conducted by Montemayor & Boersma (2017) on organisations that are currently using blockchain applications within the energy sector, revealed that 74% were less than two years old. This demonstrates the value that small start-ups can contribute when it comes to pioneering technological innovation; they are often adaptable and flexible which, as argued by Abernathy and Utterback (1978), results from them being small, unestablished, and at the beginning stages of their organisational evolution. In contrast, large and established organisations can be inflexible and less able to pioneer innovation because of the costs associated with change, (Abernathy & Utterback, 1978).

1.4 Problem Statement

South Africa needs to transition away from a fossil fuel-intensive energy system if it is to reduce its carbon emissions. There is both a need for the development of renewable energy technologies, and for systems to manage electricity trading within municipal distribution networks. Blockchain-based innovations have the potential to address both these needs. If and how these niche innovations can form part of the dominant South African energy regime are, however, largely unknown as are the implications of doing so.

1.5 Research Questions

- How is the Sun Exchange blockchain-based solar project finance innovation developing and integrating into the South African energy system, is there potential for it to form part of the dominant energy regime and what are its implications for the energy system?
- Is there potential for a blockchain-based electricity trading application within the dominant energy regime in South Africa, how could it be developed and integrated, and how might it affect the energy system?

1.6 Research Objectives

The research objectives are:

- to understand how blockchain is being used within energy systems and how these applications influence energy transitions,
- to explore an existing blockchain-based application in South Africa and understand how it is influencing the South African energy system,
- to understand which developmental strategies contributed to Sun Exchange successfully developing and integrating its innovation into the South African energy regime, and which approaches it could leverage to enhance its development, and
- to gain insights from industry experts on the viability and prospects of blockchain-based electricity trading in South Africa's electricity future.

1.7 Research Aim

The aim of the research is to contribute to the existing literature on the blockchain-energy nexus with reference to energy transition in South Africa.

1.8 Relevance of the Research Topic

Atzori (2015) argues that scholarly debate and discussion on the impacts that blockchain is having and will have on global systems at large, is in its infancy since most research focuses on financial and legal issues relating to Bitcoin. It is argued that the inclusion of blockchain applications in energy systems and markets could disrupt many government and private sector operations (Atzori, 2015). These applications and potential disruptions need to be understood so that industry-relevant organisations can make informed decisions regarding the use, effects, and necessity of blockchain applications in energy systems. This research focuses primarily on organisational implications; the societal implications are beyond the scope of the thesis. The research aims to contribute to academic knowledge surrounding the uses and implications of blockchain within energy transitions in South Africa, which at the time of writing this thesis, seemed non-existent based on a search for existing literature.

1.9 Limitations of the Research

Because the Sun Exchange innovation is very young, the effects on the greater South African energy system are as yet minimal. This makes it difficult to draw conclusions about the effects of this type of application on the energy transition in South Africa. Furthermore, determining the viability of a blockchain-based electricity trading model in South Africa is limited by the number of people knowledgeable about blockchain and its applicability to the South African energy system blockchain and the energy industry in South Africa.

1.10 Research Methodology and Design

A literature analysis was conducted to gain an overview and understanding of energy transitions, system transitions, niche innovation development, blockchain technology, and blockchain-energy applications. A participative case study was conducted to explore the existing Sun Exchange blockchain-based innovation, how it is being developed and integrated, and how it is affecting the energy system. Interviews were conducted with energy experts to gain insights into the prospects of blockchain-based electricity trading in South Africa. Below is an illustration of the research design process with each step building on the understanding of the blockchain-energy nexus in South Africa.

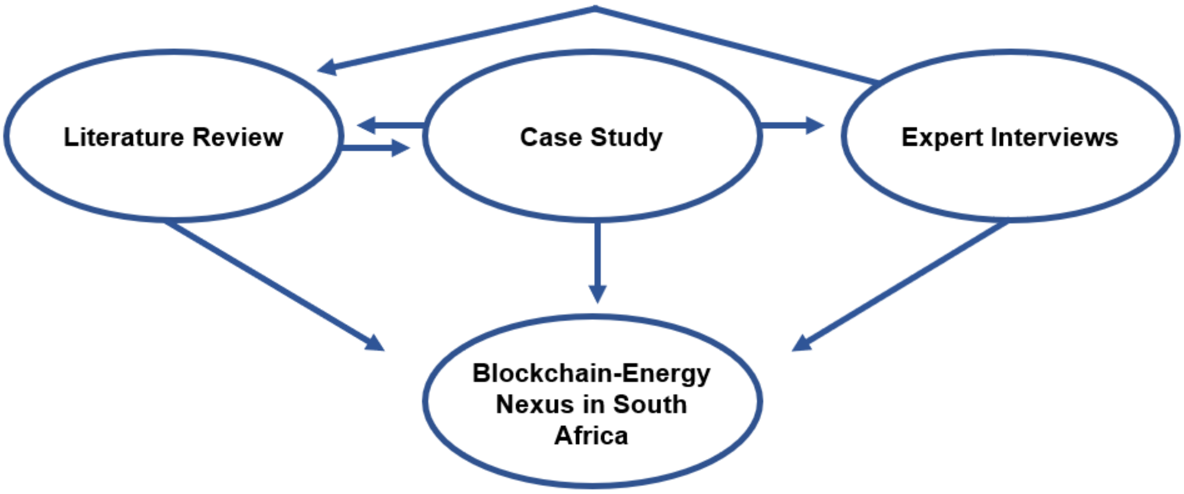

Figure 1. Research Design

1.10.1 Literature Analysis

A literature analysis was conducted to bring the researcher up to date with current literature on relevant topics and to identify where there is a need for further research (Cronin, Ryan & Coughlan, 2008). The analysis was also used to develop a conceptual framework which formed the foundation and perspective for an empirical case study design (Cronin *et al.*, 2008). The type of literature review selected is a traditional or narrative review which entails summaries and critiques of the bodies of literature and draws conclusions about the topics under review (Cronin *et al.*, 2008).

The bodies of literature and content reviewed included:

- Energy systems and the sustainability agenda
- Energy transitions
- Strategic niche management
- The multi-level perspective
- The South African energy system
- Blockchain technology
- Blockchain applications in energy systems

- Blockchain-based electricity trade

The purpose of this literature review was to assess the current state of knowledge on certain topics, and to justify the need for further research by identifying knowledge gaps in the existing literature (Hart, 1998). Cronin *et al.* (2008) note that at the end of a literature review a conclusion should be drawn which includes a summary of the findings that describe the current state of knowledge on a given topic, and reveals gaps in the knowledge demonstrating where there is a need for further research.

The two primary sources of literature were Google Scholar and the database provided by the Stellenbosch University Library. Using Google Scholar, the search strategy consisted of using combinations of search terms which can be seen in Table 1 below.

Table 1. Literature Search: Keywords and Phrases

Primary Search Phrases	Alternatives and Additions
Blockchain	blockchain applications
	initial coin offerings
	Bitcoin
	sharing economy
	consensus protocols
	blockchain energy
	guarantees of origin
	smart contracts
	blockchain architectures
	decentralised
	distributed ledger technologies
	decentralised autonomous organisation

	energy sector
	decentralised application
Energy transition	disruptive technologies
	electrifying the unelectrified
	decarbonising energy systems
	climate change and energy systems
	digitalisation
	digitisation
	energy sector
	fossil fuel energy systems
	renewable energy technology
Blockchain in Energy Systems	peer-to-peer electricity trade
	distributed ledger technologies
	decarbonisation
	energy sector
	digitalisation
	energy applications
	energy transitions
	electricity
	carbon emissions
	carbon markets
	project finance
	climate change
	internet of things
System Transitions	multi-level perspective
	strategic niche management

Using the Stellenbosch University database, the primary method used to search for relevant literature was the Boolian method which entails a search approach that uses the commands “AND”, “OR”, and “NOT” to manage keyword combinations during a database search with the purpose of assisting in finding appropriate literature and excluding irrelevant literature (Cronin *et al.*, 2008).

1.10.2 Participatory Research – Case study on Sun Exchange

A participatory case study research was conducted to achieve the research objectives of understanding how the Sun Exchange blockchain-based innovation is influencing the South African energy system, and which developmental approaches have contributed to its successful integration into the energy regime.

Sun Exchange is a start-up business using multiple blockchains in its business model which entails crowd-sourcing finance for the development of solar energy projects. One of the reasons this organisation was selected is because it is an operational business, unlike many of the organisations using blockchain in the energy industry which are in a proof of concept phase (Montemayor & Boersma, 2017). At the time of writing this thesis, it was also the only known organisation in South Africa using blockchain in the energy sector.

A case study is a research approach designed to provide increased understanding of certain phenomena through exploration in a real world context (Baxter & Jack, 2008). A case study method was selected because according to Yin (2009), case studies are useful when the research questions relate to 'how' and 'why' questions. In the case of this research, the 'how' relates to how blockchain is being used, how it might be affecting the energy system, and how the innovation developed and became integrated into the energy system. The 'why' relates to why blockchain is being used. Yin (2009) further recommends a case study approach when the boundaries between the phenomena and the context are unclear. In the case of this research, the phenomenon is the use of blockchain within energy systems, and the context is the energy system in which blockchain is being applied.

A qualitative case study methodology enables researchers to gain insight into complex phenomena within their contexts (Baxter & Jack, 2008). Due to the complex nature of the South African energy transition and the many variables to consider when assessing the affects that the use of blockchain is having, a qualitative research methodology was used. The case study followed an inductive knowledge and theory construction process as opposed to theory testing because of the lack of knowledge about what role blockchain might play in the energy transition in South Africa and because of the embryonic nature of the phenomenon. Perry (2017) notes that qualitative research methodologies are useful for case studies which research novel phenomena, and how blockchain is affecting the South African energy system is an under-researched and little-known topic which makes this method appropriate.

The case study approach chosen was an exploratory one which, according to Yin (2009), is useful when researching situations in which the intervention being evaluated has no clear set of outcomes. In the case of this research, the intervention was the Sun Exchange's use of blockchain within the South African energy system, and how the application is affecting the country's energy system constitutes an unknown set of outcomes. An exploratory approach was also used to understand how Sun Exchange has successfully developed and integrated its innovation into the energy system.

The type of participatory research chosen was a consultative approach whereby members of the organisation being researched were consulted and communicated with. Research decisions were however made solely by the researcher and not dictated in any way by those being researched (Lilja & Ashby, 1999). The reason that this type of participatory research was chosen was to ensure that the research outcomes were not dictated by the research participants.

The legitimacy and credibility of a case study increases with the use of multiple data sources (Yin, 1994). For the purpose of ensuring the reputability of the case study research, the data sources used include documentation, interviews, and direct observation which are data sources suggested by Baxter and Jack (2008). The reviewed documentation primarily consists of data relating to the Sun Exchange solar projects and their customer base. The interviews primarily entailed discussions with the founder and the CEO. The interviews were conducted according to a semi-structured approach, meaning that the researcher had a list of fairly specific questions but the interviewees had leeway in their replies and the interviewer did not necessarily follow the exact structure outlined by the schedule (Bryman & Bell, 2017). The participant observations entailed the researcher spending 20 hours per week at the Sun Exchange offices for a period of six months. Activities engaged in included participating in strategic business discussions, analysing business documentation to gain insights into the customer base; assisting the CEO, Abraham Cambridge, in day-to-day administration; attending conferences with the CEO, attending meetings with clients and support organisations such as GreenCape, and visiting sites where solar projects had been financed and constructed.

The researched documentation explored the information as indicated in Table 2 below:

Table 2: Documentation Researched at Sun Exchange

Case study data researched:
Installed power producing capacity
Energy project ownership distribution and statistics
Total electrical generation

With the intention of optimising the effectiveness of the study, four key quality factors were considered. These are: validity, replicability, generalisability, and reliability, which are considered key when judging the quality of case study research (Phondej, Kittisarn & Neck, 2011; Bryman & Bell, 2017 : 24). To establish validity, the researcher aimed to convey honest and balanced accounts of the researched phenomena by presenting the participants with his accounts to ensure that their views and perspectives did not influence the way in which the information was portrayed.

1.10.3 Interviews

Interviews were conducted with energy industry experts in South Africa, stakeholders who might be affected by the implementation of blockchain-based electricity trading, and organisations currently involved in electricity trading. The intention was to achieve the research objective of exploring the viability of blockchain-based electricity trading and what the implications might be for the energy system.

The interviews were designed to understand what forms of electricity trading currently exist in South Africa, how they are being implemented, and by which organisations. They were also designed to provide insights into how blockchain-based electricity trading might be incorporated and how it could influence the overall energy system. The interviews were conducted towards the end of the research in order to establish a level of understanding that would make it possible to have meaningful engagement with the industry experts.

The interviews followed a semi-structured approach which is recommended by Bryman and Bell (2017) as it allows for leeway in terms of the responses that respondents provide, and can assist in providing findings and insights that the questions were not necessarily designed to identify. Where possible, the interviews were conducted in person to increase the depth of the conversations, otherwise Skye and telephone calls were used. To confine the respondents to a discussion conducive to what the research intended to explore, Kothari (2004) suggests a focused interview structure. This approach was followed.

Energy industry and blockchain experts were interviewed to gain insights into their views about energy transition in South Africa, what they perceive the current challenges in electricity trading to be, and what their views were on the viability of blockchain-based electricity trading. The interviews were analysed by looking for themes relating to what the existing challenges are and what the possibilities are with blockchain. These were then compared to establish whether blockchain could contribute to eradicating the challenges related to electricity trading.

1.11 Research Participants

The participants interviewed for this research include individuals from PowerX, Energy Exchange of Southern Africa, GreenCape, the City of Cape Town Municipality, the Council for Scientific and Industrial Research (CSIR), Eskom, and well as a Chief Technology Officer (CTO) from an internet-of-things (IoT) company in South Africa.

- PowerX was selected because it is the only organisation that has managed to acquire an energy trading licence from NERSA and are therefore the only organisation in South Africa practising grid-tied third-party electricity trading (Radmore, 2018).
- Energy Exchange of Southern Africa was selected because it has been trying for the past three years to acquire an energy trade licence to act as a third-party electricity trader (Greubel, 2018).
- GreenCape was selected because it is a non-profit organisation that works with government and the private sector to support the transition to a green economy in South Africa, and it is actively involved with renewable energy technologies and the energy sector (GreenCape, 2019). GreenCape also publishes research papers on the South African transition and advocate electricity trading as a necessary model which needs to be incorporated into the energy system (Bronkhorst, Radmore & Fordyce, 2019).
- The City of Cape Town was selected because they were identified as a progressive municipality in terms of its carbon emission reduction targets, supportive legislation related to electricity trading and wheeling, and because they have a high uptake of small-scale distributed renewable energy technologies (Bronkhorst *et al.*, 2019).
- The CSIR was selected because they it has published papers on electricity trading in South Africa and has identified blockchain as a technology that would benefit electricity trade management (Carter-Brown, 2018).
- The CTO from the Internet-of-Things company was selected because of his experience with electrical engineering and blockchain technology. His research focus has been the use of blockchain for managing energy systems with distributed renewable energy technologies.

The table below contains information about the research participants, all of whom signed consent forms and did not choose to be anonymous.

Table 3: Research Participant Overview

Name	Organisation	Position
Karien Nel	PowerX	Admin Officer
Garth Greubel	Energy Exchange of Southern Africa	CEO
Jack Radmore	GreenCape	Energy Programme Manager
Mary Haw	City of Cape Town Municipality	Energy Efficiency & Renewable Facilitation
Dr Clinton Carter-Brown	CSIR	Energy Centre Head
Heinrich De Lange	BridgeIOT	Chief Technology Officer

1.12 Thesis Structure and Outline

In this introductory chapter, a background to the study was provided introducing energy system transitions with reference to the South African energy system. Some of the ways in which the South African energy regime is experiencing pressures were identified demonstrating the need for transformation. Blockchain technology was introduced with examples of how it can be used in energy systems. The need for research into the role that blockchain is playing in South Africa's energy transition and could play in the future, was demonstrated as well as how this research was conducted for the thesis.

The remaining chapters are structured as follows:

Chapter 2 offers a review of the literature on climate change and global energy transitions, revealing some of the opportunities and challenges relating to changing energy systems. It reviews the energy system in South Africa, making the argument that a radical systemic change is required if the county is to transition away from a fossil fuel-based, centralised and monopolistic energy system. The conceptual literature on systems transitions is reviewed with the intention of exploring the roles that niche innovations like blockchain play within system transitions, and how they integrate into mainstream sociotechnical regimes. The argument is made that regime pressures within the energy system in South Africa are presenting windows of opportunity for niche innovations like the one being implemented by Sun Exchange, and that these innovations have the opportunity to replace the dominant ways in which societal needs are fulfilled if appropriately developed. The chapter identifies a window of opportunity for a blockchain-based electricity trading innovation, arguing that this would be beneficial for electricity consumers, municipalities, and sustainable energy transitions if executed correctly, and that further research is required to explore the viability of such an application.

Chapter 3 offers a literature review on blockchain technology, introducing what the technology is, its history, and a brief overview of the different types of blockchain architectures and how they function. The chapter makes the argument that blockchain technology is still in a relatively early stage of development and may not be ready to be adopted on a wide scale to contribute to large-scale systemic transformations.

Chapter 4 reviews the literature on the use of blockchain within energy systems. It provides an overview of how and why blockchains can be used for energy related applications and how it could influence energy systems The chapter makes the argument that blockchain has a role to play in transitions toward low-carbon energy systems, but that if its integration is to contribute to more sustainable energy systems, careful consideration needs to be made about which blockchain types to use due to the potentially high energy demands of some of the blockchain architectures and the potential limitations on how many transactions they can process. The chapter demonstrates the need for research into the role that the technology could play in the energy transition in South Africa due to the lack of research on the topic.

Chapter 5 presents the case study research on Sun Exchange and its blockchain-based niche innovation. Research was conducted on how the business model works, how it makes use of blockchain, how it is influencing the South African energy system, and what developmental strategies have enabled its successful development and integration into the South African energy system. The chapter concludes by arguing that while the organisation is contributing to a low-carbon energy transition by financing solar energy projects and switching electricity consumers from mainly coal-based electricity to solar energy, Sun Exchange makes use of blockchains which are energy-intensive and have issues related to scalability. The argument is made that the Sun Exchange innovation is not likely to develop to a point where it replaces the dominant ways in which solar projects are financed and in which people consume electricity. This is largely because of legislative barriers which prevent the organisation from financing larger projects. It is however noted that there is potential for the innovation to become widely used within the South African energy regime. The recommendation is made that Sun Exchange should continuously question which blockchains it uses because of the evolving nature of blockchain technology, and because it currently uses blockchains which are criticised for having issues related to energy intensity and scalability.

Chapter 6 presents the interview research which explores the potential for blockchain-based electricity trading in South Africa and the potential impacts it might have on the energy system. The chapter argues that there is significant potential for blockchain to be used by micro-grid managers and municipalities to manage electricity trading in their networks, and demonstrates the impacts that its use could have.

In this way, Chapters 2 and 3 provide an overview of energy transitions with reference to South Africa and blockchain technology. Chapter 4 addresses objective 1 which is to understand how blockchain can be used within energy systems and how these applications affect energy transitions. Chapter 5 addresses objectives 2 and 3 which are to explore an existing blockchain-based energy application in South Africa to find out how it is influencing the energy system, which developmental strategies have enabled it to develop and become successfully integrated, and which developmental strategies it could leverage for further development and regime integration. Chapter 6 responds to objective 4 which was to explore the potential for blockchain-based electricity trading in South Africa, how it could be implemented, and how it might influence the energy system.

Chapter 7 ties the preceding chapters together by drawing conclusions about the research and suggesting where further research is required. The research objectives relating to the Sun Exchange innovation development strategy and influence on the energy system, helped to answer the research question relating to whether this innovation could become widely used and form part of a new energy regime. It became apparent that this is unlikely. The objective of gaining insights from energy experts on the viability of blockchain-based electricity trading helped answer the research question of determining if such an application is viable and what the implications might be for the energy system. It became clear that although such an application would face developmental challenges, it would indeed be viable and beneficial for the energy system. In conclusion, answering these questions achieved the research aim which was to contribute to the literature on the blockchain-energy nexus in South Africa.

The chapter concludes by suggesting that blockchain and its accompanying energy-related applications remain in their early phases of development and that it may therefore take some time before they develop to a mature level and become widely used and integrated into energy regimes. Nonetheless, this research is useful because it introduces applications for blockchain within energy systems and sheds light on some of the implications, challenges and benefits that this technology can result in.

Chapter 2

Energy System Transitions

This chapter provides an overview of the global sustainability agenda relevant to fossil-fuel use, greenhouse-gas (GHG) emissions, climate change and the electricity sector. An overview of the global energy transition away from fossil-fuels is provided with a focus on energy transition in South Africa. The South African energy transition is relevant because of its heavy reliance on fossil fuels for electricity production which will need to change if the country is to meet its emission reduction commitments and transition to a low-carbon economy. Moreover, it is relevant because the existing energy system regime is under pressure. This systemic pressure seems to be resulting in windows of opportunity for technological innovations. One such innovation is the blockchain-based project finance innovation offered by Sun Exchange. This will be further explored in Chapter 5. Another innovation, which is yet to be introduced in South Africa, but is being experimented with in other countries, is blockchain-based electricity trading. This research uses multi-level perspective (MLP) and strategic niche management (SNM) frameworks as theoretical starting points to understand how innovations interact with, affect, and are affected by systems and system transitions.

While fossil-fuels have played a crucial role in the advancement of human civilisation (Smil, 2017), the effects of burning fossil-fuels for energy are resulting in anthropogenically induced global warming resulting in climate change. This change is predicted to have significantly negative implications ranging from increased frequency and severity of extreme weather conditions (Mitchell *et al.*, 2006), to increased food and water insecurity (Hanjra & Qureshi, 2010). Furthermore, the effects on biodiversity loss are expected to be substantial if emission reductions are not achieved, and these effects are in many cases unknown due to the complexity surrounding the interconnected nature of life forms and natural ecosystems (Thomas *et al.*, 2004).

The purpose of this chapter is to explore the South African energy system, sociotechnical system transitions, strategic niche management, the multi-level perspective, and niche innovations to understand why system transitions occur, what they entail, and what role innovations play in system transitions.

2.1 The Sustainability Agenda, Climate Change, and the Need to Transition Energy Systems

The changing climate resulting from anthropogenically emitted greenhouse-gasses is considered to be one of the root causes of the urgent need to transition to low-carbon emitting renewable energy technologies (Gustafsson, 2017). "Decarbonisation means a decrease in the specific amount of carbon (or C02) emitted per unit of primary energy consumed" (Griibler *et al.*, 1996 : 97). Carbon dioxide (CO_2) is an important greenhouse-gas (GHG) that contributes to maintaining the earth's temperatures. Anthropogenic contributions to concentrations of CO_2 and other GHGs in the earth's atmosphere are contributing to a change in the balance of emissions and sequestration which is resulting in global warming and climate change (Griibler *et al.*, 1996).

The Intergovernmental Panel on Climate Change (IPCC) conducted research and concluded that human induced increases in greenhouse-gasses will result in the earth's climate warming by between 2 and 6 degrees Celsius by the end of the 21st Century which is expected to result in increased frequencies of extreme weather events such as heavy rainfall, heatwaves, droughts, and coastal flooding (Mitchell *et al.*, 2006). The main sources of these emissions are the burning of fossil-fuels such as coal, oil and gas (Mitchell *et al.*, 2006). The ramifications are extensive and in many cases unknown, however, some of the implications which will affect humankind the most will be food security and water availability which are expected to be substantially impacted (Hanjra & Qureshi, 2010).

In December 2015, the Paris Agreement was adopted under the United Nations Framework Convention on Climate Change (UNFCCC) with the intention of preventing global temperatures from exceeding 2 degrees Celsius compared with pre-industrial global temperatures (Rogelj, J. *et al.*, 2016). Countries that participate in the emission reduction agreement are required to submit Intended Nationally Determined Contributions (INDCs), along with plans to reduce their GHG contributions, without affecting sustainable food production and economic growth (Rogelj, J. *et al.*, 2016).

2.2 System Transitions: The Multi-level Perspective (MLP) and Strategic Niche Management (SNM)

This thesis analyses energy system transitions and the role of blockchain as a niche innovation using two theoretical frameworks, namely strategic niche management (SNM), and multi-level perspective (MLP).

SNM explores the way in which niche innovations like blockchain-based energy applications can be managed so that it increases their likelihood of becoming incorporated into existing regimes (Raven, Bosch & Weterings, 2010). SNM is a recognised methodological approach for fostering niche innovation experimentation, and focuses on the alignment between the social and the technical within sociotechnical system transitions (Raven *et al.*, 2010).

The MLP, as described by Geels and Schot (2007), interrogates transitions as changes from one socio-technical regime to another and how these transitions occur through the multi-level process. The MLP on system transitions suggests that the latter occur as a result of non-linear processes which in turn occur due to interactions between three levels within a system, namely the *niche-innovation* level, the *sociotechnical regime* level, and the *sociotechnical landscapes* level (Rip & Kemp, 1997; Hojckova, 2018).

System transitions can be defined as wide-scale changes to socio-technical regimes which entail changes to the ways in which dominant social needs are fulfilled (Rip & Kemp, 1998; Geels, 2002). Raven, Bosch and Weterings (2010) argue that experimentation with integrating niche innovations into socio-technical regimes is a useful strategy for fostering system transitions because of the learning process it involves and which, they argue, can provide useful insights into the practical social challenges which integration of the innovations with the larger system can cause.

Understanding these potential challenges can assist in developing strategies to address the challenges.

Niche innovations can refer to technological innovations which are initially unstable sociotechnical configurations with low system penetration and minimal impact (Geels & Schot, 2007). Blockchain-based innovations intended to penetrate energy markets could fall into this category because many of the blockchain-based applications are novel and have yet to develop to a point where they can become widely adopted (Chitchyan & Murkin, 2018). *Niche innovations* are commonly implemented by small networks working outside larger systems which aim to penetrate a system via an innovation (Geels & Schot, 2007). Experimentation within niches is regarded as crucial for stimulating transitions and learning about social challenges associated with the introduction of niche innovations (Raven *et al.*, 2010). Sun Exchange could be classified as a *small network* because the organisation has not been a conventional player in the South African energy market (Geels & Schot, 2007). Other blockchain-based start-ups in the energy sector also fall into this category because they too aim to use blockchain in innovative ways to offer new solutions in energy systems (Montemayor & Boersma, 2017). These organisations and innovations are explored in more detail in Chapter 4.

Regime transitions are regarded as complex long-term processes, potentially lasting decades, because regimes are often stable and resistant to change (Raven *et al.*, 2010). Regime resilience can be caused by:

- institutional structures which are rigid,
- regime actors and social networks which represent institutionalised power and often have substantial capital, and
- technologies and infrastructure used within the regime which represent the vested interests of the incumbent actors.

2.2.1 The Multi-Level Perspective

From a multilevel perspective, Raven *et al.* (2010) note that the potential for niche innovations to become widely adopted within larger systems is increased if they develop in sociotechnical niche environments where they are able to grow and mature before being integrated into larger systems.

According to Raven *et al.* (2010), *sociotechnical niches* have the following meanings:

- a location or space that is separated from the dominant regime which enables actors to experiment with a nice innovation without direct pressure from existing regimes,
- a novel and unstable set of institutions and rules,
- the micro-level of sociotechnical change,
- experimental pilot projects for niche innovations, and
- a makeup of practices that deviates from the conventional way in which social needs are fulfilled.

Sociotechnical regimes can also have several meanings in the transition literature. Some of these are (Raven *et al.*, 2010):

- a set of institutions and rules which constrain and enable the behaviour and choices of system actors,
- the meso-level in sociotechnical transitions, between niches on the micro-level, and the landscape on the macro-level,
- an assortment of practices, cultures, and structures which form the dominant way in which social needs are met, and
- the dominant sociotechnical establishment which has formed over a long period of time and is resistant to change.

Sociotechnical landscapes can take years to change because they are commonly exogenous environments which are mostly beyond the direct influence of regime actors and *niche innovations* (Hojckova, 2018). The landscape refers to the background setting for niches and regimes which are slow to develop and which are largely beyond the influence of individual actors (Raven *et al.*, 2010). Raven *et al.* (2010) note that the landscape level has several meanings as listed below:

- the source of pressure which results in the need for a regime to change,
- the social and external elements which constrain or enable changes to the regime such as demographic, socio-economic, international and political

elements, as well as global environmental forces; such a landscape pressure in the context of energy transitions could be climate change and global warming which put pressure on energy provision regimes to transition away from being high GHG emitters, and

- the macro-level of sociotechnical change.

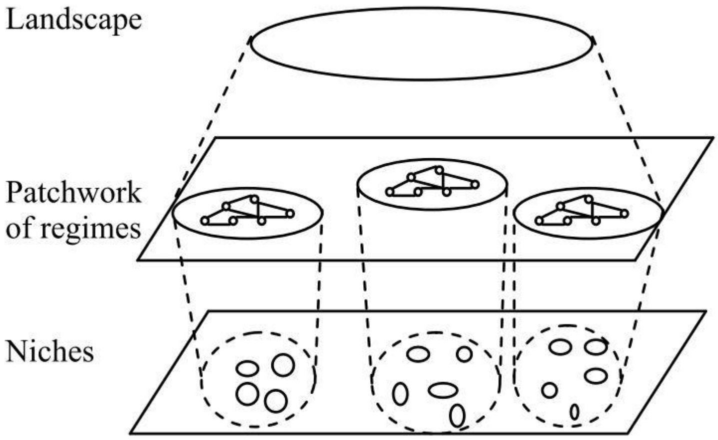

Figure 2. Illustration of the three levels within the multi-level perspective (MLP)

Source: (Geels, 2002)

Geels and Schot (2007) argue that a shortcoming of the MLP with regard to transitions is that is puts too much emphasis on niche innovations as causes of transitions. This niche-driven bias also resulted from early work on strategic niche management (SNM), which assumed that transitions occur from the ground up and would only happen if niche innovations were nurtured (Geels & Schot, 2007). Smith *et al.* (2005) suggest that transitions do not simply arise from niche innovations but rather from a conjuncture of the three transition levels within the MLP. Geels and Schot (2007) agree with this perspective noting that transition pathways are influenced by interactions between occurrences on the three levels.

Geels and Schot (2007) state that system transition trajectories will to an extent be determined by the levels of development of the various niche innovations within a system, and that their influence is largely determined by whether they are mature enough to become widely adopted when windows of opportunity present themselves.

The success of an innovation however is not solely determined by its level of maturity. An equally important component is the stability of the regime. Geels and Schot (2007) argue that radical innovations which have reached a mature level of development could be hindered from being widely adopted if sociotechnical regimes are stable.

2.2.2 Strategic Niche Management

Strategic niche management (SNM) is a process that entails developing socio-technical innovations in niche environments before introducing them into regimes with the aim of stimulating system transitions (Raven *et al.*, 2010). Experimentation with niches and the alignment between the technical and the social, is central to the SNM approach (Raven *et al.*, 2010).

Strategic niche management (SNM) is commonly broken down into three internal niche processes (Raven *et al.*, 2010), namely:

- the voicing and shaping of visions and expectations,
- the building of social networks, and
- the use of a constructive learning process.

Voicing and shaping of expectations and visions: The SNM perspective argues that the articulation of expectations is important as it can assist with attracting resources, attention, and new actors, especially when niche innovations are in the early stages of development (Raven *et al.*, 2010). Raven *et al.* (2010) recommend that this process can be effective when:

- an increasing number of actors share the same vision and expectations, and
- the expectations are based on results from experiments with the niche innovation.

Building of social networks: The SNM perspective argues that communication and collaboration between new combinations of actor types is useful for niche innovation development due to the need for new types of social networks (Raven *et al.*, 2010). Raven *et al.* (2010) argue that this process is effective when:

- the social network is broad and includes participants such as policy makers, users, firms, and scientists, and
- alignment within the network is established through effective communication management between the actors.

A constructive learning process: The third element considered important within the SNM process is the application of a learning process which enables adjustments to be made either to the technology or to the way in which it is being incorporated into a social system (Raven *et al.*, 2010). Raven *et al.* (2010) argue that this process is effective when:

- focus is not too heavily concentrated either on the technical aspects or the social aspects but the relationship between the two, and
- the learning process involves questioning assumptions when the innovation does not match the assumptions.

SNM initially focused on individual niche innovation experiments but evolved to rather focus on multiple simultaneous experiments because this seems to provide a more effective learning and development process (Raven *et al.*, 2010). The application of multiple innovations within niches increases the sample size of the experiment, enabling separate experiments to learn and build on one another (Raven *et al.*, 2010).

Figure 3 below illustrates this multi-experiment approach, demonstrating that the development and transformational potential of niche innovations is enhanced when multiple experiments develop separately, and the actors involved collaborate, communicate, and aggregate learning outcomes (Geels & Raven, 2006). Geels and Raven (2006) provide examples of how this collaboration can take place which include workshops, technical journals, newsletters, and conferences.

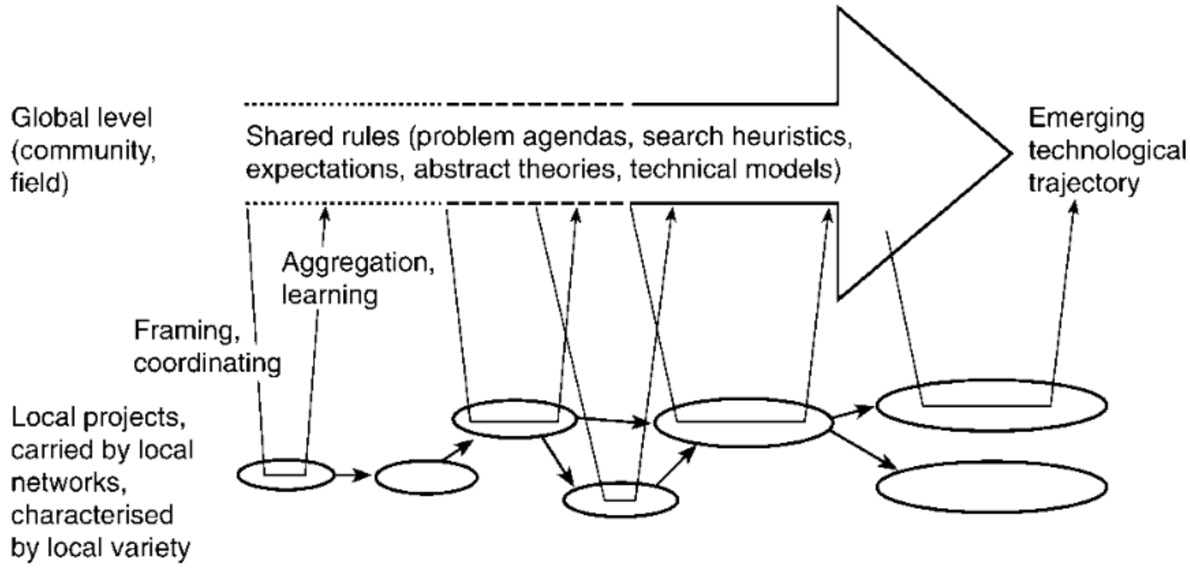

Figure 3. Niche innovation developmental trajectory with multiple experiments and collaboration

Source: (Geels & Raven, 2006)

In the case of blockchain-based electricity trading innovations, for example, many separate trial experiments are being implemented around the world (Montemayor & Boersma, 2017; Andoni *et al.*, 2018). It can be said that considering the SNM perspective, the potential for electricity trading using blockchain to become widely adopted within energy regimes internationally would be increased if the stakeholders experimenting with the applications communicated and built on one-another's knowledge by shared information and collaboration. This is however unlikely as most are private organisations and therefore in competition with one another.

2.3 Changing Status Quo Energy Systems

Global energy system transitions resulting from a shift away from fossil-fuel based technologies to the uptake of RETs, are currently under way. The adoption of these RETs are largely attributed to cost reductions and political interventions aimed at lowering carbon emissions (Smil, 2017). While the reasons for RET cost reductions vary, the most common causes are: technological advancements, financial mechanisms, national institutional development, manufacturing experience, and an increase in competition (Nemet, 2006; Eberhard & Kaberger, 2016). There are however also technological advancements in the sourcing and extraction of fossil-fuel resources such as gas, coal, and oil, and it is suggested by Chu and Majumdar (2012) that fossil-fuel based energy could therefore remain cost-competitive with carbon- free based energy sources for decades to come.

Global sociotechnical energy regime transitions are occurring for many reasons which differ according to circumstance, energy system, and region, however, arguably the most notable underlying reason for a global energy transition away from fossil-fuels relates to the goal of transitioning to low-carbon technologies to mitigate climate change implications (Facchinetti, 2018). Global emission reduction initiatives arguably fall within the landscape level of the MLP and are exerting pressures on energy regimes with windows of opportunity for niche innovations opening up.

The World Energy Council (2016) highlights three primary elements associated with the current global energy transition which it refers to as the energy trilemma: *securing global energy supply*, in a *cost effective way*, while *considering the environmental implications*. Because energy related activities are often associated with negative environmental impacts, it is important that energy systems transition to regimes which meet the needs of economies while preserving the environment, especially as increased energy access is high up on the global agenda due to energy being a primary enabler for welfare and economic development (World Energy Council, 2016).

While largely influenced by sociotechnical landscape level pressures, global energy regimes are also influenced by technological advancements and innovations which are resulting in ever-cheaper technologies such as solar panels and wind turbines, and in technological innovations which offer new approaches to how energy is generated, traded, delivered, and financed (Facchinetti, 2018). It is expected that the global energy regime pressures will have significant implications for the global structure of energy systems which presents many challenges and opportunities for organisations and governments forced to rethink their long-established energy provision business models (Facchinetti, 2018).

In the *World Energy Resources Report* published by the World Energy Council (2017), an overview of the global energy system is provided with the following key statistics:

- The average price of solar PV reduced by over 80% between 2007 and 2015 resulting in significant uptake of the technology. This increase in the use of PV poses notable challenges due to the costs associated with balancing intermittent energy resources.
- Electricity storage has experienced significant change most notably in battery technology due to increased demand resulting from a need to manage system volatility which occurs because of intermittent renewable energy technologies.
- Coal production decreased in 2014 by 0.6% and by 2.8% in 2015 but continues to account for producing 40% of the world's electricity. Climate change mitigation strategies are expected to present significant challenges for the sector.

Modern fossil-fuel based electricity systems have historically been structured in a centralised way because of expensive, specialised, and large-scale electricity generating resources which feed electricity mono-directionally to end-users via large electricity grids which are commonly owned and managed by a few vertically integrated organisations (Alanne & Saari, 2006; Orlov & Bjørndal, 2017). The centralised, large scale nature of these systems results in electricity travelling vast distances via high-voltage transmission lines before it reaches end-users (Alanne & Saari, 2006; Orlov & Bjørndal, 2017). With the ever-decreasing prices of RETs, there is an increased international push to decarbonise energy systems, increase government support for the development of low-carbon technologies, technological advancements and innovations; and an increased need to meet the energy demands of the planet which means that energy markets are becoming more receptive to innovative solutions to meet energy requirements in a low-carbon way (Gustafsson, 2017). The windows of opportunity created by the changing regime which requires low-carbon energy provision solutions is resulting in new market entrants with innovative offerings and these new models are changing the way that energy markets and systems are structured (Gustafsson, 2017). Considering the MLP approach, one can argue that changes to sociotechnical regimes, in this case the energy regime, which is affected by both innovations and landscape level pressures, are non-linear, and that system transitions are therefore the result of interlinkages between the three levels of the MLP.

Gustafsson (2017) argues that digitalisation is one of the key drivers of system transitions because digital technologies have reduced information asymmetries and enabled greater communication which in turn has increased collaboration between market actors by enhancing efficiency and transparency. As energy systems become more complex due to decentralisation and the variability of RETs, there is an increased need for vast amounts of information to be shared and co-ordinated to manage these complex systems (Gustafsson, 2017). Gustafsson (2017) argues that the effective management of complex distributed energy systems is hindered by a lack of effective information communication technologies (ICTs) which is resulting in a barrier to the further development of these types of energy systems. A reason for this is that the current business paradigm promotes the control and ownership of data resulting in silos of information which are not being shared because organisations seem to fear compromising their competitive advantages (Gustafsson, 2017).

The transition to decarbonised energy systems requires new market entrants and new actors within energy systems because decarbonisation is an interactive process which requires innovations that expand the conventional organisational domains of the energy sector (Gustafsson, 2017). The emergence and incorporation of novel technologies and technological applications rearranges systems and enables novel transformation processes to occur (Hatch, 1997; Geels & Schot, 2007). The global energy market is experiencing what is sometimes referred to as the 3Ds which are *decentralisation*, *decarbonisation*, and *digitalisation* (Verma *et al.*, 2018). These disruptions bring considerable changes and challenges to energy systems along with many opportunities for solving some of the problems they cause.

2.4 The South African Energy System – A Sociotechnical Regime Under Pressure

Baker *et al.* (2014) note that a sociotechnical energy regime refers to the way in which energy is generated, distributed, and consumed, which is a product of factors that include economics, policies, markets, and consumer behaviour. From the MLP, changes to this energy regime can result from forces on the landscape level (Raven *et al.*, 2010). Baker, Newell and Phillips (2014) note that within the South African energy system context, the sociotechnical landscape would refer to political dogmas, demographic trends, the economic performance of other sectors, and other macro-level external influences. Landscape pressures on the regime create windows of opportunity for innovations (Schot & Geels, 2008). This section explores South Africa's energy regime, the landscape pressures being exerted on it, and the windows of opportunity which are being created for niche innovations.

The energy sector in South Africa is highly exclusive, centralised, and monopolised because the state-owned entity, Eskom, supplies 94% of the country's electricity, owns the national grid, and manages all imports and exports of electricity in the Southern African power pool (Halsey *et al.*, 2017). Eskom was established in 1923 in terms of the Electricity Act (1922), following the amalgamation of a number of private enterprises (Lloyd, 2012). While Eskom purchases approximately 8% of its energy from independent power producers (IPPs) and shares electricity distribution with municipalities, its monopoly over the generation and transmission of electricity in South Africa has resulted in ineffective planning, financial mismanagement, corruption within the utility, and operational inefficiency for many years (Halsey *et al.*, 2017). The company also generates 91% of its electricity using coal, making it an extremely high carbon dioxide emitter (Halsey *et al.*, 2017). The current exclusive electricity system exists despite the 1998 White Paper on Energy (Department of Minerals and Energy, 1998), which contained the following policy objectives:

- to provide customers with the right to select their electricity supplier,
- to introduce competition into the electricity industry, mainly in the generation sector, and
- to allow for open and non-discriminatory access to the transmission system and encourage private participation in the industry.

In an effort to liberalise the electricity industry, the White Paper proposed consolidating the distribution industry into five independent regional electricity distributors (REDs) thus taking the monopolistic position away from Eskom (Lloyd, 2012). This however never happened (Lloyd, 2012). Again, in the 2012 session of Parliament, the Department of Energy announced a plan to put forward legislation to create an independent system and market operator which would take over the role of transmission and distribution from Eskom (Lloyd, 2012). While this too would have had profound implications for the liberalisation of the electricity sector in the country, it never happened either and has resulted in a monopoly controlling the market. The failed attempts at transforming the energy sector have prevented private sector participation, generation competition, and the ability for consumers to choose their preferred suppliers. One of the reasons for this is because of a 2007 Cabinet decision which determined Eskom as the single buyer in the national IPP process which essentially prevents any other organisations or municipalities from buying electricity from IPPs.

Access to electricity has increased from 50% in 1994 (The Presidency, 2013), to 91% in 2016 (StatsSA, 2016) indicating significant progress in addressing energy poverty in the country. Approximately half of the country's electricity consumers purchase electricity directly from Eskom, while the other half purchase it from municipalities who buy electricity from Eskom before selling it to end-users with a mark-up - the profits of which they use for service delivery (National Treasury, 2011; Halsey *et al.*, 2017). Electricity tariffs are regulated by the National Energy Regulator of South Africa (NERSA), and approximately 80% of the country purchase electricity using a prepaid system (StatsSA, 2016). Only 45% of the total primary energy supply ends up being consumed indicating that the energy system is inefficient (Halsey *et al.*, 2017). These energy losses result from transformation processes and from long-distance electricity transmission energy losses which, according to the World Bank, account for 10% of South Africa's energy supply (World Bank, 2016). The recognised international acceptable margin for electricity losses during distribution is 3.5%, but very few cities in South Africa are achieving this (Presidency, 2011). Among the metros, eThekwini has the lowest losses at approximately 5%, while Johannesburg loses around 12%, attributable to theft and technical losses (Presidency, 2011). The distribution losses could be dramatically reduced if energy was locally produced (Orlov & Bjørndal, 2017).

In the early 2000s The National Energy Regulator of South Africa (NERSA) reduced Eskom's applications for tariff increases to levels that were significantly below inflation and affected their ability to finance essential base load expansions (Lloyd, 2012). While this resulted in South Africa having the cheapest electricity in the world with positive implications for economic development, the unrestrained growth in demand coupled with limited increases in supply, resulted in the country running out of adequate power in 2007 (Lloyd, n.d.; National Treasury, 2011). The resultant constrained electricity supply coupled with the global economic crisis of 2008 caused significant negative implications for the South African economy (Lloyd, n.d.; National Treasury, 2011).

Electricity prices in South Africa have increased dramatically over the past two decades; increasing by 408% between 2003 and 2016 (River *et al.*, 2018). This has resulted in a large portion of the population spending as much as 20% of their household income on electricity, and often results in households with grid connections going without it to avoid the associated costs (Halsey *et al.*, 2017). As touched on in the introduction to the thesis, these increasing prices have resulted in people buying less electricity, and in some households and organisations installing private electricity generation-- both of which result in profit losses for municipalities (Zeller *et al.*, 2017; Halsey *et al.*, 2017). This poses a significant problems for municipalities considering that the national average municipal income generated from electricity sales constitutes 28% of their total income (Halsey *et al.*, 2017). Halsey *et al.* (2017), argue that a strategic transition away from this model is essential for municipalities to maintain revenue streams.

The World Economic Forum measures energy system performance based on its ability to contribute to economic growth, provide energy access and security, and ensure environmental sustainability (World Economic Forum & Accenture, 2013). By this measure, South Africa is rated 76th out of 126; a low ranking because of its environmental profile of a high greenhouse-gas emission country (World Economic Forum & Accenture, 2013). South Africa is the 13th highest carbon emitter in the world per economic unit (Halsey *et al.*, 2017), which is largely attributable to its heavy reliance on coal as an energy source.

Coal mining is responsible for the degradation of natural water systems primarily resulting from acid mine drainage which can lead to reductions in agricultural productivity, damage to biodiversity, riverine ecosystem destruction, and water sources becoming undrinkable (Greenpeace, 2017). Eskom is both the highest burner of coal and the highest emitter of greenhouse-gasses in the country (Halsey *et al.*, 2017). The production of electricity using coal also requires 1.42 litres of water for cooling for every kWh sold to end-users (Eskom, 2015). This makes Eskom the highest water consumer in the country (Halsey *et al.*, 2017).

2.5 The South African Energy Transition

At the Copenhagen Climate Change Summit in December 2009, the President of South Africa at the time, Jacob Zuma, announced the country's pledge to reduce its greenhouse-gas emissions by 34% by 2020, and by 42% by 2025 (Presidency, 2011), which was noted as being consistent with the long-term mitigation scenarios endorsed by the cabinet in 2008 (Baker *et al.*, 2014). Jacob Zuma stated that South Africa could commit to this on condition that the country was provided with the necessary support, finance, and technology from the international community (Presidency, 2011).

Despite South Africa being progressive in its approach to designing and implementing policy measures aimed at stimulating and sustaining private investment into renewable energy, such as through the Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) (Fourie *et al.*, 2015), the challenges relating to decarbonising the South African energy sector are significant because of its substantial reliance on coal to produce electricity (Eberhard & Kaberger, 2016). While a transition away from coal in the near future seems unattainable, the uptake of renewable energy has seen a reduction in the dominance of coal, primarily attributable to government intervention (Stats SA, 2018). Solar power did not feature at all in the 2013 Statistics South Africa report with regards to electrical generation, but in 2016 it contributed 2,151GWh to the country's output

(Stats SA, 2018). There has been a gradual increase in the adoption of solar PV across residential, industrial, and commercial sectors due to a combination of high Eskom tariffs and the rapidly declining prices of solar energy technology (Halsey *et al.*, 2017). There has also been a significant change in the production of wind power which increased from 18 GWh in 2013 to 2,126 GWh in 2016 (Stats SA, 2018). The report did however, reveal a 124% increase in the amount of diesel purchased by the electricity, gas and water industries between 2013 and 2016, of which most was used to generate electricity (Stats SA, 2018). This indicates that while there is a low-carbon transition under way, it is hindered by continued investment into fossil fuels.

Zeller *et al.* (2017) argue that a prerequisite for energy transitions toward the adoption of renewable energy, is energy market liberalisation which has been a contributing element in the German energy transition. Their research provides lessons learnt from Germany and offers recommendations for South African municipalities on alternatives to the current municipal business model which entails buying electricity from Eskom and reselling it to consumers (Zeller *et al.*, 2017). As already mentioned, alternative business models need to be explored because South African municipalities are losing revenue as consumers install private electricity generation due to increasing electricity costs, and reduced costs in private generation technologies (SALGA, 2018a).

A key element which contributed to an energy transition in Germany towards RETs was the changes in legislation which liberalised the energy market and increased competition, enabling new business models and service offerings (Zeller *et al.*, 2017). Halsey *et al.* (2017) advocate this approach arguing that an energy transition in South Africa would benefit from the liberalisation of the energy market. Efforts to liberalise this market have been made but have mostly in vain. As a result, the market remains largely controlled by the state-owned utility. In 2011, an Independent System and Market Operator (ISMO) Bill was introduced to ensure that electricity generation would be shared between Eskom, IPPs, municipalities, individuals, and businesses, but was rejected because it apparently failed to consider key elements such as grid ownership, grid management, and access to the grid (Davie, 2011). A revised Bill remains under consideration (Halsey *et al.*, 2017).

The National Development Plan (NDP), the Integrated Energy Plan (IEP), and the Integrated Resource Plan (IRP) contain information on the overarching vision for the future of the country's energy system. The NDP states that South Africa will need to meet approximately 29 000 MW of additional power demand by 2030, compared with the 2013 baseline (National Planning Commission, 2011). Furthermore, 10 900 MW of power generating capacity will be retired during this period meaning that an additional 40 000 MW will need to be constructed (National Planning Commission, 2011). Eskom's committed generation expansion plan will result in the construction of 10 000 MW of new generation capacity (National Planning Commission, 2011), which indicates a significant gap between future energy demand and committed infrastructure investments. Eskom will either need to increase committed investment substantially to meet future demand, or the energy market will have to be liberalised from the monopolistic model which prevents IPPs from accessing the grid so that more generation capacity can be offered, and innovations can be incorporated. The National Development plan stipulates that there is a need for cooperation between the government and Eskom, and that an independent system and market operator should be established to manage the procurement and contracting of IPPs, and preferably also manage electricity transmission (National Planning Commission, 2011). Despite this plan, Eskom retains primary control over generation, transmission, and distribution in South Africa. This market control coupled with regulatory uncertainties prevents liberalisation of the energy market in South Africa. The uncertainties relate to whether or not IPPs should be allowed to sell to customers other than Eskom and whether energy trading models should allowed and how they should be structured (National Planning Commission, 2011).

The purpose of the IEP is to provide a roadmap for achieving the envisioned energy future of South Africa by guiding energy infrastructure investments and policy development (Republic of South Africa Department of Energy, 2016). Halsey *et al.* (2017) criticise the IEP for being more of a guideline than an enforceable strategy and because lacks a plan for investment priorities.

The Integrated Resource Plan (IRP), put forward by the Department of Energy (DoE), portrays a vision to diversify the energy market in South Africa by including the private sector in electricity generation. The plan calls for the development of renewable energy infrastructure amounting to 21 500 MW between 2010 and 2030 (National Planning Commission, 2011). Two programmes were designed to support the NDP and IRP by increasing the uptake of renewable energy in South Africa (Fourie *et al.*, 2015). These were the REIPPPP, and the Renewable Energy Feed-In-Tariff (REFIT), which was approved in 2009 by the National Energy Regulator of South Africa (NERSA) (Fourie *et al.*, 2015; Export.gov, 2017).

The REFIT strategy did not succeed because of uncertainties regarding the licencing process, the nature of procurement, and because the programme was not supported by the national utility, Eskom, due to the tariffs being too high (Eberhard & Kaberger, 2016). In August 2011, the Department of Energy (DoE), terminated the REFIT programme and launched REIPPPP, a competitive bidding process for renewable energy aimed at procuring 17.8 GW of renewable energy between 2012 and 2030 (Walwyn & Brent, 2014). The REIPPPP was intended to enhance the country's power generation capacity and its transition away from a reliance on fossil-fuels, and to promote socio-economic development and environmental sustainability (Fourie *et al.*, 2015). While a further intention was to stimulate the local renewable energy industry, this has not been a notable result; the prioritisation of price reduction has prevented local industries from participating because they cannot compete with international prices (Halsey *et al.*, 2017). The programme is intended to achieve CO2 emission reductions from 912 grams per kWh to 600 grams per kWh (Walwyn & Brent, 2014). The focus of the programme is the procurement of renewably produced electricity from the private sector which includes wind power, concentrated solar power (CSP), solar photovoltaic (PV), hydropower, biomass, biogas, landfill gas, and energy generation from agricultural waste (Fourie *et al.*, 2015). The REIPPPP was established by South Africa's Department of Energy (DoE), the National Treasury, and the Development Bank of South Africa (Fourie *et al.*, 2015), and was designed in such a way that twenty-year power purchasing agreements (PPAs) had to be signed by both the independent power producers (IPPs), and by the energy off-taker, Eskom (Eberhard & Kaberger, 2016).

Despite the notable success of the REIPPPP, Eskom has undermined the government-backed programme by refusing to sign PPAs with IPPs presumably in an attempt to protect its own financial viability and its coal and nuclear interests

(Halsey, 2016). It seems that despite these progressive sociotechnical landscape level initiatives intended to transition the energy regime, the existing regime is resistant to change, most likely attributable to Eskom's monopoly over the energy market. As previously discussed, Eskom and the current energy regime are under pressure which is providing windows of opportunity for niche innovations that offer alternatives to the existing failing structures.

Sociotechnical system pressures in the South African energy system include a need to transition to a low-carbon energy system, high and increasing electricity tariffs, financial pressures on municipalities and end-users, and a natural increase in the uptake of small-scale embedded generation - often in the form of rooftop mounted solar panels. The changing energy regime resulting from the increase in distributed private generation provides windows of opportunity. For example, the utilisation of excess private generation for resale to consumers through an electricity trading business model is regarded as a new model which municipalities can adopt to adapt to the changing energy regime (River *et al.*, 2018; SALGA, 2018). Properly managed electricity trading models have the ability to increase energy security, provide consumers with affordable electricity, assist grid operators with distributed energy resource management, incentivise the uptake of small-scale-embedded-generation (SSEG), lower payback periods for SSEG systems, increase energy system efficiency, and lower carbon emissions (Hoa Nguyen *et al.*, 2018). Furthermore, such an application could provide an alternative revenue stream for municipalities (River *et al.*, 2018; SALGA, 2018).

According to the research of du Pllooy *et al.* (2017), on the relationship between economic development and sociotechnical regimes, periods of sustained economic growth and development are often associated with periods when new technologies are integrated into societies. This argument is reinforced by Shwab (2018) who, in writing about the fourth industrial revolution, argues that distributive technologies which result in sociotechnical regime transitions often result in periods of high economic growth and development. Wilson and Grubler (2011) note that supporting technological change and innovation is especially important for developing countries, and that a failure to do so could hinder energy system transitions. Considering these research findings, it seems that South Africa, as a developing country, would greatly benefit from exploring and encouraging technological innovations in the energy sector.

Halsey *et al.* (2017) suggest that two key components necessary for a transition to an equitable, low-carbon and environmentally conscious energy system in South Africa, are the avoidance of mega-projects with few beneficiaries, and maximising energy efficiency by reducing the need for transmission and the conversion of non-renewable energy resources. Considering this view, it can be said that innovative models that enable many people to participate in the ownership of distributed renewable energy resources should be encouraged.

2.6 Transitions to Decentralised Energy Systems and Distributed Energy Resources

Because of the research questions which aim to determine whether blockchain-based electricity trading is viable in South Africa and how its integration might be achieved and affect the energy regime, this sub-section looks at the uptake of small-scale private energy generation. It aims to provide insights into the hardware and infrastructure that form the necessary foundation for electricity trading within distribution networks.

Centralised approaches to electricity generation, transmission, distribution, and consumption are commonplace in modern status quo energy regimes (Alanne & Saari, 2006; Jacobsson & Lauber, 2006; Orlov & Bjørndal, 2017). A contributing factor to this system design and approach was Nicola Tesla's work with high voltage alternating current (AC), which enabled electricity to be distributed via transmission lines over long distances with reduced energy losses (Adil & Ko, 2016). These centralised energy provision models provided significant benefits and resulted in high levels of economic growth in the 20^{th} century. There are however sociotechnical regime transformations under way which are changing the ways in which electricity is produced, distributed, and consumed. Many energy transitions are resulting in a shift away from centralised sociotechnical regimes to distributed systems where electricity generation resources are modular and often located closer to where the electricity is consumed, thereby reducing the need for long distance transmission (Alanne &

Saari, 2006). Bronkhorst *et al.,* (2019) note that in the South African context, five major developments are transforming the energy regime from a centralised monopoly model to a distributed generation model. They are:

- the rising costs of electricity,
- the decreasing costs of RETs such as solar PV,
- the supportive regulation and policies implemented by local and national government,
- novel financing programmes, and
- the implementation of accredited organisations assuring the technical competence of installers.

The decentralisation and distribution of energy resources are two relevant implications occurring in the energy transition. Decentralised resources insinuate a separation and independence from a central electricity grid, whereas distributed energy resources can either be connected or disconnected from a central grid. What defines distributed resources however, is their geographically separate and modular structure (Alanne & Saari, 2006). Decentralised energy systems (DESs) that use RETs provide significant potential to contribute towards achieving some of the sustainable development goals (SDGs), namely achieving ‘clean and affordable energy’, ‘sustainable cities and communities’, ‘quality education’, and ‘climate action’ (Un.org, 2018).

Adil and Ko (2016) argue that decentralised renewable energy systems have four primary benefits over centralised, fossil-fuel based energy systems in that they:

- have significantly lower carbon emissions,
- do not require large sums of capital for infrastructure development,
- promote energy independence, and
- can make use of social capital and result in social cohesion.

While decentralisation of the physical energy producing resources is a common attribute of energy transitions, the transitions are resulting in other forms of decentralisation like the reallocation of decision making, energy asset ownership, responsibility, and expertise (Alanne & Saari, 2006). While it can be argued that these are positive implications which ultimately result in the democratisation of energy systems, there are also challenges that result from this decentralisation. Some of these include questions regarding responsibility, the compatibility of different energy related technologies, and a lack of common rules and standards (Alanne & Saari, 2006).

The South African Local Government Association (SALGA) (2018) notes that transitioning towards business models which can integrate with distributed renewable energy technologies is necessary and beneficial for municipalities in South Africa. This is because municipal electricity utilities face potential "utility death spirals" from profit losses if they do not adapt their business models to the changing energy regime in South Africa. River *et al.* (2018) describe this spiral as a reinforcing feedback loop resulting from the relationship between increasing electricity prices and the uptake of private electricity generation. Consumers are installing private electricity generation which propel municipalities to increase retail tariffs to recover profit losses (River *et al.*, 2018). As already mentioned, the increased costs increase the business case for consumers which in turn leads to further municipal losses and therefore further retail tariff increases (River *et al.*, 2018). This reinforcing feedback loop can be avoided if municipal electricity utilities adapt their business models in a way that works with the changing energy systems (SALGA, 2018a).

Multiple organisations and research papers propose alternative business models for South African municipalities which will enable them to remain relevant and profitable in the changing energy regime, and many of them involve embracing distributed renewable energy technologies (Zeller *et al.*, 2017; GreenCape, 2018; River *et al.*, 2018; SALGA, 2018). Some of the alternative business model options proposed by SALGA (2018) are the following:

- procuring electricity from SSEG for resale,
- procuring electricity from IPPs for resale,
- commissioning municipally-owned local generation capacity,
- enabling third-parties to use the municipal network to trade electricity (a concept called wheeling, and which would result in the municipality being paid a use-of-system fee), and

- operating energy storage facilities.

A growing number of municipalities in South Africa are developing regulatory provisions for SSEG which pay feed-in-tariffs to local producers feeding into the grid (SALGA, 2017; GreenCape, 2018). The National Development Plan (NDP) notes that technological developments enabling smarter management of electricity grids will open opportunities for enabling the management of distributed generation systems which will contribute to meeting energy demands (National Planning Commission, 2011).

In South Africa, "The Municipal Systems Act (No. 32 of 1998) defines the roles of municipalities as service authorities and assigns to municipalities the right to determine the service provider that will distribute electricity within their boundaries" (SALGA, 2018 : 4).

> "The Electricity Regulation Act (No. 4 of 2006) and the Electricity Regulation Amendment Act (No. 28 of 2007) defines 'municipality' that has executive authority and rights to reticulate electricity within its boundary. These regulations provide municipalities with the 'authority function' of energy reticulation. This function includes the development of policies, drafting by-laws, setting tariffs, deciding how energy reticulation services are provided and regulating the provision of these services in terms of the by-laws and other mechanisms" (SALGA, 2018 : 4)

There thus seems to be significant opportunities for municipalities to lead a low-carbon energy transition in South Africa because of their legislative authority and financial incentives to embrace and encourage localised distributed renewable energy technologies. Evidence of this can be seen in the research conducted by SALGA (2017) which shows how energy systems can transition when localised legislation is changed to encourage the adoption of RETs. Basic examples of these legislative changes include allowing SSEG installations and offering feed-in-tariffs to small scale producers of electricity.

In summary, the transition towards the use of distributed RETs would be beneficial for multiple reasons in the South African context. Such a transition could:

- provide alternative revenue streams for municipalities,

- catalyse a transition to a low-carbon economy,
- improve grid resilience, and
- potentially provide lower electricity prices to consumers.

Alanne and Saari (2006) show that there can however be challenges associated with the decentralisation and distribution of RET's which include:

- ownership and management of system infrastructures,
- a need to arrive at a common set of rules and standards,
- energy production intermittency which results from a dependence on weather conditions,
- high costs associated with energy storage which are often required to manage system variability,
- the management of bi-directional electricity flows in systems with multiple energy producing resources,
- slow and complicated licencing procedures for the construction of private SSEG (Alanne & Saari, 2006),
- a lack of uniformity and consistency,
- fragmentation of information resulting from decentralisation, and
- grid balancing and matching generation and consumption.

In systems where electricity generation is largely provided by RETs without energy storage, synchronising energy consumption with energy production can be challenging (Alanne & Saari, 2006). A graph commonly used to represent typical household electricity demand is known as the duck curve (energy.gov, 2018). This graph indicates two peaks in energy use, one in morning and another in the evening.

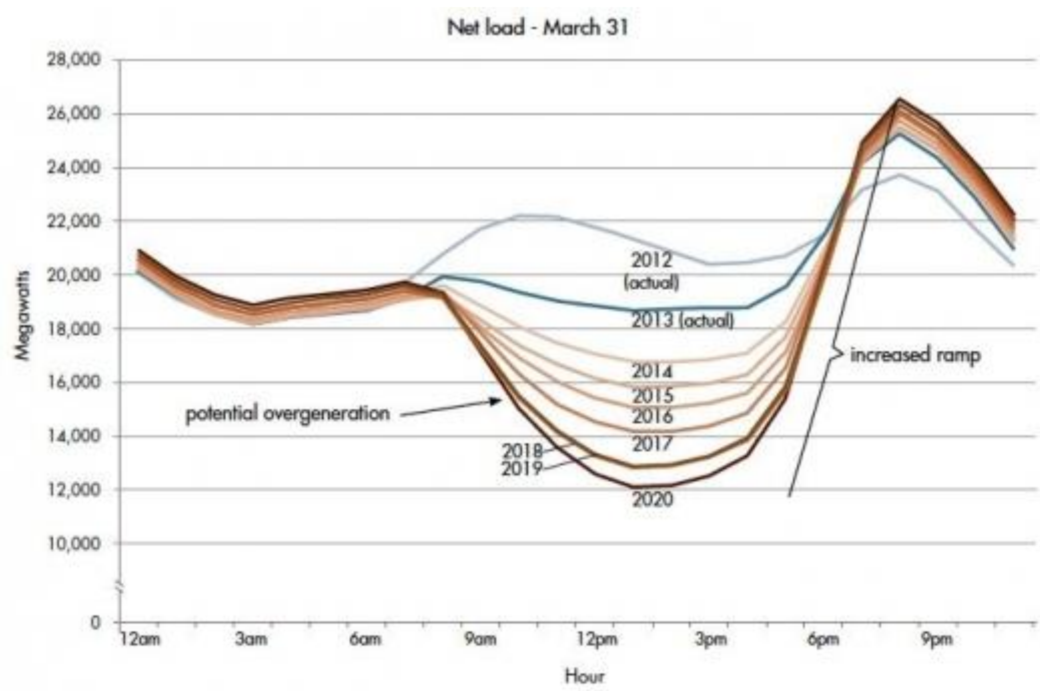

Figure 4. Typical household energy demand.

Source: (energy.gov, 2018)

The electricity production of solar PV panels, the most common form of SSEG in South Africa, is misaligned with general household consumption because peak production generally occurs during the middle of the day when the sun us at its highest. Without energy storage technologies such as batteries, matching household consumption with electricity production is challenging. One option that can assist in addressing the problem is to implement electricity trading within networks and to enable dynamic pricing which adjusts electricity prices based on the amount of electricity being fed into the system. Such a system could, for example, reduce prices during the middle of the day when there is an excess fed into the grid by PV panels, which would incentivise consumers to shift their demand to these times. This concept is further explored in Chapter 6.

2.7 New Business Models for South African Municipalities

2.7.1 Procuring Electricity from Local Generators of Electricity

One of the business models that municipalities are encouraged to consider in the changing South African energy system, is the procurement of electricity from local generators of electricity for resale to consumers using an electricity trading type approach (Montmasson-Clair *et al.*, 2017; SALGA, 2018; River *et al.*, 2018).

This approach would entail municipalities procuring electricity from sources such as small-scale energy producers with roof-mounted solar PV panels. SALGA (2018) notes that should this model be adopted,

- appropriate pricing structures would be necessary to cover grid management costs while also generating profit,
- metering and billing systems would need to be revised to cater for bi-directional electricity flows,
- clear application processes for SSEG would need to be adopted,
- appropriate tariffs would need to be established to compensate generators fairly while providing consumers with competitive tariffs,
- appropriate tariff structures could incentivise further development of SSEG due to increased financial incentives for prosumers,
- municipalities would benefit from having energy generation technologies financed by prosumers (producers and consumers of electricity), and
- municipalities would face increased system management complexity because of a need to track and manage the many generation resources and resulting bi-directional energy flows.

2.7.2 Procure Electricity from IPPs

In this energy transition scenario, municipalities could purchase electricity from an independent power producer (IPP) rather than from Eskom (SALGA, 2018a). SALGA (2018) notes that should this approach be adopted,

- there could be risks for municipalities because power purchasing agreements (PPAs) might incorporate tariff increases which may result in municipalities paying more for electricity than they might have from Eskom, and
- there may be challenges in matching supply and demand if IPPs have renewable energy technologies because generation would be intermittent.

2.7.3 Generate Localised Renewable Energy

In this scenario municipalities would construct an energy generation facility which would be used to feed electricity into the municipal grid (SALGA, 2018a). SALGA (2018) however notes that a barrier to this option are the costs that would be incurred by the construction of such a facility which may be beyond the means of some municipalities.

2.7.4 Wheeling of Private Sector Electricity

In this scenario, municipalities would offer use-of-grid agreements along with use-of-grid fees, enabling entities to use the municipal grid to transfer electricity from producers to consumers (SALGA, 2018a). SALGA (2018) notes that should this model be adopted by municipalities,

- it could result in increased localised economic development,
- appropriate use-of-grid fees could result in the development of local energy production because of financial incentives for producers, and
- the costs of these generation resources would not need to be covered by municipalities.

There are however barriers associated with this model. SALGA (2018) notes that implementing use-of-grid fees which are profitable for the municipality and which incentivise wheeling, could be challenging. Billing and grid management systems would become more complex and therefore require revisions and additional technological solutions (SALGA, 2018a). Additional financial, administrative, and legislative challenges and barriers associated with this model are discussed in more detail in Chapter 6 which aims to determine the viability of blockchain-based electricity trading in South Africa using blockchain technology.

2.7.5 Operate Storage Facilities

In this scenario, municipalities could profit by providing energy storage systems such as batteries, hydro-electric pumped storage, or concentrated solar power (SALGA, 2018a). Should this approach be adopted, SALGA (2018) notes that there may be challenges associated with high storage costs although energy storage is considered a key component in long-term renewable energy baseload operations.

2.7.6 Electric Vehicles (EV's)

Increasingly, countries are supporting the adoption of electrified mobility such as EVs, although there are barriers to their adoption such as : lack of a charging infrastructure, the high costs associated with EVs, lack of charging system interoperability, and lastly the time needed to charge EVs which is high compared to the time to fill the tank of a combustion car (Gustafsson, 2017).

It can be argued that an important component of an energy transition away from fossil-fuels towards low-carbon energy systems requires a shift away from combustion engines that run on fossil-fuels to alternatives such as EVs that run on low-carbon electricity. While there are barriers which hinder transitions to the use of EVs, these barriers arguably present opportunities for niche innovations. SALGA (2018) notes that a key component in the long-term transition to renewable energy is the use of energy storage systems such as batteries. Because energy transitions often involve the natural adoption of EVs, there are opportunities to utilise the battery capacities of these vehicles to act as grid storage devices when they are not in use. Research conducted by Kempton and Tomic (2005) reveals that the energy storage of EVs offers significant potential to provide storage for renewable energy generation which would assist with electricity grid balancing and with reducing the total RE installed capacity that energy systems require.

Considering the South African energy mix which, as demonstrated, remains heavily coal-based, the adoption of EVs in the current energy mix would not result in substantial emission reductions because they would still be powered by fossil fuel-based electricity. It can be argued that until such time that the energy mix is comprised of more RETs, the uptake of EVs will not contribute substantially to an energy transition to a low-carbon energy system. Halsey *et al.* (2017) argue that EVs are a necessary component in South Africa’s transport planning, but that the coal-dominant energy system reduces the advantages of their current adoption.

2.7.7 Electricity Trade in South Africa

Electricity trading is seen as a viable and beneficial business model which municipalities can adopt to remain relevant and profitable in the changing South African energy system (River *et al.*, 2018; SALGA, 2018). In this model a municipality procures excess electricity from local producers through a feed-in-tariff model and resells at a profit to consumers. This can be done either by purchasing from registered commercial IPPs, or from producers with generation that is either 10MW or smaller and which does not require generation licences from NERSA, for example buildings with private generation (Caboz, 2019). River *et al.* (2018) note that this model is especially beneficial for municipalities which have a high uptake of private generation in the form of SSEG. The proposed electricity trade business model enables municipalities, as grid operators, to profit from the uptake of SSEG by buying excess energy for resale (SALGA, 2018a).

River *et al.*, (2018) identify the benefits of an appropriate tariff structure as follows:

- It can optimise an energy system and stimulate local economic development.
- It can generate municipal profits and provide affordable electricity.
- It can maintain cross-subsidies for the benefit of the poor.
- It supports local economic development.
- It can assist with grid balancing and system optimisation.

River *et al.* (2018) identify challenges associated with this model as follows:

- It results in regime transformation.
- Progress and implementation are generally slow.
- It requires new and innovative business models.
- It requires a plan for when and how to procure energy.
- Municipalities often lack procurement experience and competence.
- There is a disconnection between municipalities because they often work in isolation.

- Departments within municipalities work in silos.
- Budget constraints limit planning and execution.

Of the 164 municipal electricity distributors in South Africa, 41 allow for SSEG installations, 29 of which have official application systems (SALGA, 2018b; Bronkhorst *et al.*, 2019). Of these municipal distributors, 25 offer tariffs to small-scale producers feeding excess electricity into the grid (SALGA, 2018b). These figures are rapidly increasing as more municipalities change their legislation in favour of allowing SSEG and feed-in-tariffs. For example, the number of municipalities allowing SSEG went up from 10 in 2016, to 41 in 2018, and the number of municipalities offering SSEG feed-in-tariffs from 5 in 2016, to 25 in 2018 (SALGA, 2018b). These statistics indicate the rapid growth in the SSEG market as well as the growth in the number of municipalities adopting basic electricity trading as a business model.

2.8 Conclusion

This chapter provided a brief overview of the global energy system transition that is under way, resulting from a shift away from fossil-fuels as a primary source of energy to the use of renewable energy for electricity generation. The primary drivers of the global energy transition were identified as being the decreasing costs associated with RETs plus a global drive to decarbonise human activity and to reduce anthropogenically induced global warming and climate change. The literature on system transitions, including the multilevel perspective (MLP), and strategic niche management theories, were explored. These theories form the theoretical framework for this thesis and are used as perspectives for analysing and thinking about the South African energy system transition.

An overview of the South African energy system was provided, demonstrating how the energy system, as a sociotechnical regime, is experiencing a transition in the adoption of distributed renewable energy technologies. The changes to the energy system are resulting in sociotechnical regime pressures. These pressures, such as the changing way in which energy is produced, are creating windows of opportunity for niche innovations. One such niche innovation is the small-scale electricity trading business model which has been made possible by the uptake of distributed small-scale-embedded-generation (SSEG). This innovation is explored in more detail in Chapter 6 with the aim of determining what role blockchain might be able to play in enhancing the model. Another niche innovation aiming to become widely used in the changing sociotechnical regime is a blockchain-based solar PV project financing mechanism offered by the start-up, Sun Exchange. Chapter 5 explores this innovation and its integration in the South African energy system via a participative case study research method using the multi-level perspective (MLP) and strategic niche management (SNM) frameworks.

Chapter 3

Blockchain Technology

This chapter provides an overview and brief history of blockchain technology which is relevant because the niche innovations explored in research of this thesis, namely blockchain-based energy project finance and blockchain-based electricity trading, are enabled by blockchain as a foundation technology. It is therefore useful to consider blockchain as a niche innovation itself using multi-level perspective (MLP) and strategic niche management (SNM) frameworks to understand the potential for the technology to become widely used in sociotechnical regimes and when this is likely to occur.

Different blockchain architectures are explored providing insights into their various characteristics, strengths, and weaknesses. The literature reveals that while blockchain has significant disruptive potential to change the way systems and sociotechnical regimes like the banking system, function, blockchain is arguably still a niche innovation. The technology is however developing rapidly and seems to have significant potential to become widely used.

The chapter demonstrates that there are many blockchain variations, each of which can be considered as separate niche innovation experiments from the SNM perspective. The high number of variations and experiments combined with the high levels of collaboration and communication are considered effective from the SNM perspective since they guide the development and prepare the innovation for regime integration and transformation.

The chapter concludes by showing that blockchain remains within the niche level of the MLP and is yet to result in notable regime disruption. The development and maturity of blockchain is however supported and enhanced by the fact that the blockchain community is highly effective in communicating and collaborating. The argument is therefore made that a widescale adoption of blockchain within regimes is likely to occur within the next few years.

3.1 What Are blockchains?

The term ‘blockchain’ is sometimes used as though it refers to a single technology, however, many blockchains exist which vary in functionality based on their design and architecture (Zheng *et al.*, 2017). Blockchains are ledgers of records shared between networks of computers, commonly referred to as public ledgers, which contain records of all digital events and transactions which occur amongst participating parties within a given blockchain network (Crosby, 2016). Transactions are verified through various consensus methods depending on the blockchain architecture. These transactions that occur are irrefutable because they are commonly transparent and can be viewed by network participants. Recorded transactions generally cannot be tampered with or reversed once added to the blockchain (Crosby, 2016). A blockchain allows participants in a network to have identical lists of records that specify the details of all historical transactions among all participants. In many blockchain architectures, for two individuals to transact with one another, they need other network members to approve the transaction, making democracy a common underlying characteristic.

One can think of a blockchain as a group of people who transact amongst themselves without a central management individual. Each time a transaction occurs between two people, everyone is notified and witnesses the transaction, and everybody adds the transaction to their list of records. This results in all participants in the group having an identical transaction history list. This ultimately means that all transactions are transparent and cannot be manipulated by individuals without everyone else knowing. Furthermore, two individuals in a blockchain ecosystem do not need to trust one another because the rest of the network witnesses and verifies their interaction.

Drescher and Basics (2017) define a blockchain as a distributed peer-to-peer system of ledgers for managing ownership of assets, and argue that such a system needs to overcome the following challenges for it to function:

- Describing the ownership of assets

- Protecting ownership
- Storing transaction information
- Distributing ledgers to untrustworthy nodes within a network
- Adding and verifying new transactions to the distributed ledger
- Deciding which ledgers within the network represent the truth.

3.2 History of Blockchain

The first well-recognised blockchain application was publicised in 2009 when a whitepaper was published by an individual, or group of individuals, under the pseudonym Satoshi Nakamoto (Crosby, 2016). The paper proposed a digital currency whereby the “purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution” (Nakamoto, 2009 : 1). The intention of the proposed Bitcoin blockchain was that it would serve as an “electronic payment system based on cryptographic proof instead of trust” (Nakamoto, 2009 : 1). The Bitcoin blockchain operates using a distributed network of nodes and wallets which allows for cheap, fast, borderless and anonymous transactions, unlike what is offered by conventional banks.

Distributed ledger technologies such as the Bitcoin blockchain innovation have implications for traditional financial regimes given that they are structured according to vastly different operating logics (Krause, 2015). A credit card transition using the conventional finance system typically takes three business days before it is confirmed whereas an international Bitcoin transaction will take 10 minutes at most (Krause, 2015). Conventional financial exchanges also entail significant transaction fees because multiple parties are involved and need to collaborate, which further increases when transactions occur internationally (Krause, 2015). On the Bitcoin blockchain however, transaction fees are comparatively low because there are no intermediaries and transactions occur directly between two parties (Krause, 2015).

An example of the shortcomings of traditional banking is reflected in international remittance statistics which reflect the transfer of money from individuals working abroad to people in their home countries. Tapscott (2016) writes about the dynamics of these international remittances and note that they constitute one of the largest flows of capital to developing countries. While this flow of capital has positive impacts on the some of the world's poorest and most vulnerable people, the administration involved is extensive and the costs associated often exorbitant. Remittance flows to developing countries are estimated to be three to four times greater than foreign aid; despite their enormous potential to lift people out of poverty, transaction fees can be extremely costly, in some cases exceeding 20% commission(Tapscott & Tapscott, 2016). When one considers that in many cases international remittances are being sent by people with low incomes such as unskilled labour workers, a 20% commission on their transfer can result in major implications to the basic needs they can afford. It can therefore be said that the use of blockchain and cryptocurrencies such as Bitcoin**,** could have positive implications for people transferring money internationally. Removing the need for trusted third-parties in a world where the primary means of transacting with someone unknown is to go through a trusted third party, such as a bank, is considerable. While there is little consensus, some application developers are suggesting that the Internet has evolved to become the Internet 3.0. (Barassi & Treré, 2012). Internet 1.0 refers to an Internet of information and Internet 2.0 refers to an Internet where users become active participants and generators of content, primarily due to publishing capabilities offered by social media platforms (Barassi & Treré, 2012). Internet 3.0 refers to an Internet of value, where users' data is integrated to enable user cooperation and value exchange (Barassi & Treré, 2012). Blockchain technology enables online cooperation through providing a tool for value exchange. This is arguably a contributing element to Internet 3.0 because it has the potential to enable a new level of cooperation in a way that is decentralised, and which does not rely on trusted intermediaries.

3.3 How Blockchains Function

3.3.1 Hashing Data

Distributed peer-to-peer systems will naturally result in a need to manage many transactions, each of which will have to be uniquely identifiable. In blockchains, this is done by hashing which is a process of transforming data via encryption into a unique hash value of fixed length, regardless of data size, which can be thought of as an ID number or fingerprint (Drescher & Basics, 2017). A hash value is typically a long code consisting of numbers and letters and the process is known as cryptography. Transaction input data, such as how much digital currency person A would like to transfer to person B, will be encrypted to a unique hash function. Other qualities of hashing data as explained by Drescher and Basics (2017) include the following:

- It is as impossible to recover input data from a hash value as it is to determine anything about a person from an isolated fingerprint.
- Hashing data is collision resilient which means that different data inputs will never result in the creation of an identical hash value.

When a piece of data also contains a hash reference to another piece of data, it is referred to as either a *chain* or a *linked list* (Drescher & Basics, 2017). Figure 5. below illustrates how these chains of data (blockchains) are structured, starting with a piece of data labelled Data 1, which contains no hash reference. Data 2 however contains a hash reference that links back to Data 1, and Data 3 contains a hash reference that links it to Data 2, which is linked to Data 1. This chain represents the sequence of transactions that has been recorded and documented in the blockchain. Each piece of data is referred to as a block. We can hence see the origins of the name blockchain. R3 is known as the head of the chain and represents the most recent data addition to the chain and with it, all subsequent transaction history can be accessed.

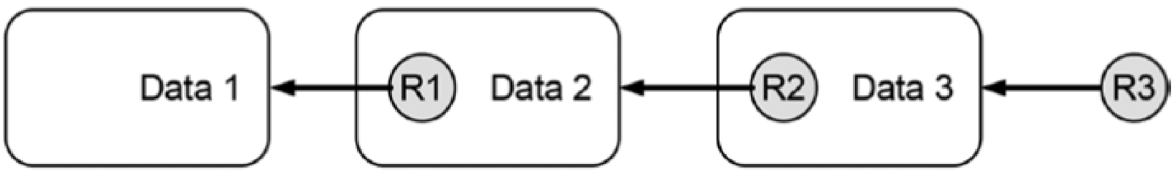

Figure 5. Data blocks linked in a chain

Source: (Drescher & Basics, 2017)

While hash values are useful for managing and recording data, they are also useful as a means of forcing computers to challenge other computers to work out the hash values; a processes called ‘mining’ which can be thought of as complicated puzzles (Drescher & Basics, 2017). The only way to work out hash values is through computational power and work, and for this reason mining computers require significant amounts of electricity to run. Mining is the process of working out hash puzzles to arrive at a combination lock which is a unique sequence of numbers. The only way to work out this sequence is to try every possible combination through trial and error (Drescher & Basics, 2017). In the case of the Bitcoin blockchain, the mining process results in computers which figure out hash values being rewarded with the digital currency, namely Bitcoin (Nakamoto, 2009). Other blockchains also reward nodes that figure out hash values with digital currencies. This is how digital currencies are created and results in incentives for nodes to participate in the running of blockchains. The high demand for electricity required to run mining computers is a topic of controversy from a sustainability perspective because it will often be the case that mining computers run off electricity generated by using fossil fuel technologies such as coal-fired power stations (Truby, 2018).

3.3.2 Cryptography

Identifying people and protecting them within blockchains is done using what is known as asymmetric cryptography which is intended to ensure that only rightful owners can access certain data (Drescher & Basics, 2017).

The concept of cryptography ensures that data is protected from unauthorised people accessing it. This is done by encryption and decryption. Data is encrypted to another format as a means of making it unrecognisable to unauthorised parties. It is then decrypted by authorised parties so that they can access the original encrypted data (Drescher & Basics, 2017). Encrypted data is referred to as cypher text which commonly looks like a random mix of numbers and digits to someone who does not know how to decrypt it. The encrypted information is thus only useful to someone who has the decryption key.

Figure 6. Illustration of cryptography process

Figure 6. Illustration of cryptography process

Source: (Drescher & Basics, 2017)

For many years a method of cryptography was used where the same key could be used to both encrypt and decrypt data (Drescher & Basics, 2017). This is known as symmetrical cryptography. Because this is not always desirable, asymmetric cryptography was invented which entails using two complementary keys whereby cypher text created by one key can only be decrypted using another key, and vice versa (Drescher & Basics, 2017). This ultimately allows one to separate the group of people who can create cypher text from those who are able to decrypt it. In real world applications these keys are given names, commonly a public and a private key, and what generally happens is that public keys are given to everyone and private keys are kept private.

Blockchains use asymmetric cryptography to authorise transactions and verify accounts (Zheng *et al.*, 2017). Account numbers in blockchains are the public keys. Asymmetric cryptography is also used to verify transactions. When a node in a network or a person with an account wants to transfer an asset, they create cypher text with their private key. Other nodes in the network can verify the transaction and the account holder’s desire to transfer the asset using the public key which conveniently is the account number of the node that is trying to transfer the asset (Drescher & Basics, 2017). This process is called the digital signature and it ensures that an individual’s transaction desires can be verified by everyone but changed by no one other than the person who created it.

Digital signatures are used to sign transactions and to verify transactions. For an account holder to transfer an asset, they need to create a digital signature. This is done by: specifying transaction information such as a recipients account number and the amount to be transferred, creating a cryptographic hash value of the transaction data, encrypting the hash value with the private key, and adding the cypher text created using the private key to the transaction as a digital signature (Drescher & Basics, 2017).

To verify a transaction, a hash value of the transaction data needs to be created by the verifier. The digital signature of the transaction needs to then be decrypted using the account number of the node wanting to make the transaction, which is the public key. If the hash value created corresponds to the value generated by decrypting the digital signature, the transaction is successfully authorised (Drescher & Basics, 2017).

3.4 Consensus Mechanisms: Approaches to Verifying Transactions Within Blockchains

The differences in the various blockchain designs are largely determined by the consensus protocols used in the blockchain architectures. Consensus protocols, or consensus algorithms, are different ways in which consensus is determined about which transactions can take place (Zheng *et al.*, 2017). The different protocols use different consensus methods to establish which transitions are legitimate, and can be added to the distributed and shared ledger (Gustafsson, 2017). When consensus is reached, transactions are verified and added to blocks of data which are then added to the chain of data blocks (Zheng *et al.*, 2017). Different consensus protocols have different qualities, strengths and weaknesses, making each useful for different applications. The two most common types of consensus protocols are proof-of-work (PoW) and proof-of-stake (PoS), while other protocols include: proof-of-authority (PoA), practical byzantine fault tolerance (PBFT), delegated proof of stake (DPOS), Ripple, and Tendermint (Zheng *et al.*, 2017). As blockchain technology develops and evolves, other consensus methods are experimented with such as proof-of-luck, proof-of-time and proof-of-ownership, however these are not discussed in this thesis.

3.4.1 Proof-of-Work (PoW)

PoW is a popular consensus protocol used by the Bitcoin blockchain, amongst others (Vukolie, 2015). PoW relies on network participants using their computational capacity to solve calculations to verify and add data blocks to the blockchain (Nakamoto, 2009). The methodology can be likened to a lock that can only be opened with the correct combination, and which can only be found by trying every possible combination. The complexity of the calculation is automatically adjusted relative to the total computing capacity of the network to ensure that the right solution is found at regular intervals (Gustafsson, 2017). The nodes which do the calculations to validate transactions are referred to as miners and they are rewarded for their work in digital currency (Zheng *et al.*, 2017). In the case of the Bitcoin blockchain, miners are rewarded with Bitcoin cryptocurrency. Essentially, if you work to contribute to the management of the system, the system will reward you. PoW is known for its decentralised, robust and tamper-proof qualities. PoW however requires large amounts of electricity due to the substantial amounts of computational power which mining computers run on. Truby (2018) argues that it makes this consensus method expensive and often unsustainable, especially if mining computers are using power generated by stations that run on fossil fuels. Even where PoW mining computers are using renewable energy, some consider this methodology to be a waste of resources (Gustafsson, 2017). Another issue with the PoW consensus mechanism relates to scalability. For example, the Bitcoin blockchain is only able to run seven transitions per second (Zheng *et al.*, 2017). It can be said that these limitations are a significant barrier to widescale adoption of this blockchain architecture. There are however proposals relating to how scalability can be achieved, although they remain mere proposals for the time being (Zheng *et al.*, 2017).

3.4.2 Proof-of-Stake (PoS)

PoS is a consensus protocol that uses a method which allocates transaction calculations to nodes in a network based on their stake in the network, which is determined by the value of digital currency (specific to that blockchain) in their possession (Zheng *et al.*, 2017). While this method is known for being less energy-intensive than PoW, it is sometimes criticised for not possessing the blockchain qualities that many consider to be its greatest strengths, namely its decentralisation, robustness, and security (Gustafsson, 2017). In PoS blockchains, opportunities and rewards are given to those that already have currency which is what Bitcoin aimed to change (Nakamoto, 2009). The PoS consensus method increases the potential for a select few to control what happens in the blockchain if they have the currency to enable this control. While this defeats the purpose of an application such as Bitcoin which was designed to be decentralised (Nakamoto, 2009), it may be useful for other applications that do not require the same level of decentralisation and security, such as managing and streamlining operations within a business for example.

3.4.3 Proof-of-Authority (PoA)

In a PoA consensus mechanism, the network nodes that validate and create data blocks constitute a pool of known network participants (Hartnett *et al.*, 2018). One of the characteristics that some might consider to be a negative attribute is that this method is centralised due to its reliance on selected and predetermined validators (Hartnett *et al.*, 2018). The results of this centralisation however are a number of positive attributes. Hartnett *et al.*, (2018) note that these include:

- consistent block creation times making it known when a transaction will be verified and added to the blockchain,
- low energy demands which means that unlike PoW mechanisms, validators do not have to race to create blocks which results in less collective computational capacity being used,
- increased throughput enabling more transactions to be processed compared with the PoW consensus mechanism,
- low transaction costs because the reduced computational requirements and energy demands compared with PoW mechanisms translate into costs that are significantly lower for validators which in turn lowers the overall costs per transaction, and
- simplified protocol upgrades: because the validators are known and relatively few, coordinating updates to the blockchain can be done through planned collaboration between stakeholders.

3.4.4 Practical Byzantine Fault Tolerance (PBFT)

PBFT is a consensus protocol which uses a majority vote system to determine which node should order a transaction and add a data block to the blockchain (Zheng *et al.*, 2017). A potentially negative aspect of this system however is it requires that every node is known to the network which might not always be practical. The Hyperledger blockchain uses PBFT as a consensus method making it a more energy- efficient blockchain than the Bitcoin blockchain due to the reduced need for computational capacity. While there is arguably a need for a scalable and sustainable blockchain architecture, there is a lack of research on this topic (Vukolie, 2015).

3.4.5 Delegated Proof of Stake (DPOS)

DPOS is a consensus protocol which uses a method whereby network participants elect their delegates to generate and validate blocks (Zheng *et al.*, 2017). This method enables transactions and blocks to be quickly generated and validated and requires significantly less energy than a PoW method.

3.4.6 Ripple

Ripple is a consensus algorithm which uses trusted subnetworks within a larger network in the consensus process (Zheng *et al.*, 2017). In this blockchain network nodes are divided into two participant types: *servers*, which are able to participate in the consensus process, and *clients,* which are only able to transfer funds (Zheng *et al.*, 2017). Servers have access to a unique node list and every time a transaction is requested by the clients, the servers query the unique node list; if 80% of the servers agree on the transaction it takes place and is added to the shared ledger (Zheng *et al.*, 2017). The ledger therefore remains resistant to tampering so long as faulty or malicious nodes do not exceed 20% of the total number of server nodes.

3.4.7 Tendermint

Tendermint is a consensus algorithm which uses voting rounds to add data blocks to the blockchain (Zheng *et al.*, 2017). Each round is divided into a pre-vote, a pre-commit and a commit stage (Zheng *et al.*, 2017). In each round, a proposer is selected to broadcast unconfirmed blocks. In the pre-vote stage validators decide whether to broadcast a pre-vote for a block (Zheng *et al.*, 2017). Assuming they do, in the subsequent pre-commit stage if a node receives 66% pre-votes from other nodes for a proposed block, it broadcasts a pre-commit for that block (Zheng *et al.*, 2017). If the node receives more than 66% of the votes for pre-commits, it enters the commit stage for that block, and if the node receives more than 66% of the commit votes, the block will be accepted and added to the blockchain (Zheng *et al.*, 2017).

As blockchain technology develops, new consensus protocols and system architectures evolve, each with their own strengths and weaknesses (Zheng *et al.*, 2017). While there is discussion about which designs are better and which will stand the test of time, the reality seems to be that different applications and needs will require different blockchain architectures based on characteristics which applications require. For example, and as already mentioned, a company using blockchain internally to streamline logistical processes will not necessarily require the decentralised, transparent and anonymous characteristics of a proof-of-work consensus protocol.

3.5 Public, Private and Consortium Blockchains

Public, private and consortium blockchains can have similar blockchain architectures. The primary characteristic of public, private or consortium blockchains is the level of accessibility which influences the degree of centralised control over a given blockchain (Buterin, 2015).

Public blockchains such as the Bitcoin blockchain are open to the public which means that in theory anyone in the world can participate in the network (IBM, 2017). They allow for anyone to read the blockchain, send transactions, and participate in the consensus process (Buterin, 2015). Public blockchains are secured and governed by what Buterin (2015), refers to as crypto-economics which are a combination of economic incentives for participation and cryptographic verification through consensus mechanisms. Public blockchains are known for generally being fully decentralised whereby no central authority has control over the network (Buterin, 2015). Once transactions occur within a public blockchain, they cannot be reversed which can be a benefit but also a problem if the transaction needs to be reversed (Buterin, 2015).

Private blockchains are centralised in that permissions are controlled by the participants in a network who are the only ones with writing permissions and the authority to decide who to give reading and writing permissions to (Buterin, 2015). Unlike public blockchains, private blockchains allow for central authorities to change and reverse transactions. Transactions on private blockchains are easier and less energy-intensive than on public blockchains because they need only be verified by the centralised controlling participants, and not by multiple participants as is the case with public blockchains (Buterin, 2015).

Consortium blockchains are a hybrid between public and private blockchains in that the consensus process is controlled by a predetermined set of network participants, and the ability to read the blockchain could be either public or restricted (Buterin, 2015). Consortium blockchains can be considered partially decentralised, however the level of decentralisation is determined by the degree of accessibility and the number of participants with write and read permissions.

3.6 Energy Consumption and Sustainability of Blockchains

The environmental sustainability of blockchains is a controversial topic because of the resource requirements needed to run the system (Giungato *et al.*, 2017). Sustainability concerns are a topic of debate and controversy because of the high energy demands of some blockchain architectures such as those that use the PoW consensus protocol. From a sustainability and resource efficiency perspective, the most energy intensive protocol is the PoW due to miners having to hash block headers continuously in order to reach target values (Zheng *et al.*, 2017). PoS and DPOS still require miners to hash block headers to find target values, however the energy requirements are substantially lower (Zheng *et al.*, 2017). PoA also uses miners, however, they are predetermined and do not need to compete to validate transactions making this consensus mechanism resource efficient and therefore a comparatively low energy consumer (Hartnett *et al.*, 2018). PBFT, Tendermint, Ripple and Tangle require no mining process (Zheng *et al.*, 2017), making them the most energy efficient of the researched distributed ledger designs.

Donnerer and Lacassagne (2018) note that the Ethereum blockchain uses five terawatt hours (TWh) of electricity a year, and that the Bitcoin blockchain has the same energy demands as Denmark for it to operate. Truby (2018) argues that the security, trust, and transactional benefits of PoW are dwarfed by the intentionally resource-intensive design of the Bitcoin blockchain which he notes, is becoming a threat in terms of its contributions to global warming and climate change. Truby (2018) suggests that without encouraging more sustainable development of the various blockchain applications with forced intervention, their combined effects could pose a serious threat to the global commitment to mitigating greenhouse-gas emissions. The United Nations Framework Convention for Climate Change Mitigation note that blockchain offers the potential to act as a tool for combating climate change due to its uses within carbon trade markets and for measuring and verifying emission reductions (UNFCCC, 2017). It can however be said that its use will only be beneficial if appropriate blockchain architectures are used which do not rely on unsustainable levels of energy consumption.

One could argue that blockchains that make use of a PoW consensus protocol could be sustainable if the computers within the network are powered with renewable energy. The issue with this argument however is that it is challenging to ensure that nodes are powered by RE considering that participants are often anonymous and globally distributed. This means that various miners will be using different sources of electricity. The majority of the world’s electricity generating resources are still fossil fuel-based (World Economic Forum & Accenture, 2013), which means that energy-intensive blockchains are unsustainable because they are primarily run using carbon-emitting technologies.

3.7 Decentralised Value Exchange

The potential that blockchain provides to enable value exchange between untrusted parties presents opportunities to contribute to decentralised applications which rely on collective resource sharing, rather than on centralised models that rely on organisations providing infrastructure and resources to end-users.

Over the past twenty years, business models have undergone many changes in transitions away from models of centralised organisations providing services and resources to passive consumers, towards models of decentralised organisations which aggregate resources from multiple people to provide services (De Filippi, 2017). This can lead to organisations no longer needing to own resources, assets, or even offices, because they can rather use information communication technology to facilitate transactions between suppliers and buyers (De Filippi, 2017). Examples of these types of organisations include Uber and Airbnb. While these models provide opportunities for more people to participate in industries, a problem that can arise is that the value produced by the participants is not evenly distributed amongst contributors but can instead be captured by the large intermediaries that operate the platforms (De Filippi, 2017). Blockchain offers the potential to address this issue because of its ability to facilitate the exchange of value in a decentralised and secure manner without the need for intermediaries (De Filippi, 2017). Huckle *et al.* (2016) argue that blockchain offers opportunities for the creation of a myriad of sharing applications based on peer-to-peer sharing networks which do not rely on centralised organisations for facilitation. The ability to remove the need for central intermediaries and connect customers directly with suppliers may have the potential to contribute to the development of sharing economies. As has been established however, the complete decentralisation and removal of intermediaries currently requires the use of public blockchains that use PoW consensus protocols. The reviewed literature has also revealed that these blockchain designs are not scalable because of their high energy demands and comparatively low transaction throughput. It can therefore be said that while blockchain could in theory enable the development of peer-to-peer sharing platforms and remove intermediaries altogether, this will not be realised on a large scale until the barriers relating to scalability and energy efficiency are overcome.

There is however significant potential for organisations like Uber and Airbnb to use blockchain to manage and automate the vast number of transactions and interactions that are occurring on their platforms. While this does not address the issues related to fair distribution of compensation, blockchain technology could offer benefits for these distributed business models. For instance, an organisation with a platform that uses people's private resources in its offerings could use a PBFT or delegated PoS consensus protocol and a consortium blockchain structure, granting platform users with the ability to view all transactions. This would improve business efficiency and transparency which would be beneficial for the organisation and users of the platform.

3.8 Blockchain and System Transitions

From the MLP perspective, the development and use of blockchain can be classified as a sociotechnical niche. This is evident when considering some of the defining characteristics of niche innovations as listed by Raven *et al.* (2010):

- *A new and unstable set of institutions and rules*: Blockchain is a relatively new technology. When looking at the many ways in which blockchains can be designed and are being experimented with, a stable set of rules as to how they should be designed and integrated into sociotechnical regimes is still lacking.
- *The micro-level of sociotechnical change:* While the Bitcoin and Ethereum blockchains are the most widely used, it can be said that blockchain cases remain within the micro-level of sociotechnical systems and are yet to result in widescale regime transitions.
- *A makeup of practices that deviates from the conventional way in which societal needs are fulfilled*: Through the automation of value exchange and the reduced need for trusted intermediaries, it can be said that blockchain promises a new way of managing systems which fulfil societal needs. For example, the Bitcoin blockchain aims to offer a radically different way of fulfilling the societal needs that conventional banks fulfil.

Reviewing blockchain and its related developments from the SNM perspective provides insights into its developmental trajectory and likelihood of becoming widely used and integrated into sociotechnical regimes. Comparing the way in which blockchains development is being managed with proposed best practices of SNM, is useful for understanding whether the current developmental trajectory will result in sociotechnical regime integration. To recap, the best practices as proposed by Raven *et al.* (2010) are:

- voicing and shaping visions and expectations,
- building social networks, and
- using of a constructive learning process.

It seems that the development of blockchain as a niche innovation is effective because its development follows many of the SNM best practices.

Raven *et al.* (2010) note that a high level of communication and collaboration between stakeholders experimenting with a niche innovation is useful because the development of the innovation becomes a product of the shared learnings of multiple developmental experiments. It can be argued that the international blockchain community is effective when it comes to collaboration and communication. There are reasons to support this view which include the following:

- There are online groups and forums used by blockchain developers and enthusiasts to communicate and remain updated on the latest blockchain related developments. Many of these groups are hosted on Reddit, Twitter and Telegram. Some Reddit group discussions include; r/blocktech, r/BlockChain, r/CryptoCurrency, and r/OntologyNetwork. Some Telegram groups include Whale Team, Cointelegraph, DeCenter, Bitcoin Bravado, DASH Knights, and Bitcoin Channel. There are however many, many more.
- There are many events and Meetups designed to bring the blockchain community together. Coindesk (2019) is one website which lists international blockchain specific events and conferences. It has 68 events listed for 2019 alone.
- The inception of blockchain, as introduced by Satoshi Nakamoto (2009), was intended to be open source and a product of decentralised collaboration.

Raven *et al.* (2010) note that the experimentation of multiple separate niche innovations is an effective approach for developing an innovation, and it seems that the current approach to the development of blockchain as a niche innovation is indeed effective. The reason for this is that there are many separate instances of people and organisations experimenting with the development of blockchain as is evidenced by the multitude of approaches to designing consensus protocols plus the varying levels of decentralisation which result from different approaches to blockchain privacy. Furthermore, journal articles such as those published by Montemayor and Boersma (2017), Vukolie (2015), and Zheng *et al.* (2017), which review various blockchain developments that provide insights into the strengths and weaknesses of different blockchain designs and projects, contribute to effective blockchain development. These papers as well as online discussions guide the development of blockchain, thereby increasing its usefulness and potential as a niche innovation becoming widely used in sociotechnical regimes.

3.9 Conclusion

This chapter provided an overview and brief history of blockchain technology providing high level information on varying blockchain design approaches and functionalities. The developmental trajectory of blockchain was assessed using the multilevel perspective (MLP) and strategic niche management (SNM) theoretical frameworks.

Blockchain can be used in different ways for different types of applications aimed at delivering value in different sociotechnical regimes. It can therefore be said that whether blockchain technology as a niche innovation, becomes widely used in sociotechnical regimes and results in system transitions, depends on the niche innovations that blockchain enables and the sociotechnical regimes they aim to integrate with, and not on blockchain itself. For example, the Bitcoin innovation, while very successful compared with other blockchain innovations, has not succeeded in replacing the dominant ways in which conventional banking systems fulfil societal needs.

It seems that the development of blockchain is following many of the best practices proposed by the SNM perspective. From a multi-level perspective however, it can be argued that sociotechnical regime disruption depends on the combination of the blockchain used and the innovation it enables. Because blockchain is still experiencing development as a niche innovation, it can be said that organisations using blockchain to develop applications should remain adaptive in terms of the blockchains they use and the ways in which those blockchains are designed. Because blockchain technologies continue to change and improve, organisations should avoid becoming tied to a single blockchain or blockchain architecture in case it becomes outdated.

Chapters 5 and 6 explore the South African energy system as a sociotechnical regime with the aim of determining whether regime conditions are providing windows of opportunity for blockchain-based niche innovations. The innovation explored in Chapter 5 is Sun Exchange's project finance mechanism, and the innovation explored in Chapter 6 is blockchain-based renewable electricity trading which has yet to be introduced into the South African energy market.

Chapter 4

Integrating Blockchain Into Energy Systems

Chapter 2 provided an overview of the global and South African energy systems exploring how and why they are experiencing sociotechnical regime transitions. It demonstrated that the sociotechnical landscape level pressures being exerted on the South African energy regime are resulting in windows of opportunity for niche innovations. Chapter 3 explored innovation, blockchain technology, and assessed its development from the strategic niche management (SNM) and multi-level perspective (MLP). The chapter concluded that as a niche innovation, blockchain seems to require further development before it can be widely adopted in sociotechnical regimes. It was further concluded that the implications of blockchain on sociotechnical regimes will depend on the innovations that blockchain enables, as well as the regimes they are aiming to integrate with, and not on blockchain itself.

This chapter explores the energy-related niche innovations that blockchain is enabling with a focus on project finance and electricity trading.

4.1 Blockchain Innovations and Energy Regime Transitions

Rifkin (2008) argues that when two innovative and disruptive technologies converge, economic regime shifts are likely to occur, as was the case with the first industrial revolution which he argues resulted from two coinciding inventions, namely the steam engine and the printing press. This technological convergence resulted in cheap, quick to produce, and widely available print material which changed how information was spread within societies (Rifkin, 2008). This economic shift occurred again in the second industrial revolution when centralised electricity generating resources such as coal-fired power stations converged with developments in telephone, radio, and television technologies which arguably resulted in a mass consumer society (Rifkin, 2008). The third industrial revolution refers to the convergence of developments in energy technologies with developments in information communication technologies (ICTs) (Rifkin, 2008). In the context of this thesis, this convergence could entail blockchain-based ICT innovations and renewable energy technologies. Other disruptive technological innovations entering energy markets could lead to further regime transformation. Schwab (2018) suggests that we are experiencing a fourth Industrial revolution which he argues is resulting from the simultaneous convergence of many disruptive innovations including blockchain, artificial intelligence (AI), 3D printing, the internet of things (IoT), smart devices, driverless cars, electric vehicles, smart cities, machine learning, genetic engineering and quantum computing. Many of these innovations have potential implications for energy regimes. It seems that because of landscape pressures on energy regimes to decarbonise, coupled with an abundance of niche technological innovations in the energy sector, radical energy system transitions are likely to occur.

Blockchain technology is increasingly being used and recognised as a technology with beneficial uses within energy systems. As energy systems increasingly incorporate distributed generation technologies and devices that are connected to the internet such as smart meters, electric vehicles, and other smart electric devices such as geysers, the need for a technology to manage communications and transactions between these devices becomes advantageous. As has been demonstrated, blockchain is useful for automated communication and transaction management in systems with many decentralised network nodes. Some of the blockchain-based energy applications being experimented with internationally include electricity trade management, electric vehicle (EV) charging, carbon asset and emission tracking and trading, smart energy grid management, and energy infrastructure financing (Orlov & Bjørndal, 2017; Gustafsson, 2017). Some of these innovations result from a need to address the challenges presented as energy regimes transition away from centralised models with relatively few large-scale electricity producing resources, to systems with distributed and intermittent renewable energy technologies which require more advanced management systems due to increased system complexity (Gustafsson, 2017; Orlov & Bjørndal, 2017; Chitchyan & Murkin, 2018; Donnerer & Lacassagne, 2018; Tushar *et al.*, 2018). While energy regime transitions are resulting in opportunities for blockchain-based innovations such as peer-to-peer electricity trade management between distributed energy resources (DERs) (Zhang *et al.*, 2017), blockchain-based innovations are arguably also contributing to transitioning energy systems. For example, innovations exist which enable the development of renewable energy infrastructure using crowd-financing models (Montemayor & Boersma, 2017; Orlov & Bjørndal, 2017). These innovations are directly affecting energy regime transitions.

The potential usefulness of blockchains in energy systems are described below:

- *Automation*: Blockchain can act as a tool to automate the management of decentralised energy generating resources thus improving system control and efficiency (Burger *et al.*, 2016).
- *Markets and trading*: It can facilitate small-scale electricity trades thereby presenting new market opportunities and potentially disrupting and transforming conventional large-scale wholesale electricity markets (Burger *et al.*, 2016; Grewal-Carr & Marshall, 2016).
- *Billing*: It can facilitate automated billing for electricity consumers and for distributed generators of electricity (Andoni *et al.*, 2018).
- *Sales and Marketing*: Electricity sales may change in that customer preferences such as generation sources could be incorporated into purchasing decisions (Andoni *et al.*, 2018).
- *Data management*: It can be used for data transmission, communication and management between smart devices in energy grids (Andoni *et al.*, 2018).
- *Sharing of resources*: It can facilitate the management of shared infrastructures such as electric vehicle charging stations, energy generating infrastructures, and energy storage units by automating and recording transactions and ownership information (Andoni *et al.*, 2018).
- *Transparency*: Transparent ledgers and immutable records plus the common characteristics of blockchains could greatly improve regulatory compliance and auditing (Andoni *et al.*, 2018).

Montemayor and Boersma (2017) conducted research on 65 organisations with blockchain-based applications designed for energy systems. Below is a list of primary insights from their research:

- Over 64% of the energy organisations using blockchain are in Europe.
- The top three countries for blockchain-energy innovation are the US, Germany and Netherlands.

- The most common application of blockchain is the facilitation of peer-to-peer electricity trading.
- Approximately 50% of the applications use the open source Ethereum blockchain.
- Around 74% of the organisations were founded between 2016 and 2017.
- A total of 25% of the reviewed organisations have run or were planning to run Initial Coin Offering (ICOs). ICOs are sales of the digital currencies that the various applications use. For example, SUNEX is the digital currency used by Sun Exchange (Cambridge, 2018). The pre-sale of a digital currency can help organisations raise funds for developing and growing their innovations.

The Energy Web Foundation (2018) conducted research on 41 organisations using blockchain in the energy sector and the following insights were established:

- Europe is the dominant location for blockchain-energy innovators which is host to 25 of the 41 organisations.
- Of the researched organisations, 85% have been founded since 2015 and 46% between 2017 and 2018.
- Most organisations are small start-ups with between 5 and 10 employees.
- Most of the organisations specialise in one of three areas; peer-to-peer electricity trade, renewable energy integration, and demand response management.
- Only 39% of the organisations researched had launched their products.
- The Ethereum blockchain is used by 64% of the organisations.
- The Energy Web Chain, a private, permissioned blockchain created by the Energy Web Foundation specifically for energy related applications, was being used by 22% of the organisations (Hartnett *et al.*, 2018).

The following conclusions can be drawn from the insights generated by the research done by the Energy Web Foundation (2018) and Montemayor and Boersma (2017):

- It seems that because most of the blockchain-energy applications use the Ethereum blockchain, this blockchain holds the most promise in terms of developing niche innovations that can take advantage of windows of opportunities presented by transitioning energy regimes. This is evidenced by the commercialisation of the Sun Exchange innovation which utilises the Ethereum blockchain, and which has become integrated into the South African energy regime.

- Most of the blockchain-energy innovations remain within the niche innovation level of the MLP and are not yet ready to integrate with energy regimes. This is evidenced by the fact that most innovations have been created in the past three years and remain in a developmental phase. Furthermore, only 39% of the organisations researched by the Energy Web Foundation (2018) had launched their solutions.
- Considering the MLP it can be argued that the organisations researched by the Energy Web Foundation (2018) and Montemayor and Boersma (2017) and their accompanying innovations will likely compete to take advantage of the windows of opportunity created by energy regime transitions. The competition between these varying approaches to achieve similar objectives such as peer-to-peer electricity trading, will likely result in some innovations succeeding and others failing. The ones that survive will have the opportunity to become widely used within energy systems and result in new sociotechnical regime equilibriums.

4.2 Energy Infrastructure Finance

Research conducted by the Energy Web Foundation (2018) and Montemayor and Boersma (2017) demonstrates that most of the blockchain-energy applications that exist focus on electricity trading. While the use of blockchain for energy infrastructure finance is less common, it has seen some notable success in terms of being integrated into existing energy regimes. The South African start-up, Sun Exchange, is one such example whose niche innovation and integration into the South African energy system is explored in detail in Chapter 5. Other organisations using blockchain to finance energy projects include Solar DAO (2018), Sun Fund (2018), ImpactPPA (2018) , WePower (2018), and MyBit (2018). These project finance business models generally utilise a crowdfunding-type approach in that the target investors are private individuals as opposed to conventional financing organisations (Cislaghi, 2018; Orlov & Bjørndal, 2017). Crowdfunding is a non-discriminatory open call via the internet for financial resources in exchange for some form of reward in order to support initiatives (Cislaghi, 2018). The use of blockchain for this approach is beneficial because it enables investors from all over the world to take part in the financing of projects without having to go through conventional banks, thereby significantly lowering transaction costs and making microtransactions possible (Orlov & Bjørndal, 2017). This innovative model benefits from blockchain by connecting investors in energy projects with energy consumers via platforms which disintermediate centrally organised financial mechanisms (Orlov & Bjørndal, 2017).

Power purchasing agreements are commonly signed between the organisation facilitation the development, and the consumer of electricity (Orlov & Bjørndal, 2017). Projects normally comprise renewable energy technologies such as solar panels, meaning that consumers benefit from access to low-carbon electricity, often offered at a cheaper rate that what they would otherwise have access to (Montemayor & Boersma, 2017; Energy Web Foundation, 2018).

The shared ownership is sometimes enabled through tokenisation, which is the process of selling digital currencies to investors in exchange for a stake in the project (Conley, 2017). Orlov and Bjørndal (2017) note that the implications of these innovations on existing energy regimes include:

- decentralised ownership of energy assets,
- greater access to small-scale private electricity generation for people and organisations that might not otherwise have been able to afford these investments,
- access to cheaper electricity for consumers,
- individual investment in renewable energy projects without going through conventional project-finance mechanisms, and
- stimulated development in low-carbon energy technologies.

One of the identified drawbacks of these innovations is that they fail to address the challenges associated with shifting load curves to match consumption with energy production which results in overproduction during the day (Orlov & Bjørndal, 2017).

One approach that can assist with alleviating this problem is using dynamic pricing; a mechanism commonly used within peer-to-peer electricity trade markets.

4.3 Peer-to-peer Electricity Trading

Since energy systems increasingly incorporate localised, distributed RETs, it is expected that electricity trade models will emerge which enable local energy producers and consumers to trade electricity (Murkin *et al.*, 2016; Andoni *et al.*, 2018). The integration of blockchains with energy systems has the capacity to enable consumers and producers to buy and sell electricity in decentralised open markets without the need for intermediaries (Murkin *et al.*, 2016; Park & Yong, 2017a; Orlov & Bjørndal, 2017; Tushar *et al.*, 2018) Such a system could enable end-users to select supplier preferences based on price, proximity, or generation type (Murkin *et al.*, 2016).

Murkin *et al.* (2016) present three requirements for peer-to-peer electricity markets, which they note blockchain provides:

- The electricity generated needs to be verified with the amount and time of production, especially in set-ups where electricity prices change based on supply and demand.
- A unit of electricity should only ever be represented by a single token on a network.
- All trades should be traceable and auditable to enable accurate calculation of electricity bills.

Many organisations are experimenting with and using blockchain as a tool to manage and facilitate the trade of electricity in grids with multiple energy producing resources. Chapter 3 demonstrated how blockchain offers the potential to facilitate decentralised peer-to-peer transactions with minimal intermediary interventions. This section explores how these value exchange capabilities can be used for peer-to-peer trading of electricity and carbon assets, such as tradeable renewable energy certificates (TRECs), and certified emission reductions (CERs). Blockchain is useful for the management of this process because it provides the ability to automatically record and store energy flows and transactions in a secure manner (Donnerer & Lacassagne, 2018). Furthermore, it enables continuously updated documentation on the users who have energy, and how much of it they have sold, bought or produced (Donnerer & Lacassagne, 2018).

One relatively well known p2p electricity trade project is the Brooklyn Microgrid which allows households to trade electricity amongst themselves (Mengelkamp, 2017). The Brooklyn microgrid is run by LO3 Energy and the majority of the electricity generating households in the network have embedded generation in the form of Photovoltaic (PV) solar panels on their roofs (Mengelkamp, 2017). The proof-of-concept uses blockchain to manage distributed, intermittent, renewable energy resources in a way that rewards people who generate electricity; allows energy consumers to select their preferred generation sources; and protects the community from grid failure (Basden, J & Cottrell, 2017). The grid is fully functional and is one example that has demonstrated the viability of a blockchain-based p2p electricity sharing network (Mengelkamp, 2017). There are many other examples of successful blockchain-based p2p electricity trading applications in networks with distributed renewable energy technologies (Mihaylov *et al.*, 2014; Zhang *et al.*, 2017b; Dorri *et al.*, 2018; Hoa Nguyen *et al.*, 2018; Singh *et al*, 2018).

The implementation of peer-to-peer trade market networks can result in an increase in the uptake of private generation because the ability to sell unused electricity can help asset owners to pay off systems faster (Mengelkamp, 2017; Andoni *et al.*, 2018; Hoa Nguyen *et al.*, 2018). P2p electricity trading is also useful for assisting with grid balancing because of its ability to manage electricity demand and supply by changing electricity prices based on availability (Zhang *et al.*, 2017b). Other benefits of p2p electricity trading include increased grid resilience, management of intermittent energy generating resources, peak-load shifting, and lowered carbon footprints (Hoa Nguyen *et al.*, 2018). P2p electricity trading is also being experimented with on a large scale. Austria's largest utility conglomerate, Wein Energie, is experimenting with the use of blockchain as a tool to enable large scale trade between other energy utility companies (Basden, & Cottrell, 2017).

Basden and Cottrell (2017) note that a blockchain-based system which enables the p2p trade of electricity would function as follows:

- Each generator would need a smart meter to measure, manage and validate the amount of electricity produced, the time at which the electricity was generated, as well as the identity of the generator.
- This information would then be passed on through an oracle which manages the flow of information from the real world and converts it into digital information to be stored on a blockchain.
- The oracle would tokenise electricity generation and associate it with the address of a user on the blockchain ledger.
- The tokenisation process enables the generation to be represented as a sub-currency enabling it to be traded. For example, 1 token could represent 1 kWh of electricity.
- For the oracle to perform this task, people with generators would first need to register with the oracle to associate their generation with their digital wallet address.
- The trades of electricity could be managed by smart-contracts. Smart contracts are self-executing, reside on blockchains, and enable the automation of multi-step processes (Christidis & Member, 2016).

Research conducted by Zhang *et al.* (2017) on organisations exploring p2p electricity trading using blockchain, reveals some potential transformational effects of these innovations on energy regimes namely:

- changes to the way in which energy is traded, ranging from a small household scale to inter-utility electricity trading,
- changes to the way in which power production is procured by enabling individuals and communities to initiate energy production projects through crowd-sourcing,
- transfer of energy related services such as billing and supplier switching from established retailers to software companies,
- introduction of previously non-existent services such as household energy consumption management systems which can automate and schedule energy use, and

- changes to the role of households in energy systems, transitioning them from passive consumers to active participants which can contribute to the ownership of infrastructure and production of energy.

Of the existing organisations that are using blockchain for applications that facilitate p2p electricity trading, the vast majority have built their applications using the public, open-source blockchain, Ethereum (Montemayor & Boersma, 2017; Andoni *et al.*, 2018). As was demonstrated in Chapter 3, Ethereum uses a proof-of-work (PoW) consensus protocol, making it resource intensive from an energy consumption, and therefore carbon emission, perspective. Furthermore, there are issues regarding transaction volumes and scalability (Andoni *et al.*, 2018). This indicates that blockchain-based p2p applications may require further development before these issues can be addressed for niche innovations to gain momentum and become widely adopted.

Despite Ethereum being the most commonly used blockchain for electricity trade management, others are also being experimented with. The energy utility, Ponton, uses the Tendermint blockchain discussed in Chapter 3. This blockchain is more sustainable than a PoW blockchain because it requires no mining process (Zheng *et al.*, 2017). LO3 uses a private blockchain called Exergy, which is permissioned and uses a consensus mechanism that relies on predetermined validators to verify transactions (Exergy, 2017). While this blockchain is more centralised and exclusive than other blockchains that use PoW consensus protocols, it is efficient and scalable.

The Energy Web Foundation is a non-profit organisation in the process of creating a public and open source blockchain called the Energy Web Chain which is specifically designed for energy-related blockchain applications (Hartnett *et al.*, 2018). In the same way that the Ethereum blockchain functions, developers have open access to the software and have the freedom to create their own applications on the Energy Web Chain blockchain (Hartnett *et al.*, 2018). The organisation seems to acknowledge the issues surrounding energy consumption of PoW consensus mechanisms, and as a result has opted for a model which strives to be open and decentralised while providing an energy-efficient validation mechanism using a proof-of-authority consensus mechanism (Andoni *et al.*, 2018; Hartnett *et al.*, 2018). While the blockchain remains in a test and development phase, nine organisations are already using it for energy-related applications (Energy Web Foundation, 2018). The Energy Web Chain seems to be a niche innovation with promising potential to be integrated into energy regimes because the Energy Web Foundation has made a point of fostering communication and collaboration between organisations involved in blockchain-based energy innovations. This approach is considered effective from the strategic niche management (SNM) perspective (Geels & Schot, 2007; Raven *et al.*, 2010). It seems that the Energy Web Foundation are close to creating a blockchain that solves the energy consumption and scalability issues, while providing a blockchain that remains relatively decentralised albeit not to the extent of a PoW blockchain. The levels of decentralisation offered by a PoW blockchain may be unnecessary for many energy-related applications which still require and benefit from having organisations acting as centralised service providers. For example, a distribution network operator wanting to implement peer-to-peer electricity trading may want to retain control over the network while using the benefits of blockchain for managing billing and transactions between network participants.

Hoa Nguyen *et al.* (2018) argue that alternative distributed ledger technologies to blockchain may be better suited to managing p2p electricity trading because of the drawbacks that blockchain presents which include the high energy demands of some consensus protocols and their accompanying carbon emissions, and issues related to scalability (Hoa Nguyen *et al.*, 2018). Andoni *et al.* (2018) note that a challenge associated with the use of blockchain for p2p electricity trading and grid management, is the need for blockchain designs to provide faster transaction speeds and greater throughput to enable real-time verification. They further note that the incorporation of blockchain would require metering, communication systems, and grid infrastructures to be connected to distributed ledgers which would result in substantial new datasets that would need to be managed and secured from potential cyber-attacks (Andoni *et al.*, 2018).

4.4 Electric Vehicle Charging

As the automotive industry transitions to the use of electric vehicles (EVs), challenges and opportunities arise for managing EV charging and integrating the potential sources of energy storage into electricity grids (Adil & Ko, 2016; Kang *et al.*, 2016). The characteristics of blockchains make them suitable for managing many of the components related to EV charging, especially when it comes to EV identity and transaction management (Montemayor & Boersma, 2017; Orlov & Bjørndal, 2017). Innogy is an example of an energy company in Germany using blockchain to automate the billing process for EV charging stations (Basden, J & Cottrell, 2017). The integration and effective management of EV charging into energy grids can also assist with grid balancing and energy storage, which is becoming increasingly necessary for flattening electricity supply curves as variable renewable energy technologies are adopted (Adil & Ko, 2016; Kang *et al.*, 2016).

4.5 Carbon Asset and Emission Management

The United Nations Framework Convention on Climate Change (UNFCC) recognise blockchain as a tool with potential benefits in combating climate change because it offers the potential for greater trust, transparency, stakeholder involvement, and overall engagement (UNFCCC, 2017). Some of the innovative ways in which blockchain can be used for climate change mitigation include carbon asset trading, low carbon electricity trading, and emission tracking and reporting (UNFCCC, 2017). The documentation capabilities of blockchains offer potential to act as a management tool for energy certification and verification methodologies, especially when used for managing guarantees of origin and carbon emission trading systems (Donnerer & Lacassagne, 2018). The recording of these assets on a public distributed ledger in the form of a blockchain could ensure that assets are valid, that transactions are transparent, and that ownership is automatically transferred and settled (UNFCCC, 2017).

In South Africa, the City of Cape Town along with Johannesburg, Tshwane, and eThekwini have made bold commitments toward climate action in that they are all striving toward absolute carbon neutrality by 2050 (City of Cape Town, 2018a). A component of this vision is to update their GHG inventory by developing management systems to facilitate performance tracking (City of Cape Town, 2018a).

If an appropriate low-carbon blockchain design can be used, it could offer potential to assist these cities in managing and tracking their carbon emissions which would ultimately help them to achieve their emission reduction targets.

4.6 Electricity Grid Management

Blockchain can be used as a tool by grid managers to control and monitor energy use in real time via smart meters in a transparent manner (Donnerer & Lacassagne, 2018). Having researched seventeen blockchain-based energy projects, most of which are being used for distribution system management, Donnerer and Lacassagne (2018) highlight the following opportunities and advantages:

- ability to secure transactions in real time with smart contacts,
- reduced transaction costs due to the ability for smart contracts to self-execute transactions which can also assist with balancing supply and demand,
- automation which makes management cheaper and easier,
- facilitation of peer-to-peer networks without the need for an intermediary such as an energy service company, and
- lowered transaction costs which result in lower overall costs and savings which can be used to reduce energy bills for vulnerable consumers and to assist in the alleviation of energy poverty.

Donnerer and Lacassagne (2018) also highlight challenges and potential issues which local authorities can encounter with blockchain as follows:

- A blockchain can be energy-intensive depending on the architecture used.
- Authorities run the risk of placing too much trust in the technology and people behind the technology such as miners and software developers. While there is beneficial potential in removing intermediaries and service providers, the societal and economic implications are largely unknown. Donnerer and Lacassagne (2018) argue that blockchain could act as gateways for large tech companies to dominate markets as is the case with Google, Apple, Amazon and Facebook.

- The complexity behind blockchain can be more of an annoyance than a benefit to end-users. Many of the researched pilot projects require effort from consumers which can act as a barrier to successful integration.
- The lack of political and legal frameworks can act as barriers to implementation. The majority of experts interviewed by Donnerer and Lacassagne (2018) agreed that setting up legal and political frameworks were necessary for the widespread adoption of blockchain in energy systems.

4.7 Challenges for Blockchain in Energy Systems

4.7.1 Consensus Mechanism and Architecture Use

As was demonstrated in Chapter 3, there are many ways in which blockchains can be designed. The varying architectures and designs have different strengths and weaknesses. In the energy sector blockchains need to demonstrate that they can offer the security, speed, and scalability required to be integrated into energy systems and can manage processes like p2p electricity trading (Andoni *et al.*, 2018).

4.7.2 High Development Costs

While blockchain can lower transaction and management costs by circumventing intermediaries, it can be expensive to develop and may not always be viable compared to other existing solutions such as conventional relational databases (Indigo Advisory, 2018).

4.7.3 Standardisation and Regulation

Before blockchain technology can become widely used and a commonly adopted solution, standardisation and regulation are likely going to be required (Christidis & Member, 2016; Weber *et al.*, 2016). For instance, smart contracts, a function of blockchains, have the potential to streamline interactions and transactions between stakeholders in energy systems, but require supportive regulatory frameworks if they are to be considered legally binding (Gustafsson, 2017).

4.7.4 Technological Complementarities

Some of the energy industry experts interviewed by Gustafsson (2017) noted that the adoption of blockchain into energy systems requires complementary technologies to be implemented first. The adoption of blockchain is therefore hindered to an extent by the development of complementarities. Adner and Kapoor (2016) support this argument that the emergence of a technology within an ecosystem can only successfully occur once the necessary complementarities have been resolved. A further potential challenge is that smart meters might be installed which do not have the computational capabilities to be interfaced with distributed ledger technologies (Andoni *et al.*, 2018). This could mean that integrating blockchain into existing energy grids would be administratively intensive and costly, especially if electricity meters need to be replaced.

4.7.5 Data Management and Storage

The integration of blockchain entails the need for vast amounts of data to be securely managed and stored. This requires consumption of natural resources for hardware infrastructures to be developed and further additional energy expenditure in order to run the hardware (Andoni *et al.*, 2018).

4.7.6 Regulatory Framework Misalignment

In general, conventional energy regulations do not allow small-scale electricity trading and therefore new contract types will need to be designed to accommodate trade relationships between prosumers and consumers (pwc, 2016).

4.7.7 Collaboration with Centralised Monopolistic Utilities

As previously demonstrated most organisations using blockchain in the energy sector are start-ups which have been founded in the past few years. The possible reasons for this can be attributed to the flexible nature of small under-established organisations where communication in the organisation is strong and the model is open to experimentation (Abernathy & Utterback, 1978). A challenge that this presents is that in order for blockchain to be integrated into energy systems on a large scale, the status quo, namely established utilities need to be included in the process (Gustafsson, 2017). The problem this presents is that centralised utilities have little incentive to let go of their monopolistic advantage and open up their networks for shared use (Gustafsson, 2017).

4.7.8 Blockchain and Energy System Structure Misalignment

It is often the case that energy systems are by nature centralised and monopolistic (Orlov & Bjørndal, 2017) whereas blockchains generally follow a decentralised and democratic approach (Zheng *et al.*, 2017). The incompatibility of blockchain with many current sociotechnical energy regimes acts as a barrier to its integration into energy systems (Gustafsson, 2017). Furthermore, current energy system structures seem to result in a natural inertia effect on digital and technological transformations due to the nature of institutionalised decision-making and long investment cycles (Gustafsson, 2017).

4.7.9 Lack of Expertise that Combines Blockchain and Energy

While the potential for blockchain in energy systems seems extensive and useful for solving many problems, especially as systems become more distributed and intermittent, there is a lack of individuals who possess detailed understanding of both blockchain and energy systems (Gustafsson, 2017).

4.8 Conclusion

This chapter introduced how blockchain can be used in energy systems to facilitate crowd-sourcing to finance energy projects, peer-to-peer electricity trading, electric vehicle charging, carbon emission and asset management, and electricity grid management. The challenges associated with the adoption of blockchain were explored, revealing that for successful integration blockchain may require further development: supportive legal frameworks are needed, hardware integration needs to be considered, human capital needs to be developed, and existing stakeholders need to be included. While these challenges pose a threat to successful integration of blockchain-based innovations, it seems that through careful planning they can be overcome. If this can be achieved the applications hold significant promise to create more resilient, lower carbon-emitting, smarter energy systems which benefit more individuals than the existing energy regimes.

The next chapter presents primary participative research on the blockchain-based solar project finance innovation implemented by Sun Exchange in South Africa, exploring its development trajectory and influence in the existing energy regime. Chapter 6 researches the viability of blockchain-based electricity trading in the South African energy system, how it might be incorporated into the current regime, and what its implications might be.

Chapter 5

Case Study: Sun Exchange

Chapter 2 demonstrated that from the multi-level perspective (MLP), the South African energy regime is under pressure, and there are windows of opportunity for niche innovations in the ways of fulfilling the social needs related to electricity provision. Chapters 3 and 4 introduced blockchain technology and its associated innovations in the energy sector demonstrating how they are being applied to transitioning energy systems. Blockchain-based crowd-financing for renewable energy projects was introduced as one such innovation, demonstrating how blockchain has enabled ordinary people to collectively contribute to the financing and ownership of renewable energy projects. This chapter offers participatory case study research on Sun Exchange, a start-up which has developed a blockchain-based niche innovation which it has been integrating into the South African energy regime. Sun Exchange offers an alternative solution to the provision of electricity in South Africa while also providing a new way for solar energy projects to be financed and owned. This innovation was selected because it is the only known commercial blockchain-based innovation that has been incorporated into the South African electricity system.

A background and overview of Sun Exchange is provided with information on how the start-up utilises blockchain technology. Strategic niche management (SNM) best practices are compared to the development approaches used by Sun Exchange to assess whether there is a correlation between their successful sociotechnical regime integration and what the SNM framework proposes. This comparison is also done to find out if Sun Exchange might be able to improve its developmental trajectory and increase its potential for becoming widely adopted in the South African energy regime. The research explores how the innovation is influencing the South African energy regime and whether it has the potential to replace the dominant ways in which electricity provision is fulfilled. The innovation's effects on the energy system are reviewed with regards to energy asset ownership, carbon emissions and energy security.

The chapter concludes by demonstrating that there are many overlaps between SNM best practices and those used Sun Exchange which have likely played a role in enabling Sun Exchange to successfully integrate its innovation into the energy regime. Areas where Sun Exchange could improve its developmental approaches are also identified. This could for example, enable them to adapt their innovation as blockchain technology evolves and develops. The chapter argues that while the Sun Exchange platform has had considerable success in being integrated into the existing energy system, it is unlikely that it will replace dominant energy regime structures. The reason for this is that the scale of the energy projects which Sun Exchange develops are limited to 10 MW because South African legislation stipulates that anything larger than this is required to have a generation licence granted by NERSA (Caboz, 2019).

5.1 Overview of Sun Exchange

A sociotechnical niche is described by Raven *et al.* (2010) as a makeup of practices that deviates from the conventional way in which societal needs are fulfilled. Geels and Schot (2007) define a niche innovation as a technological innovation which is initially an unstable sociotechnical configuration with minimal impact on and penetration into dominant regimes. Sun Exchange seems to fall under both categories. It can be classified as a sociotechnical niche because it deviates from the conventional ways in which consumers access electricity, and in which solar energy projects are financed. It can also be classified as a niche innovation because its penetration into and impact on the dominant South African regime is minimal.

The Sun Exchange platform enables people to collectively finance and co-own solar energy projects. Once financed, the projects are constructed at points of consumption selected by Sun Exchange. Consumers sign twenty-year power purchasing agreements (PPAs) which gives assurance to project investors that the electricity which their solar cells produce will be sold, giving them a guaranteed return on investment. While returns vary depending on project specifications, investors can typically expect to make a 10% internal rate of return (IRR) on the capital they invest into projects over the twenty-year period (Cambridge, 2018). Electricity consumers selected by Sun Exchange, typically schools or environmentally and socially beneficial organisations, benefit by accessing low-carbon electricity that is more affordable than electricity supplied by municipalities and Eskom (Cambridge, 2018). Sun Exchange has limited the size of solar projects to 1 MW to avoid having to register for generation licences which is a NERSA requirement for projects larger than 1 MW (Cambridge, 2018). This limit was however increased to 10MW during the course of 2019 when the Minister of Energy Jeff Radebe gave NERSA approval to do so in an effort to enable large consumers such as malls and factories to install private generation without the barriers of having to apply for generation licences from NERSA (Caboz, 2019).

Sun Exchange uses the Bitcoin and Ethereum blockchains and their accompanying cryptocurrencies to facilitate transactions between itself and solar project investors. The use of these blockchains has enabled Sun Exchange to bypass conventional banks in transactions with project investors. This has significantly reduced costs, enabling micro-transactions to be paid to investors wherever they are in the world with minimal time delays (Cambridge, 2018). It also enables investors to buy into projects from as little as five USD, and to receive monthly payments based on the electricity their cells produce which may only amount to a few cents. Exchanging these values internationally would not be administratively and financially viable using conventional banking systems (Cambridge, 2018).

Projects financed on the Sun Exchange platform can have as many owners as there are solar cells in each project because the investment buy-in is broken down to the level of a single solar cell within a solar panel. This novel approach to solar project finance is resulting in the decentralisation of project ownership and therefore the distribution of profits generated by the projects.

In addition to solar cell owners being paid in Bitcoin, Sun Exchange has partnered with Solar Coin which is a global rewards programme for solar electricity generation (SolarCoin, 2018). SolarCoin is the organisation’s digital currency; each coin represents 1 Megawatt hour (MWh) of solar electricity generation (SolarCoin, 2018).

The purpose of SolarCoin is to incentivise the global uptake of solar energy, and verified users of the SolarCoin platform receive 1 SolarCoin for every MWh of electricity they produce (SolarCoin, 2018). Sun Exchange platform users are automatically verified as SolarCoin users and therefore start earning SolarCoin when their cells start producing electricity (Cambridge, A. 2018).

Sun Exchange also has its own digital currency called SUNEX. The tokens are built on the Ethereum blockchain and have multiple uses:

- Holders of the tokens receive discounts and bonuses on the Sun Exchange platform.
- The tokens unlock priority access to new solar projects.
- They can be earned by buying solar cells, generating electricity, and diversifying a solar cell portfolio.
- They can be sold on public digital currency exchanges.

The creation and pre-sale of SUNEX tokens has been used as a method to raise capital to further develop the Sun Exchange platform. This process of preselling a digital currency before it becomes used in an application is called an *initial coin offering* (ICO) or *token sale*. These are vehicles that some companies use to raise the capital required to implement and develop their blockchain-based business models (Conley, 2017).

Other blockchain-based energy start-ups that have used ICOs and token sales are: Grid+, ImpactPPA, MyBit, Power Ledger, and WePower (Deign, 2017). ICOs and token sales can be a very successful means of attracting finance and remove the need to make an initial public offering (IPO) of stock and convince venture capitalists to invest in a business or approach a bank for a loan (Conley, 2017).

5.2 Sun Exchange from the Strategic Niche Management Perspective

This section reviews the Sun Exchange organisation and its niche innovation from the perspective of the strategic niche management (SNM) framework. It is done to review the processes that Sun Exchange uses in developing its innovation and integrating it into the South African energy regime and to identify which strategies are effective and which could be improved upon.

This SNM approach suggests that the *voicing and shaping of visions and expectations* is a useful strategy because of its ability to attract resources, attention, and new actors (Raven *et al.*, 2010); a strategy that Sun Exchange seems to use effectively. This was evident during the participative case study research because of the efforts the company has made to send the CEO to attend many international events to present the business concept, to increase public awareness, and to network with potential collaborators. Sun Exchange has also made considerable effort to engage and collaborate with other organisations. They have partnered with PowerHive, Solar Coin, and the United Nations Development Programme (Cambridge, 2018). This collaboration increases the number of people and organisations that share the same vision and expectations which increases the impact that a niche innovation can have (Raven *et al.*, 2010).

This inter-organisational collaboration also forms part of another SNM approach which is the *building of social networks* (Raven *et al.*, 2010); an approach which seems to be used and encouraged by Sun Exchange. For example Sun Exchange employed someone whose job is to identify organisations they could collaborate with and to develop strategies for collaboration. Raven *et al.* (2010) note that the building of social networks is especially effective when it involves policy makers, researchers and scientists. Sun Exchange seems to encourage this too which was supported by the fact that they were keen to have me conduct a case study on the organisation. Furthermore, during the participative research, a meeting was organised with GreenCape, an organisation aimed at developing a green economy in South Africa by facilitating relationships between the government and the private sector (GreenCape, 2019). This was done to assess what collaboration and support GreenCape could provide.

Building social networks is encouraged in organisations because it increases communication and enables internal alignment (Raven *et al.*, 2010). This approach seemed to be effectively applied at Sun Exchange in that team meetings as well as social company events are frequently held. For example, at the time of the study management meetings were held at 4:00pm from Monday to Friday to communicate what had been done and to strategise about what needs to be done. The organisation also encourages team building and social events; for example, employees go hiking together on weekends. Annual gatherings are organised where all employees are flown to Cape Town for a week. The week would entail daily meetings to collaborate and strategise followed by dinners where employees would socialise. It seemed that because of these events, the employees have close relationships and conversations which were casual and honest. People are not intimidated by one another and feel comfortable voicing their opinions and ideas. This strong internal network seemed to be highly effective in terms of ensuring that all employees are on the same page and collaborating effectively.

A *constructive learning process* is a SNM approach which involves using a process that enables adjustments to be made during the development of an innovation either to the technology or to the way in which it is gets integrated into a regime (Raven *et al.*, 2010). The approach is effective when assumptions are questioned and new avenues for integration into regimes are explored (Raven *et al.*, 2010). Because Sun Exchange has an employee dedicated to new strategies and partnership opportunities, it can be said that they value the importance of questioning their existing approaches to implementing their innovation. When it came to the development of the innovation however, questioning assumptions seemed to be lacking. Chapter 3 demonstrated that blockchain technology remains in its early stages of development. It also showed that there are challenges in the Bitcoin and Ethereum blockchains associated with scalability, energy requirements, and carbon emissions. The conclusion was made that blockchain technology needs further development and organisations using it should remain adaptive in terms of which blockchain they use. Through observation it seemed that the questioning of the blockchains used by Sun Exchange was not a focus. Bitcoin and Ethereum are the primary blockchains used by Sun Exchange, and there seemed to be general acceptance that these were the blockchains that the platform should use. This may have been because the development of the platform had been based on these blockchains, or because they are widely used and therefore well understood by the users of digital currencies. Considering that blockchain, as an umbrella technology, has been identified as a developing niche innovation, it can be argued that Sun

Exchange should assign greater importance to questioning which blockchains their solution should use. This is especially relevant considering the organisation's intentions of decarbonising energy systems and the high carbon footprints of Bitcoin and Ethereum blockchains. As blockchains and their related architectures and consensus mechanism evolve, there is potential for the conventional Bitcoin and Ethereum blockchains to become outdated which would have a negative impact on Sun Exchange.

The SNM framework promotes the implementation of multiple experiments during the development of a niche innovation (Geels & Raven, 2006). This enables different strategies to be trialled and the learning outcomes from various experiments to be aggregated (Geels & Raven, 2006). The different solar projects that Sun Exchange has implemented can arguably be thought of as separate experiments in that each project has a different type of electricity consumer, different investors, and a different marketing strategy.

Sun Exchange intentionally reviewed and compared the different solar projects to identify which elements in the different projects were successful, and which were not working. This revealed that in each new project, most of the project investors were first-time Sun Exchange platform users and led to the insight that attention needs to be paid to identifying why existing users are not reinvesting in new projects; a valuable piece of information that could alter the developmental direction of the organisation. While the reason for this was not identified during the participative research period, it made the Sun Exchange team aware that there was an issue with what they were doing and that it needed to be addressed.

Another insight that was revealed through reviewing and comparing the different projects, related to the type of electricity consumer which people wanted to invest in. A plastics factory was published onto the platform giving users an opportunity to invest, and the project was poorly received in that it took significantly longer for the cells to sell compared to the other projects. Sun Exchange had historically focused on serving schools or rehabilitation centres with either a positive social or environmental cause. The slow-to-sell project revealed that Sun Exchange platform users wanted to invest in projects which were either socially or environmentally beneficial, and the net effect of this insight was that Sun Exchange returned to focusing on these types of projects.

5.3 Sun Exchange's Impact on the South African Energy System

This section explores how the Sun Exchange innovation is influencing the South African energy system from the perspectives of energy asset ownership, carbon emissions, and energy access and security. During the research it become apparent that these were the primary ways in which Sun Exchange is affecting South Africa's energy system.

5.3.1 Energy Asset Ownership

One of the primary ways in which the Sun Exchange innovation deviates from conventional energy regime structures is the way in which energy projects are financed and owned. Halsey *et al.* (2017) argue that transitions to equitable energy systems require the avoidance of megaprojects with few beneficiaries. They further note that in the South African context, the REIPPPP has fallen short of facilitating social ownership of energy projects (Halsey *et al.*, 2017).

Considering this argument, it can be said that the Sun Exchange innovation contributes positively to the South African energy transition because the financing mechanism results in energy projects being cooperatively owned by many people; the investment buy-in is broken down to a single solar cell level. For example, one of solar projects installed at a plastics factory has 204 owners (Sun Exchange, 2018).The platform also avoids the development of mega-projects because the projects never exceed 10MW to skirt the need to apply for a generation licence from NERSA. From an energy asset ownership point of view, the Sun Exchange model contributes positively towards the decentralisation of the South African energy system and to making the energy system and market more inclusive. The ownership of the projects is however distributed throughout the world which means that some of the profits generated by the projects are channelled out of South Africa. For example the Sun Exchange platform user-base is distributed over 137 countries (Sun Exchange, 2019). Internal company documentation reveals that approximately half of the project owners are South African (Sun Exchange, 2018). The Sun Exchange nevertheless contributes to social ownership of energy resources in South Africa since large portions of the projects are South African owned. Furthermore, the costs of investing in the projects, as demonstrated, are very low, making the projects accessible investments to most income groups.

5.3.2 Carbon Emissions

Because all the existing electricity consumers being served by Sun Exchange would otherwise be connected to the South African electricity grid, which as demonstrated in Chapter 2 is a high carbon emitter, it can be said that Sun Exchange is contributing positively to emission reductions of the electricity system. Consumers are being switched from using a grid that is powered by primarily coal-based high carbon-emitting electricity generation technologies to low-carbon solar energy. Sun Exchange is however still a sociotechnical niche and its influence within the greater energy regime is minimal. For instance, the company has a total installed capacity of 745.5 kW. The total installed capacity in South Africa is 51,309 MW (Republic of South Africa, 2018) which means that Sun Exchange contributes 0.000015% to the total generation capacity of the country. While the solar projects are enabling consumers to utilise low-carbon electricity, the small-scale nature of the projects is unlikely to have any significant impact on the total carbon emissions of the South African electricity system. Sun Exchange's emission reduction effects are nevertheless not negligible. Sustainable Energy Africa (SAE) (2017) estimate that for every kWh of electricity consumed in South Africa, 1.03 kg of CO2 is emitted into the atmosphere. Sun Exchange has generated 693,665 kWh of solar power for its customers since its inception (Sun Exchange, 2019), and because this electricity would otherwise have been supplied by the national energy grid, 714,474.95 kg of CO2 has been prevented from being emitted into the atmosphere via the standard energy system. Solar panels however do have their own carbon footprints. While PV CO2 emission estimates vary between 12.28 and 58.81 grams of CO2 per kWh (Stylos & Koroneos, 2014), using the estimate calculated by Hondo (2005) of 53.4 grams of CO2 per kWh, the carbon footprint of the electricity produced by the Sun Exchange projects would be 37,041.71 kg of CO2. It can therefore be calculated that Sun Exchange has contributed to preventing 677,433.24 kg of CO2 (714,474.95 -

37,041.71) from being emitted into the atmosphere by switching South African electricity consumers form standard to solar based electricity.

5.3.3 Energy Access and Security

The provision of embedded generation to electricity consumers in South Africa who would otherwise have relied on Eskom, arguably increases their energy security because they are not subject to Eskom-initiated load-shedding. Load-shedding is planned power outages implemented by Eskom as a result of the constrained energy system (Eskom, 2019). The Sun Exchange projects however do not currently have any form of energy storage which means that consumers are still subject to power outages when the sun is not shining, and the panels are not generating electricity. Sun Exchange focuses on servicing customers whose energy demand profiles match the production profiles of solar panels. Examples of these are schools, offices, and factories which operate during the day and use minimal electricity at night. As a result, it can be said that for consumers who are serviced by Sun Exchange, energy security is significantly increased. In terms of contributing to electricity security in the greater South African energy system, its influence remains minimal because of the small customer base which it currently has. This could however change if the Sun Exchange continues to develop and grow.

From an energy access perspective, it can be said that Sun Exchange is currently not having any notable impact; the customers they service already had access to electricity. They have however partnered with an organisation called PowerHive which develops micro-grids in unelectrified rural areas in sub-Saharan Africa. The inclusion of these types of projects will result in Sun Exchanged contributing positively to energy access.

5.4 Prospects for Sun Exchange

This section explores what the future may hold for the Sun Exchange innovation, touching on important elements that may affect its further development and integration into the South African energy system.

5.4.1 Investor Retention

The development of Sun Exchange and its solar projects are dependent on a reliable investor user base. Research reveals that new solar projects primarily comprise of new investors which means that existing users are not reinvesting in new projects. Sun Exchange should focus on identifying the reason for this since it may affect the long-term sustainability of the organisation and platform.

5.4.2 Sun Exchange's use of Bitcoin and Ethereum

Another element which has an influence on the prospects of Sun Exchange is the development and adoption of Bitcoin and Ethereum because Sun Exchange is built on and relies on these blockchains for the platform to function. The development and adoption of the blockchains will therefore play a significant role in determining the success of Sun Exchange in the future. Through analysing Sun Exchange from the SNM perspective it was identified that a strategy which the organisation could adopt to improve its development and long-term sustainability would be to question the assumptions made in terms of the blockchains they use, and to remain adaptive should they need to change the underlying technology. This is especially relevant as these blockchains are known for having issues related to scalability and high energy demand, and as a result innovations and developments are under way to address these issues.

5.4.3 Generation Capacity

Sun Exchange focuses on developing projects below 10 MW in size to avoid legal barriers related to legislation in South Africa which requires projects larger than 10 MW to have a generation licence (Cambridge, 2018). CEO, Abraham Cambridge (2018), explained that this presents a barrier for the company because it prevents them from financing larger solar projects which would increase the organisation's impact in the South African energy system. Sun Exchange is however primarily the finance vehicle for energy projects and thus it is in theory possible for developers with generation licences to use the Sun Exchange platform to finance large-scale projects. This does not seem to be an avenue that Sun Exchange has explored however, if initiated, could increase the impact that Sun Exchange has on the energy system in South Africa. It seems that if Sun Exchange continues with the current business model, whereby they find electricity consumers to switch to solar (Cambridge, 2018), then these project size limitations will restrict the organisation's potential impact on the dominant energy regime in South Africa.

The figure below shows the size of their projects in kilowatts (kW) and the dates on which the projects completed their crowd sales and moved into construction.

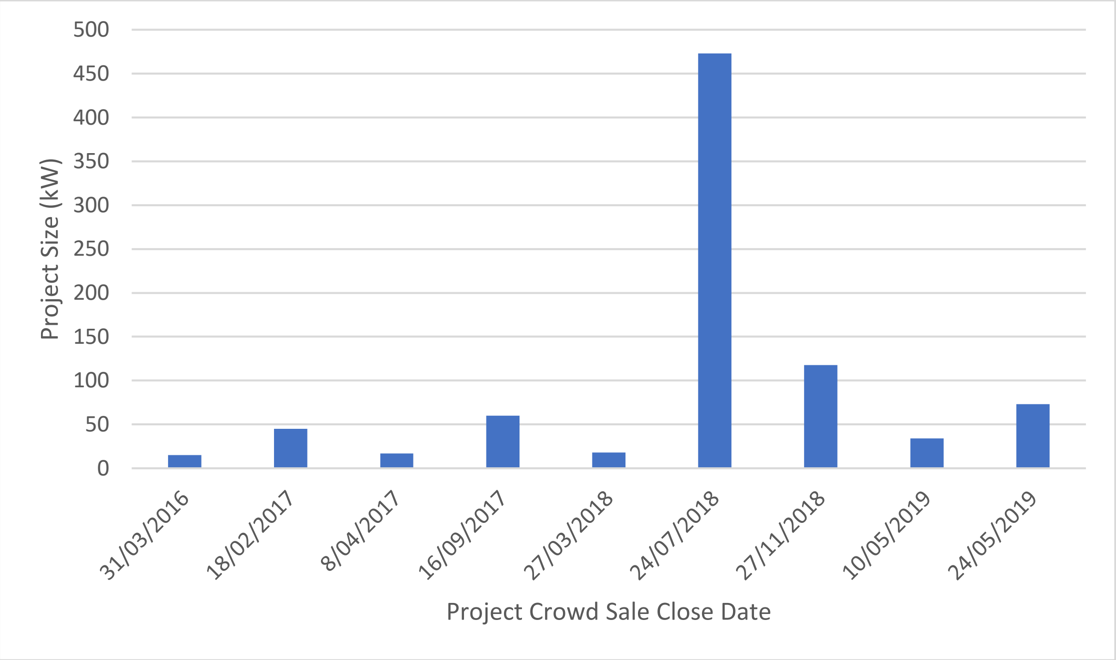

Figure 7: Sun Exchange Project Sizes

The number of projects average approximately three per year, but the size of the projects being financed and contracted is increasing as can be seen in the graph below.

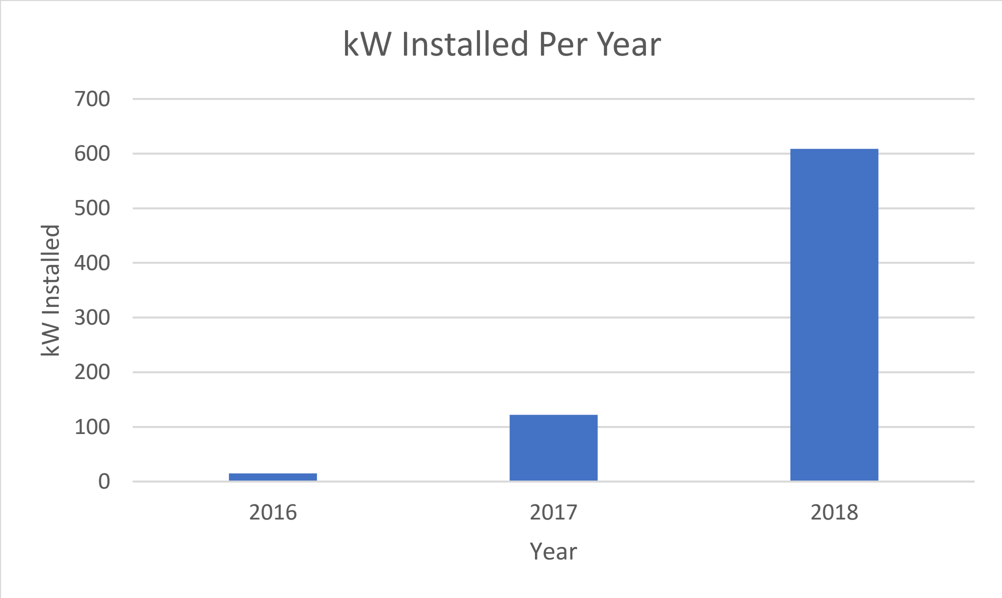

Figure 8: Installed Annual Capacity

The amount of solar generation installed in 2016 was 15kW and 122kW in 2017 meaning that there was an 813% increase in installed capacity. The installed capacity grew further from 112kW in 2017, to 608.5kW in 2018 which was a 543% growth in the amount of solar capacity installed. This demonstrates that the influence which Sun Exchange is having on the energy system is growing substantially, and there is significant potential for the number of projects financed by Sun Exchange per year, to also increase. As the platform develops it becomes increasingly automated which means that Sun Exchange will eventually be able to finance many solar projects simultaneously (Cambridge, 2018), and there is potential for the platform to become widely used by South African consumers.

Factors that limit the organisation’s growth are the number of people willing to invest in solar projects as well as the number of consumers who will sign twenty-year power purchasing contracts with Sun Exchange (Cambridge, 2018). One of the challenges with procuring power purchasing agreements, is the fact that electricity consumers need to be the owners of the buildings and certain that they will occupy the buildings for the next twenty years (Cambridge, 2018).

5.5 Conclusion

This chapter provided an overview of the Sun Exchange organisation and its niche innovation. The strategic niche management (SNM) framework was used to review the developmental approaches used by the organisation. It was identified that Sun Exchange employs many of the best practices advised by the SNM framework; primarily relating to communicating the vision of the organisation, building strong social networks, and using a constructive learning process. It was identified that there is opportunity for Sun Exchange to foster a more constructive learning process through questioning its underlying use of the Bitcoin and Ethereum blockchains. Blockchain technology is arguably still a niche innovation and is therefore likely to experience further development. It may therefore be beneficial for Sun Exchange to consistently question the underlying blockchain technology which the platform relies on to ensure that the platform adapts as blockchain technology develops.

The impacts that Sun Exchange is having on the South African energy system was explored revealing that the organisation is contributing positively in terms lowering carbon emissions, distributing ownership of energy projects, lowing electricity tariffs, contributing to the development of renewable energy technologies, and improving energy security. The impact of the organisation is however minimal and limited by the scale of its projects so long as they continue with their current business model which focusses on projects that do not require generation licences. The conclusion is therefore that from the multi-level perspective, the likelihood of Sun Exchange progressing past being a sociotechnical niche and developing to a point where it integrates into the sociotechnical regime and replaces the dominant ways in which energy projects are financed and electricity is consumed, is improbable. There is however still potential for the organisation to develop and become widely used in South Africa.

Chapter 6

Blockchain-based Electricity Trading in South Africa

Chapter 2 discussed the changing South African energy system. Chapters 3 and 4 introduced blockchain and its associated niche innovations in the energy sector. Chapter 5 researched an existing blockchain-based solar project finance innovation in South Africa. This chapter explores the viability and potential implications of a blockchain-based electricity trade innovation in South Africa.

The increase in small-scale-embedded-generation (SSEG) in the form of distributed renewable energy technologies such as private roof-mounted PV solar panels was explored in Chapter 2 along with its associated implications for South African municipalities. It was demonstrated that there is a need for municipalities to adapt their policies and business models to accommodate the uptake of distributed private generation. One of the proposed ways is to enable and cater for electricity trading between producers and consumers in their distribution networks. This can be achieved through municipally managed buying and reselling, wheeling between producers and consumers, and third-party facilitated trading.

Challenges for municipalities resulting from the uptake of SSEG include financial losses resulting from decreased demand for electricity and challenges related to managing distributed and variable electricity generating resources. While electricity trading presents an opportunity for municipalities, there are barriers and challenges associated with adopting these models because they are new functions and municipalities often lack the resources and capital for effective implementation (Montmasson-Clair *et al.*, 2017; River *et al.*, 2018; SALGA, 2018a). Blockchain technology has the capacity to overcome many of these challenges and therefore may have a role to play in South Africa's transition to a low-carbon electricity system.

Using the data generated from interviews with energy experts and relevant stakeholders in the South African energy market, this chapter explores the potential for a blockchain-based electricity trade application innovation in South Africa. It aims to identify which form of trading would be (i) most suitable for blockchain to be applied to and (ii) would have the most potential to enable a blockchain-based electricity trading platform to progress past being a niche innovation to become widely used in South Africa. The electricity trading types explored include: wheeling electricity between producers and consumers using distribution network infrastructures, third-party electricity trading, municipal distribution system operator (DSO) managed electricity trading, and trading between consumers and producers within microgrids.

The research findings presented in this chapter demonstrate that there is significant potential for a blockchain-based electricity trading application in South Africa and that the application type with the most potential for becoming widely used would be one implemented by municipal DSOs. The chapter suggests what such an application might look like by providing a proposed application breakdown which includes information on the blockchain architecture it could follow and the features it could include. These recommendations are based on insights from the literature review and from the research interviews. Strategic niche management (SNM) and multi-level perspective (MLP) frameworks are used to make recommendations on how the proposed application could be developed and integrated into the South African energy regime.

The potential implications of the proposed application are explored. These are: increased municipal profitability, a catalysed transition to renewable energy technologies, lowered carbon emissions, increased energy security, decentralisation of the energy sector, supply and demand matching, grid balancing, and peak load shifting.

The chapter provides considerations and suggestions regarding where there might be a need for further research. It is argued that successful development and integration of the proposed application is dependent on multi-disciplinary collaborative efforts between municipalities, software companies, research organisations and policy makers, and that further research is needed to determine how such collaboration could be established.

6.1 The Viability of Blockchain-based Electricity Trading in South Africa

Chapter 4 demonstrated the potential for blockchain to remove intermediaries and to facilitate decentralised peer-to-peer electricity trading. Although the technology can theoretically disintermediate third-parties and enable decentralised networks where producers and consumers connect to trade electricity, several of the research participants were of the view that this level of decentralisation is not viable for the grid-tied context in South Africa because of centralised network infrastructure ownership and because the energy systems are heavily regulated (Carter-Brown, 2019; De Lange, 2019; Radmore, 2018). There are however varying levels of centralisation between different blockchain architectures, as was demonstrated in Chapter 3. Carter-Brown (2019) suggests that there is still potential for a blockchain-based application to be incorporated into the South African electricity system in a way that enables the benefits of blockchain-based trading to be realised while adhering to existing legislation and regulations, and taking into consideration and catering to the needs of existing stakeholders. In the interview with De Lange (2019), he noted that building an electricity trading application on a highly decentralised proof-of-work blockchain like Ethereum adds unnecessary complications, would be limited in terms of scalability and throughput, would be expensive to build, and would consume large amounts of energy because of the energy-intensive nature of these blockchains. De Lange (2019) suggested that a more suitable option would be to opt for a private permissioned blockchain which, although more centralised, would provide the benefits of blockchain in terms of transparency, trust, and automation, but would be scalable and energy-efficient (De Lange, 2019). This suggestion is supported by IRENA (2019) who argue that private permissioned blockchains are more suitable for energy utilities looking to implement electricity trading within regulated markets.

While at the time of writing this thesis there were no known blockchain-based electricity trading applications in South Africa, Carter-Brown (2019) noted that the CSIR, the organisation he works for, advocates its use for electricity trading and grid management. He also noted that the CSIR are developing a blockchain application which can be used for managing inter-distribution system electricity trading as well as inter-blockchain application communication (Carter-Brown, 2019). He said that they were working on this because they expect numerous blockchain-based energy system management applications to enter the South African market and foresee the need for a centralised blockchain platform to manage communication between the applications. Their application was however in its very early phases of development. The remainder of this section presents the findings from the research interviews relating to what form of electricity trading is more suitable for a blockchain application.

6.2 Potential Electricity Trading Applications for Blockchain

The literature review identified municipal DSO managed electricity trading and wheeling as two forms of electricity trading that municipalities are encouraged to consider as new business models to adapt to the changing South African energy system. The interview research identified a further two electricity trade models that blockchain could potentially be applied to, namely third-party trading and trading within microgrids. The research focused on exploring which of these forms of electricity trading would be most suitable for a blockchain-based application seeking to become widely used and to form part of a new energy regime in South Africa.

6.2.1 Municipal / Eskom DSO Managed Electricity Trading

In this electricity trading scenario the distribution system operator (DSO) buys locally produced electricity from within their distribution networks, either using a PPA or with a feed-in-tariff, and resells it for a profit to consumers (River *et al.*, 2018). In instances where municipalities purchase electricity from owners of small-scale-embedded-generation (SSEG) such as roof-mounted solar panels on houses, feed-in-tariffs are paid to producers for exporting their excess electricity into the distribution network (Bronkhorst *et al.*, 2019). If municipalities purchase electricity from registered IPPs, PPAs are required (SALGA, 2018b). The City of Cape Town municipality for example pays people with SSEG a feed-in-tariff of 84.95 cents (ZAR) per kWh of electricity that is fed into the grid which they then resell for 185.32 cents (ZAR) per kWh to consumers (City of Cape Town, 2018b). As was demonstrated in Chapter 2, many municipalities lack the capacity and capital to implement and manage this form of electricity trading (SALGA, 2018b). Furthermore, where it is implemented a basic model seems to be used whereby local production and consumption are not coordinated through time-of-use tariffs based on local supply and demand. In the interview with De Lange (2019), he noted that the implementation of a blockchain-based electricity trading application could assist with local supply and demand matching if a variable pricing structure was introduced which would automatically adjust tariffs based on local supply and demand. SALGA (2018b) notes that for this energy trade model to be effectively implemented, DSOs need to revise metering and billing systems to enable management of bi-directional electricity flows between many variable renewable energy technologies. The installation of smart meters enables the remote tracking of bi-directional energy flows, and their integration with a blockchain-based application would enable the billing systems to be revised in a way that enables automated billing for many producers and consumers (De Lange, 2019).

In the interview with Haw (2018), she noted that an issue which the City of Cape Town municipality faces is that many buildings with SSEG are not registering their installations. She noted that this was not only dangerous because network maintainers would not be aware of electricity being fed into the network and could be electrocuted, but also prevents the municipality from being able to pay producers appropriate feed-in-tariffs. Instead, unregistered producers are essentially rewinding their electricity meters when feeding into the grid meaning that they are receiving consumption tariff rates for their electricity rather than feed-in-tariffs (Haw, 2018). For example, an unregistered SSEG owner would receive 185.32 cents (ZAR) per kWh rather than of 84.95 cents (ZAR) per kWh. This situation prevents the municipality from profiting from prosumers feeding into the grid. It is therefore essential that small-scale producers are effectively registered and managed if municipal DSO's want to maintain sustainable energy trade business models using the feed-in-tariff approach.

The use of the electricity trading model enabled by feed-in-tariffs has substantially been increased in municipal distribution networks over the past few years. As can be seen in Figure 9 below, out of the 165 municipal DSOs, the number that offer feed-in tariffs for owners of SSEG has gone from five in 2016, to twenty-five in 2018 (SALGA, 2018b). While this is still comparatively low, the number is expected to increase significantly, making SSEG feed-in tariffs commonplace in South Africa in the near future (Bronkhorst *et al.*, 2019).

Figure 9: Uptake of SSEG Processes in Municipalities

Source: (Bronkhorst *et al.*, 2019)

A result to the implementation of feed-in-tariffs is that they stimulate the uptake of SSEG because the pay-back periods for systems decrease and the business case for investing SSEG is improved (SALGA, 2018b). An issue which prevents this from occurring however is that producers do not have security or certainty regarding future feed-in-tariffs because the tariff structures have been changing from year to year (Bronkhorst *et al.*, 2019). It can be said that the implementation of a tariff structure which provides certainty to potential investors in SSEG would be beneficial from the perspective of increasing the amount of renewable energy in a system since it would enable them to make calculated decisions regarding their investments into SSEG.

Although this form of electricity trading is already taking place within twenty-five municipal distribution networks, it seems that there is still potential for a blockchain-based application to be created for municipal DSOs, many of which are underresourced (Radmore, 2018), to assist them with implementation and management. For more advanced municipalities like the City of Cape Town who have implemented this form of trading there still seems to be an opportunity to use a blockchain application which incorporates dynamic tariffs based on local supply and demand to assist with grid-balancing, local supply and demand matching, and peak-load shifting. Bronkhorst *et al.* (2019) note that there is a disparity between local production from renewable energy technologies and local demand because peak production occurs during the middle of the day when demand is low. They also note that with the current feed-in-tariff structure, producers are not incentivised to feed electricity into the network when the demand is high (Bronkhorst *et al.*, 2019). De Lange (2019) suggests that a blockchain application which incorporates automated dynamic pricing could overcome this issue by incentivising consumption during times of high production, and by incentivising feeding into the grid during times of high demand. He noted that smart-contracts could adjust feed-in-tariffs and consumption tariffs based on local supply and demand (De Lange, 2019). The effective management of such a system seems to have the capacity to improve the energy independence of municipal DSOs and reduce the negative repercussions resulting from Eskom implemented load-shedding.

6.2.2 Wheeling

Wheeling entails the trade of electricity between producers and consumers using municipal or Eskom owned distribution networks (Bronkhorst *et al.*, 2019). A power purchasing agreement (PPA) between the producer and consumer is required as well as a use-of-distribution network agreement which is accompanied by a use-of-grid fee which is payable to the network owner (Greubel, 2018; Nel, 2018; Radmore, 2018). While wheeling has not historically been allowed in South Africa, legislation is changing in favour of wheeling and it is expected that by 2022 there will be widespread municipal adoption (Bronkhorst *et al.*, 2019).

Two of the primary challenges associated with wheeling identified in the interviews and literature review are use-of-grid charges and administration involved in working with municipalities and acquiring use-of-grid agreements.

Both PowerX and Energy Exchange of Southern Africa experience municipal resistance to facilitating third-party trading in South Africa. Greubel (2019) suggests that this municipal resistance results from the economics of third-party trading which are often not attractive to municipalities because the electricity is sold for the same price that the municipality would sell it for. He explains that in order for a third-party to make a profit from trading electricity, they would either have to sell it for a price higher than the municipality charge or pay the municipality a use-of-grid fee which is less than what they would make if they were to buy and sell the electricity themselves. This view is also held by Haw (2018) who notes that a challenge with allowing wheeling in the City of Cape Town distribution network is agreement on use-of-grid fees that is attractive to all the parties involved. Adding to this, Nel (2018) explained that PowerX encounters significant municipal resistance to their acting as a third-party electricity trader, noting that they often struggle to acquire use-of-grid agreements with municipalities. She also adds that because of high use-of-grid fees, they struggle to make a financially attractive offering in terms of buying and reselling electricity while paying municipal use-of-grid fees. The South African Local Government Association (2018a) has noted that the challenges associated with use-of-grid fees are well-recognised, and act as a barrier to the adoption of wheeling in South Africa

Both PowerX and Energy Exchange of Southern Africa have experienced considerable challenges associated with municipal administration involved with facilitating third-party trading in the country. Greubel (2018) states that it could take months or even years to make progress with municipalities and get use-of-grid agreements signed. Nel (2018) notes that PowerX experiences the same issues stating that administrative processes in municipalities are “challenging and lengthy.” The South African Local Government Association have also identified this problem stating that,

> [a] final challenge with wheeling is the increased administration burden associated with new types of customers. For example, the billing system would need to be revised to accommodate wheeling charges and to differentiate between electricity provided as municipal electricity and electricity provided by a third party (SALGA, 2018 : 14).

A blockchain-based application seems to have the potential to manage the wheeling process because it could assist with trade, agreements, and fees payable to the DSO (De Lange, 2019). This view is supported by IRENA (2019), who argue that there is significant potential for network operators to implement blockchain solutions for managing electricity trading within their networks because it provides transparency to the DSO and to parties wanting to trade, and can assist with automating transactions. While the traders could use a blockchain-based application, it would require acceptance from the municipal DSO which would likely prove difficult in South Africa considering the identified challenges which PowerX and Energy Exchange of Southern Africa have encountered in trying to work with municipalities. There may however be potential for the DSO (municipality or Eskom) to implement a blockchain-based energy trade application which would enable consumers and producers to connect and trade in a way that is supported and controlled by the DSO. In the interview with Radmore (2018), he suggested that a viable solution would be for a software organisation to provide municipal DSOs with the software to facilitate trading and to manage distributed renewable energy technologies. He noted that this would be beneficial considering the manual processes many South African municipalities use to manage billing and the fact that many do not have the resources to manage the uptake of SSEG in their networks.

In the interview with Haw (2018), she noted that one of the challenges that the City of Cape Town municipality faces when allowing wheeling in its distribution network is ensuring that traders pay the use-of-grid fees due to the municipality. She noted that this was a challenge because municipal commission is based on kWhs of electricity traded, and there is currently no way the municipality can be certain of the quantities being traded. This challenge presents an opportunity for a blockchain-application because if the traded transactions were managed by a municipally implemented blockchain application, it would be possible to see exactly how much electricity is being traded and the commission payable could be automated using smart-contracts. The International Renewable Energy Agency (2019) suggests that there is an opportunity for DSOs like municipalities to implement private permissioned blockchains to track transactions in their networks. While this type of application would be relatively centralised in the sense that it would be managed and controlled by the municipality, it could offer transparency and trust to stakeholders using distribution networks to trade electricity. In the interview with De Lange (2019) he supported this view, noting that decentralised blockchains are unnecessary for electricity trading in centralised grid-tied networks, and that they can have issues related to scalability and transaction throughput. He added that it would be possible to use smart-contracts built into the blockchain application to facilitate power purchasing agreements (PPAs), use-of-grid agreements, and to automate commissions payable to network owners. It can be said that if DSOs provided a platform to parties wanting to wheel electricity through municipal distribution networks, it could remove many of the administrative and legal challenges currently experienced by organisations like PowerX and Energy Exchange of Southern Africa.

While wheeling is expected to become more common amongst municipal electricity utilities, there are still facilitation and administration challenges (Bronkhorst *et al.*, 2019). Considering these realities and the fact that municipalities would benefit from a transparent platform that enables them to ensure they are paid what they are due when producers and consumers trade electricity, it seems that there is significant potential for a blockchain application to be implemented. There is also no evidence to suggest that there are barriers which would prevent a municipal DSO from implementing such an application. The implementation of a system which promotes wheeling in a standardised and structured way has the potential to stimulate local economic development in regions where wheeling is taking place, to provide DSOs with profitable revenue streams, and to stimulate the development of local renewable energy technologies (Bronkhorst *et al.*, 2019).

6.2.3 Third-Party Trading

In this scenario, a blockchain-based application could be designed and implemented by an organisation like PowerX which buys and resells electricity for a profit, transporting it through distribution networks. Initially, this seemed to be the most viable way for such an application to be implemented because it would in theory simply require an organisation to acquire an energy trade licence from NERSA, a use-of-network agreement with a DSO such as a municipality, and power purchasing agreements with producers and consumers (Nel, 2018).The research interviews however soon revealed significant barriers and challenges associated with this model which lead to the conclusion that while a blockchain-based application could be used for this type of trading, it would be unlikely that it could progress past being a niche innovation and become widely used in South Africa if the current regime remains as it is (Greubel, 2018; Radmore, 2018). On top of the challenges associated with wheeling which third-parties face, a further barrier relates to the acquisition of energy trade licences from the national energy regulator which are necessary if an organisation wishes to act as a third-party electricity trader (Greubel, 2018; Radmore, 2018).

A major challenge associated with third-party trading revealed through the research interviews is the fact that NERSA is not providing energy trade licences to the many organisations that are applying for them. In the interview with Radmore (2018), when asked about the viability of a blockchain application being implemented by a third-party energy trader, he noted that a considerable challenge and barrier to achieving this related to the improbability of an organisation being able to acquire an energy trade licence from NERSA. He noted that for no obvious or known reason, many applications which meet the necessary requirements, including one submitted by GreenCape, had been rejected by NERSA (Radmore, 2018). He suggested that a more viable approach to implementing a blockchain-based energy trade application would be for the organisation implementing the application to act as an energy broker rather than an energy trader, which would entail facilitating direct transactions between producers and consumers rather than purchasing electricity for resale. He noted that this was the approach used by the Energy Exchange of Southern Africa who had not been granted the energy trade licence they applied for. In the interview with Greubel (2018), the CEO of Energy Exchange of South Africa, this consideration was raised, and he noted that acting as a broker was still extremely challenging because of the municipal resistance and administrative challenges associated with wheeling electricity through municipal distribution networks. Greubel (2018) suggested that considering the challenges associated with being a third-party energy trader and an energy broker, the most viable way to implement a blockchain-based energy trade application would be within a microgrid context such as a set-up where multiple buildings with SSEG were situated behind a single municipal or Eskom electricity meter.

While PowerX, the only organisation that has been granted an energy trade application, could use a blockchain application to manage their electricity trading, it seems that the viability of this application progressing past a niche innovation stage and becoming widely used in South Africa is unlikely because of the many challenges associated with wheeling, which the organisation is still subject to.

6.2.4 Electricity Trading Within Microgrids

In South Africa, electricity trade and electricity reselling are considered two separate concepts from a legal perspective (NERSA, 2018). While electricity trade requires a licence from NERSA, electricity reselling does not. The primary difference between trading and reselling is that trading entails buying electricity from a generator and selling it to and end-user elsewhere on the grid, whereas reselling refers to the buying of electricity from a registered distributor of electricity and selling it on to end-users behind a single supply point such as a municipal electricity meter (NERSA, 2018). An example of a reseller would be an estate manager supplying multiple houses situated behind a single municipal electricity meter. Each house would have a private meter managed by the estate manager, and an estate of this nature would be regarded as a grid-tied microgrid.

There seems to be significant potential for a blockchain-based electricity trading application to be implemented in this type of microgrid because electricity reselling, such as the in the example above, remains largely unregulated (NERSA, 2018). The incorporation of such an application would require that the microgrid has local producers and consumers, and that the buildings be fitted with smart meters (De Lange, 2019). An energy trade application could then theoretically be implemented to facilitate trading and billing within the microgrid network. During the interview with Greubel (2018), he suggested that this would be the most viable way to implement a blockchain-based energy trade application in South Africa.

While the application of a blockchain-based trading application in the context of a microgrid would have little impact on the greater South African energy system, it seems it would be a suitable niche environment in which to develop and experiment with a blockchain-based electricity application as recommended by the SNM framework. The experimentation of the application within a microgrid could prove useful in developing it to a point where it can be demonstrated to municipal DSOs, who might consider trialling the solution within a grid tied context. Haw (2018) stated that the City of Cape Town municipality was interested in using blockchain to manage trading and billing within their distribution network but noted that before they could consider implementing the application, they would want to see it demonstrated elsewhere.

6.3 Summary of Interview Research Findings

The insights obtained from the research are summarised below:

- The two organisations involved in third-party electricity trading face many barriers in trying to wheel electricity through municipal distribution networks. These include municipal resistance, difficulty in obtaining use-of-grid agreements, and extremely lengthy and complicated administration (Greubel, 2018; Nel, 2018). Organisations wanting to act as third-party traders also face significant challenges associated with obtaining electricity trading licences from NERSA (Greubel, 2018; Radmore, 2018).
- The City of Cape Town faces challenges associated with billing local small-scale producers of electricity and with getting owners of private electricity generation to register their assets (Haw, 2018).
- The City of Cape Town was optimistic about the potential for blockchain to manage localised electricity trading and were exploring how it could be applied (Haw, 2018).
- A blockchain design which completely disintermediates and decentralises electricity trading between producers and consumers is not viable for grid-tied trading in South Africa because of the centralised nature of the energy system (Greubel, 2018; Haw, 2018; Radmore, 2018, Dr Carter-Brown, 2019).
- A blockchain application implemented by municipalities could be viable, however many municipalities lack the capital and resources to implement it (Radmore, 2018).

- An appropriate blockchain design to facilitate electricity trading within South African distribution networks would be a private, permissioned blockchain implemented by local municipal authorities. Unlike the very decentralised Bitcoin blockchain which is not controlled by any individual, this blockchain would be controlled by the authority. This recommendation is supported by IRENA (2019) who argue that private permissioned blockchains are more suitable for energy utilities looking to implement electricity trading within regulated markets.
- There is potential for a blockchain application to incorporate smart-contracts which could facilitate use-of-grid agreements, power purchasing agreements (PPAs), and automate commissions payable to municipalities in a transparent and tamper-proof way (De Lange, 2019).
- A blockchain application which utilises a dynamic pricing model that automatically adjusts electricity tariffs based on local supply and demand could assist DSOs in matching local supply and demand which would assist them in balancing their grids and make them more independent from Eskom (De Lange, 2018).
- An appropriate environment in which to develop a blockchain-based electricity trading application would be a microgrid, isolated from a municipal distribution network (Greubel, 2018).

These findings are used to make recommendations on what a viable electricity trade application might look like and how it could be developed. Considering the challenges faced by parties wanting to wheel electricity through municipal distribution networks and the challenges faced by municipalities in managing electricity trading, there is clear potential for a municipally implemented application which assists with managing wheeling. The automation of the administrative processes into a blockchain application would remove the barriers associated with wheeling.

6.4 A Viable Blockchain-based Electricity Trading Application

Chapter 2 demonstrated that from the MLP, the South African sociotechnical energy regime is experiencing pressures exerted from the landscape-level, namely falling prices in PV generation and rising costs in Eskom supplied electricity. These pressures are creating windows of opportunity for niche innovations to integrate with the energy system and to potentially replace the dominant ways in which societal needs, in this case electricity provision, are fulfilled. Geels and Schot (2007) note that system transactions result from a multi-level process, meaning that the innovations which take advantage of the windows of opportunity will have just as much potential to change the energy system as the landscape-level pressures have. It is therefore important that niche innovations are developed in such a way that it considers the potential repercussions and aims to integrate them into the regime to have a positive influence on the energy system.

While there are several potential electricity trading models that blockchain could be applied to in South Africa, it seems that the application with the most potential for becoming widely used and which would have the most impact on the transition to a low-carbon energy system, would be one which is implemented by municipal DSOs. The application could assist them with the management of buying and reselling local low-carbon electricity, with managing and enabling producers and consumers to use the distribution networks to trade low-carbon electricity, and with balancing their networks and improving their energy independence from Eskom. The reason why this blockchain application seems viable is because of a combination of facts which suggest that it would be in the best interests of municipalities to do so, and because they have the legal autonomy and authority to do it.

6.5 Proposed Blockchain-Based Energy Trade Application

The following recommendations for the municipal DSO blockchain-based energy trade application are based on insights obtained from the literature review and from the research interviews.

6.5.1 A Private, Permissioned Blockchain Build on the Hyperledger Blockchain, Using a PBFT Consensus Mechanism

Considering the research done by IRENA (2019) on the applicability of blockchain for electricity trading and the interview research with De Lange (2019), it seems that the most appropriate blockchain type for a municipal DSO to implement would be a private permissioned blockchain architecture. This blockchain type will provide the DSO with a level of control over the application yet will provide the automation and transparency benefits of blockchain. While this approach may be criticised by some blockchain advocates who promote the decentralisation characteristics of blockchain and its effect on the systems it gets applied to, it can be argued that considering the highly regulated nature of the South African energy system, a public, decentralised blockchain is not appropriate for the South African energy system. De Lange (2019) recommended that the application could be built on the Hyperledger blockchain and use a practical byzantine fault tolerant (PBFT) consensus mechanism. Chapter 3 demonstrated that this consensus mechanism is highly energy efficient and scalable which would be beneficial for the application as it would need to manage thousands of transactions between the energy producers and consumers. Furthermore, South Africa is aiming to reduce its carbon footprint making an energy efficient application more suitable than many other blockchain architectures which are often criticised for being energy-intensive.

6.5.2 Features to Connect Producers and Consumers Wanting to Wheel Electricity

Considering the extensive challenges associated with wheeling which were identified in the research interviews, and the fact that South African legislation and regulations are changing in favour of wheeling (Bronkhorst *et al.*, 2019), there seems to be significant potential for the blockchain application to act as a municipally provided platform which producers and consumers can use to connect and to trade electricity. The DSO would be able to grant permissions to producers and consumers wanting to use the platform to trade electricity via their distribution network. This would give the DSO a detailed and transparent view of the transactions taking place, and overcome the challenge raised by Haw (2018) about ensuring that the municipality gets paid what it is owed per transaction via its distribution network. Smart-contracts built into the platform could facilitate PPAs, use-of-grid agreements, and automate transactions and use-of-grid commissions payable to the municipality. The feature would also overcome many of the identified issues related to municipal resistance and administration.

6.5.3 Automate Local Municipal Electricity Procurement and Resale

Considering the lack of municipal capacity and capital to implement and manage electricity trading in the form of purchasing from owners of SSEG, using a feed-in-tariff structure for resale to consumers, there is potential for the application to assist with the management of this process. For the feature to work however, producers and consumers would need to have smart meters which would need to be integrated in the application. Once set up, the software would be able to automatically manage all transactions between small-scale producers and consumers and to assist with matching supply and demand using variable tariff structures. When there is a deficit of local production, consumers would simply be switched to municipal/Eskom provided electricity.

6.5.4 Registration Feature for SSEG Systems

Considering the challenges some municipalities are having in terms of getting SSEG systems registered (Haw, 2018), the application could include a feature which allows local small-scale producers (or the installers of their SSEG) to register systems and electricity meters via the platform. This would simultaneously solve the SSEG registration challenge, and onboard local producers onto the electricity trading and billing management platform.

6.5.5 Digital Prepaid Wallets for Consumers and Producers

(SALGA, 2018a) notes that for an effective electricity trading model to be implemented, billing and metering systems would need to be revised for bi-directional electricity flows. With the implementation of the DSO application, prosumers and consumers could be switched to a pre-paid billing system which could be accessed via a digital wallet located on users' personal devices such as smartphones of tablets. The digital prepaid wallet could be remotely topped up and the balance would either debited or credited depending on whether the user is feeding in or exporting from the grid. As mentioned, smart meters would be a necessary requirement for the successful implementation of the application.

6.5.6 Dynamic Pricing

The implementation of dynamic pricing would assist grid managers with local supply and demand matching, grid balancing and peak load shifting, and could improve network energy independence because local supply and demand matching would reduce the need to import electricity from Eskom. The implementation of a digital pre-paid wallet would enable this feature since wallet balances could be remotely credited or debited in real-time according to time-of-use tariffs.

6.5.7 Renewable Energy Certificates (REC's) Integration

The application could utilise smart contracts to automatically generate RECs as producers with renewable energy technologies (RETs) generate electricity. This feature would enable consumers to select their preferred generation technology and choose electricity generated by RETs. Consumers would receive RECs proving that they are running off low-carbon electricity. Using smart-contracts to generate and track renewable energy generation can assist with energy certification and verification and carbon tracking.

6.6 Developing and Integrating a Blockchain-Based Electricity Trading Application in South Africa

The SNM management framework and multi-level perspective (MLP) were used to propose a development strategy to increase the potential of the proposed application for regime integration. It seems that there is an opportunity, considering the windows of opportunity present in the South African energy market, for radical energy system transformation if a blockchain-based electricity trading application can be effectively developed and integrated into the energy system.

Because many municipalities lack capacity and capital to manage and implement electricity trading models (River *et al.*, 2018; SALGA, 2018b) there is arguably an opportunity for a private organisation to develop the software and collaborate with municipalities in the form of a public private partnership. This approach avoids the need for a private organisation wanting to implement blockchain-based electricity trading application to act as a third-party trader which has been demonstrated to have many barriers and limitations and can leverage the legal authority for municipalities to implement such a system in their distribution networks.

The MLP and SNM frameworks are used to identify strategies that can be used to promote the successful development of a blockchain-based energy trade application. These guidelines are intended to increase the potential for the application to become widely used in South Africa and to replace the dominant ways in which electricity is provided and managed.

6.6.1 Developing a Proof-of-Concept (PoC) Within a Microgrid

Raven *et al.* (2010) suggest that niche innovations benefit from being developed in niche environments where they can develop and mature before being integrated into dominant sociotechnical regimes. Microgrids, either connected to or separate from the main electricity grid, have been identified as ideal environments in which to develop the proposed blockchain-based electricity trading application. Experimenting with the application in a microgrid environment would enable actors to develop the technology without direct pressure or influence from the dominant actors in the South African energy system, namely regulators, municipalities, and Eskom. Experimentation within a microgrid would enable actors to implement a makeup of practices that deviates from the conventional regime. The use of a microgrid for the early phase of development will enable the application to become refined and reach a stage where the concept can be demonstrated to municipal DSOs.

6.6.2 Creating a Collaborative Development Group for the Proof-of-Concept (PoC)

The voicing and shaping of expectations and visions is an SNM approach useful for attracting resources, collaborating with relevant actors, and ensuring that stakeholders share expectations and a common vision (Raven *et al.*, 2010). The

Building of social networks is a SNM approach useful for creating new combinations of actor types, and for increasing communication and collaboration between them (Raven *et al.*, 2010).

It may not be necessary for a municipality to be involved in the development of the application in its early phases of development in the microgrid. It would however be valuable for a relevant set of stakeholders and researchers to collaboratively work on the development of the application to ensure it becomes a relevant solution suitable to meet the needs of municipal DSOs. Clinton-Brown (2019) identified CSIR and CRSES as suitable entities to collaborate with an organisation developing the software. SALGA would arguably be another useful organisation to involve in the development because, as a representative of municipalities, SALGA could ensure that the application is appropriate for the needs of municipal DSOs. The Development Bank of South Africa is also an organisation that it would be beneficial to involve because of its mandate to advance the development of South Africa by expanding access to development finance and to effectively implement and integrate sustainable development solutions (DBSA, 2019). The effective communication and collaboration between these and potentially other organisations would ensure that the application receives as much support as possible. Such a collaboration could be set-up to pull resources, capital, knowledge, and experience, and to ensure that the necessary communication and collaboration with local governments and policy makers occurs.

Raven *et al.* (2010) note that the *voicing and shaping of visions and expectations* is effective where an increasing number of actors share the same vision and expectations. They further note that the expectations and visions should be based on results from experiments with the niche innovation (Raven *et al.*, 2010). Considering this, it can be said that experimentation within the microgrid should be encouraged and that the vision and expectations should be flexible enough to adapt as the application develops. Raven *et al.* (2010) also note that the *building of social networks* is effective when combinations of new actor types are formed and could include private companies, policy makers, research groups, and users of the innovation. Considering that the suggested organisations are the CSIR, CRSES, DBSA, and SALGA, it can be said that such a collaboration would achieve a diversity of actor types. It would also be beneficial for users of the application within the microgrid, such as the prosumers and consumers, to be involved in the development process and communicated with. Raven *et al.* (2010) suggest that effective communication between actors is essential. It is therefore recommended that a collaborative application development group be formed with dedicated representatives from each organisation. Having organisational representatives dedicated to the project will ensure that the necessary attention and time is given to the project from each organisation. It would also be beneficial if status update meetings are frequently held to ensure that visions and expectations are aligned.

6.6.3 Fostering a Constructive Learning Process

A constructive learning process is an SNM approach for enabling the development of niche innovations to be adjusted if necessary (Raven *et al.*, 2010). This approach is said to be effective when attention is given to the relationship between the technology and the social dynamics of the environments in which the innovation is being applied (Raven *et al.*, 2010). It can therefore be said that when developing and applying the electricity trading application to a microgrid, special focus should be given to the people living in the microgrid and the way in which they interact with the application. These people should be included in the developmental process to understand what their needs, desires, and concerns are and to ensure that the application adds value to their electricity consumption and production experience.

This *constructive learning process* also encourages the questioning of assumptions (Raven *et al.*, 2010). Considering the embryonic nature of blockchain technology and blockchain-based electricity trading applications, this is arguably one of the most important recommendations to consider. As was demonstrated in Chapter 5, assumptions about the blockchain type that than an application uses should be questioned because blockchains are evolving, and new and improved versions are constantly being created. During the interview with De Lange (2019), he recommended that the development of an electricity trading application should be designed in a way that makes it agnostic of the blockchain on which it runs, so that It can be transferred onto a different blockchain if a more suitable design becomes available.

This approach should also be emphasised during the integration of the application and when people start using the platform. Because the proposed application would change the way that people buy electricity, and profit from their excess being sold, assumptions about what people would be willing to do and how they would like to engage with the platform need to be constantly questioned. This will ensure that the platform is not simply given to them, but that their needs and desires form part of the development process.

6.7 Implications of Blockchain-based Energy Trade Application in South Africa

The implementation of the proposed blockchain-based electricity trading and billing management application by municipal DSOs in South Africa is expected assist with:

- distribution network grid-balancing,
- securing municipal profitability,
- increasing municipal energy independence,
- incentivising investment into local renewable energy technologies,
- stimulating local economic development,
- lowering-carbon emissions,
- lowing electricity tariffs, and
- integrating energy storage and electric vehicles (EV's).

6.7.1 Distribution Network Grid-Balancing

As demonstrated in Chapter 2, one of the main challenges associated with the transition towards distributed RETs is balancing an energy grid being fed by variable energy generation technologies. While energy storage can assist with overcoming this challenge, energy storage technologies such as batteries and pumped storage, is expensive. As South Africa becomes increasingly reliant on distributed RETs there is increasing potential for a blockchain-based electricity trading application with dynamic tariffs based on supply and demand to assist with automating grid balancing by incentivising supply and demand matching.

6.7.2 Securing Municipal Profitability

The financial threat posed to municipalities by the uptake of private generation was explored in Chapter 2 along with potential ways in which they can adapt their business models. The implementation of the proposed application would enable and facilitate two of the proposed business models that municipalities could adopt to adapt, namely wheeling and acting as an energy trader (River *et al.*, 2018).

6.7.3 Increasing Municipal Energy Independence

The effective management of local energy generation would make municipal DSOs less reliant on importing electricity from Eskom because the matching of local supply and demand would optimise the use of local energy generating resources. This which would not only lower their carbon footprints but also make them less susceptible to Eskom implemented load shedding which can have negative economic and service delivery implications. De Lange (2019) notes that the application could even channel local electricity generation to important consumers such as hospitals when Eskom implements load-shedding.

6.7.4 Incentivising Investment into Local Renewable Energy Technologies

The effective implementation of localised electricity trading can stimulate local investment into renewable energy technologies (SALGA, 2018a). Considering that current feed-in tariff uncertainty is unattractive to potential investors in SSEG (Bronkhorst *et al.*, 2019), it can be argued that the implementation of the application could provide certainty to investors if a defined tariff structure is established and integrated into the application. A challenge could however arise if dynamic pricing structures are implemented because the feed-in-tariffs would vary based on local supply and demand. The tariffs could however be set between maximum and minimum amounts so that financial forecasts and pay-back periods can be estimated.

6.7.5 Stimulating Local Economic Development

Because the application would enhance localised energy consumption and enable local producers to enhance their ability to monetise their energy generating assets, the profits generated would be circulated within the physical geography of the distribution networks. This would, as a result, stimulate the local economy (River *et al.*, 2018).

6.7.6 Lowering Carbon Emissions

The electricity generation verification and carbon tracking feature proposed for the application could assists in catalysing the transition to a low-carbon electricity system in South Africa. As discussed in Chapter 4, the United Nations Framework Convention on Climate Change (UNFCC) recognises the significant potential for blockchain to assist with combating climate change because of its ability to track and verify emission reductions and origins of electrical generation in a way that is transparent and trustworthy (UNFCCC, 2017). Chapter 2 revealed that the tradeable renewable energy certificate (TREC) programme in South Africa was not effective due to a lack of adoption and stakeholder participation. The application could theoretically integrate with the legally recognised TRECs which could increase participation and adoption of the programme. This might become increasingly relevant in South Africa as the carbon tax is implemented and the fees due per ton of CO2 increase with time (Republic of South Africa, 2019). The implementation of an emission tracking and generation source certifier could also assist municipalities with meeting their emission reduction targets. The cities of Tswane, Cape Town, Johannesburg, and eThekwini aim to reach carbon neutrality by 2050 (City of Cape Town, 2018a). In reaching these targets it is acknowledged that the implementation of a system that tracks performance and updates an emission inventory is required (City of Cape Town, 2018a). The automated tracking of electrical consumption and its associated emissions would arguably be a useful component of such a system considering the high emission profile of electricity generation in South Africa. The application could associate an emission value to electricity being imported from Eskom, and emission values to electricity being generated locally enabling municipal DSOs to calculate the emissions of net electricity consumption in their distribution networks.

6.7.7 Lowing Electricity Tariffs

While this implication is dependent on the tariffs implemented by municipal DSOs and approved by NERSA, there is potential for the application to reduce electricity tariffs for consumers. The reason tariffs could decrease is because municipalities would be less dependent on Eskom's electricity and its associated tariffs, and if the dynamic pricing feature is implemented, price sensitive consumers could plan their consumption for times when local feed-in is high and electricity prices are cheaper.

6.7.8 Integrating Energy Storage and Electric Vehicles (EV's)

Chapter 4 demonstrated the potential for blockchain to manage energy storage and EV charging. These technologies are inevitably going to become more prevalent in the South African energy system and the implementation of the proposed application could assist DSOs with managing their integration. (SALGA, 2018a) notes that there is potential for municipalities to profit by providing energy storage facilities. The integration of energy storage facilities and EVs into energy systems and their integration with the blockchain application could automate the purchasing of local electricity when prices are favourable. The storage facilities would be able to profit by reselling electricity when demand and feed-in tariffs are high. EVs can also be used as energy storage devices, supplying the grid with energy during times of low production and assisting with grid balancing (Kempton & Tomic, 2005).

6.8 Considerations and Further research

6.8.1 Political and Legal Integration

Donnerer and Lacassagne (2018) note that a challenge to integrating blockchain can be a lack of supportive political and legal frameworks. While the recommendations made in terms of the development and integration of the proposed application are intended to involve policy makers and mitigate these challenges, there is likely still a need for further research into how the proposed application can be integrated into the existing system. This would be especially relevant in ensuring that smart-contacts built into the application are legally recognised as PPAs and use-of-grid agreements. Gustafsson (2017) notes that while blockchain can streamline transactions and interactions between stakeholders within energy systems, they require supportive regulatory frameworks to ensure that they become legally binding. The implementation of renewable energy certificates would also require collaboration with stakeholders currently involved in certifying and managing tradeable renewable energy certificates (TRECs) in South Africa to ensure that the embedded application energy generation certificates are legally recognised.

6.8.2 Collaboration Between Software Companies and Municipal Utilities

Chapter 4 demonstrated that most existing organisations using blockchain within the energy sector are start-ups. It would therefore be likely that an organisation that works on the development of the application in collaboration with municipal DSOs would be a relatively new organisation. Gustafsson (2017) argues that the successful integration of blockchain applications into an energy system is reliant on including utilities in the development and integration process. While the developmental recommendations aim to foster this collaboration and stakeholder involvement, further research is required to establish what this collaborative relationship might look like and how it could function.

6.8.3 Electricity Meter Integration and Ownership

Gustafsson (2017) notes that a necessary hardware component for the successful integration of a blockchain-based electricity trading application are 4-quadrant smart meters, which can track bi-directional electricity flows and send information to the application. While smart meters are being rolled out in South Africa and may therefore provide this requirement, there could be challenges associated with ownership of the meters in that companies that own them would need to be included in the billing and transaction processes of the application. Further research would be required to assess how these stakeholders could be included in integration of the proposed application.

There may also be challenges associated with hardware and software compatibility related to the smart meters and the blockchain application. Andoni *et al.* (2018) note that there is a risk that smart meters might not have the computational capabilities to integrate with distributed ledger technologies. It would therefore be important for municipalities to consider smart meter compatibility before commissioning further installations if they want to roll out an application like the one proposed.

6.8.4 Blockchain Use

Chapter 3 provided an overview of blockchain and demonstrated that it remains in its early stages of development. The argument was made in Chapter 5 that blockchain-energy applications should consider the evolving nature of blockchain and constantly question the blockchains which they use to ensure the applications remain relevant and updated. While the suggested application is advised to run on the Hyperledger blockchain, it can be said that the application developers should consider the potential for new and more appropriate blockchains to become available in the future. The development initiative should therefore aim to build the application in a way that makes it agnostic of the blockchain that it runs on so that should a more suitable blockchain become available, the software can be transitioned to run off the new blockchain.

6.8.5 Inter-Distribution Network Trade and Inter-Blockchain Application Integration

As noted by Clinton-Brown (2019), it is likely that multiple energy-blockchain applications for managing transactions and billing will enter the South African energy system. He states that this is the reason why the CSIR are researching the development of an application that will be able to connect and manage various applications. It can be argued that without knowing what these applications are and how they function, achieving this will be challenging. It would therefore be beneficial for organisations that are developing blockchain-energy applications to collaborate with the CSIR to ensure that there is interoperability between them. Ensuring this interoperability could enable a future energy system in South Africa where bi-directional electricity trading occurs not only within distribution networks, but between distribution networks and between different blockchain applications.

6.9 Conclusion

This chapter explored the viability of blockchain-based electricity trading in South Africa. Research interviews were conducted with relevant stakeholders and industry experts to identify which form of electricity trading would be most suitable for blockchain-based applications to be applied to. The electricity trade types explored were third-party trading, wheeling, municipal distribution system operator (DSO) managed trading, and trading within microgrids such as grid-tied estates situated behind a single municipal/Eskom meter. The research revealed that the electricity trading type which had the most potential for enabling a blockchain-based application to become integrated into the South African energy system, and with the most potential to become widely used, would be a municipal DSO implemented application.

A possible blockchain-based electricity trade application was proposed which included recommendations on the features it could include and the blockchain architecture it could follow:

- It was recommended that a private, permissioned blockchain be implemented because this would provide the automation, transparency, and trust that blockchain enables, while ensuring municipal DSOs have a degree of control over the application.
- The application could contain features which enable parties within distribution networks to use the platform to administer private electricity trading in the form of wheeling. This would enable the trades to be overseen by DSOs and to assist with the administration of the wheeling process which currently poses a significant barrier to parties wanting to trade electricity.
- The system could be designed to automate local procurement and the reselling of electricity produced by SSEG infrastructure.

- The system could include a feature which enables owners of SSEG to register their assets and automatically be integrated onto the electricity trading system.
- Digital pre-paid wallets could be implemented for producers and consumers which would be automatically be debited or credited depending on whether the users are consuming or producing electricity.
- Dynamic pricing was recommended due to the benefits it can provide in terms of grid balancing, supply and demand matching, and peak load shifting. The implementation of a pre-paid digital wallet would enable this as the balance could be debited or credited according to time-of-use tariffs which is not currently possible with standard prepaid meters.
- The integration of renewable energy certificates (RECs) for guarantees of origin was recommended because of blockchain's ability to utilise smart-contracts to automatically generate certificates of origin as electricity is produced by renewable energy technologies.

The strategic niche management (SNM) framework and multi-level perspective were used to provide recommendations regarding how the proposed blockchain electricity trade application could be developed and integrated into the South African energy system. The recommendations are listed below:

- developing a proof-of-concept within a microgrid,
- creating a collaborative development group made up of municipal representatives, a blockchain-energy software company, policy makers, research organisations like CSIR, SALGA, GreenCape, and CRSES, and financial support organisations like DBSA, and
- fostering a constructive learning process using experimentation and research,

The potential implications of the proposed application into the South African energy system were explored and given below:

- distribution network grid-balancing,
- securing municipal profitability,
- increasing municipal energy independence,
- incentivising investment into local renewable energy technologies,

- stimulating local economic development,
- lowering-carbon emissions,
- lowing electricity tariffs, and
- integrating energy storage and electric vehicles (EVs).

Implementation considerations and the need for further research were presented:

- There would be a need to explore how the proposed application could be integrated into the energy system in a way that adheres to regulatory and legal requirements. This would be especially important for ensuring that PPAs, use-of-grid agreements, and renewable energy certificates, converted into a digital format, would be legally recognised.
- It was noted that research into how an effective working relationship would be established between the proposed developmental group, especially between municipalities and the organisations that develop the blockchain-based electricity trade application.
- As a prerequisite to the implementation of the proposed application, smart meters are a necessary requirement which would need to interface with the software. There may be challenges associated with compatibility and meter ownership. Research into how the application could interface with existing meters would be required.
- Considering the evolving nature of blockchain technology, an important element of the successful implementation of the application would be to design it in a way that makes it blockchain agnostic. This would mean that the application could run off different blockchains should new blockchain be developed which may be more appropriate for the application requirements.

Based on the literature and research findings, it seems that the implementation of a blockchain-based electricity trade application is viable in South Africa. Furthermore, its implementation and integration by municipalities into the South African energy system would contribute positively to the energy system because it offers significant potential to assist municipalities in overcoming many of the challenges associated with adapting their business models to the changing energy system which is increasingly made up of distributed, localised, renewable energy technologies. It could also play a significant role in catalysing a transition to a low-carbon energy system in South Africa.

Chapter 7

Conclusion

Chapter one introduced the research motivation for conducting a study on the blockchain-energy nexus, demonstrating how the introduction of blockchain and its associated applications into the South African energy system might have the potential to rearrange its sociotechnical configuration and contribute to South Africa's energy transition. It introduced the primary research topics that would be explored, namely the existing Sun Exchange blockchain-based solar project innovation and the possibilities of the introduction of a blockchain-based electricity trading innovation. A participative case study and interviews were selected as research methodology to analyse Sun Exchange and to assess the viability of its electricity trading application.

Chapter 2 introduced the global sustainability agenda, emphasising the pressing need to decarbonise energy systems in order to lessen the impact on the environment, especially in relation to global warming and climate change which are posing serious threats to life on earth. The South African energy transition was explored revealing that as electricity prices increase and the system contains ever more distributed renewable energy technologies, pressures are exerted on municipalities to adapt their business models to remain profitable. There are many other challenges and pressures on the system, however, increasing electricity tariffs and the rise of small-scale private RETs are the focus of the study because of their relevance to blockchain applications. These pressures are presenting windows of opportunity for innovative solutions to be explored that might have the potential to meet the electricity needs of consumers in a way that benefits municipalities, electricity consumers, and investors in RETs. One such opportunity is electricity trading between local producers and consumers. Multi-level perspective (MLP) and strategic niche management (SNM) frameworks were chosen as theoretical frameworks throughout the research to form a perspective from which to analyse the integration of Sun Exchange and electricity trading innovations into the dominant

South African sociotechnical energy regime. The MLP was explored because of its ability to unpack different dynamics within socio-technical transitions. The SNM framework was useful because it focuses on the niche level in the MLP.

Chapter 3 offered a literature review on blockchain technology which is the backbone of both researched applications, demonstrating that there are many ways in which blockchains can be designed, each of which have different strengths and weaknesses. It showed that blockchain technology was in itself a developing and evolving niche innovation and that its capacity to transform sociotechnical regimes was equally dependant on the application type it enabled and the sociotechnical regime into which an application was being introduced, as it was on the blockchain design. The literature review revealed that organisations using blockchain technology should be cognisant of the fact that it is an evolving and developing technology and that they should remain adaptive in order to develop their applications as the technology evolves.

Chapter 4 explored the existing literature on the application of blockchain technology within energy systems. The application types which were reviewed included project financing, electricity trading, electric vehicle charge management, carbon trading and emission management, and energy grid management. It was shown that internationally, applications predominantly remained within the niche level and are yet to develop to a point where they could become widely used in energy systems and potentially replace the dominant ways in which electricity needs are fulfilled. It was identified that in order for blockchain-based applications to become integrated into energy systems, supportive legal frameworks, hardware complementarity, human resources and the participation of diverse stakeholders must be developed. Should these elements be appropriately addressed, blockchain-based applications have significant potential to work with other technologies, such as RETs and smart meters, and contribute towards creating lower carbon emitting energy systems that are more resilient, and which benefit more individuals than the centralised status-quo energy systems.

Chapter 5 offered a participative case study on Sun Exchange and its solar project financing innovation. The SNM framework was useful in identifying the elements that have contributed to the relative success of the organisation and which could be leveraged to further develop and integrate the application into the South African energy regime. Successful elements included the way in which the organisation communicates and shares its vision, the way that it builds strong and diverse social networks with relevant stakeholders, and the way in which it utilises a constructive learning process while continuing to develop its platform. It was identified that Sun Exchange could enhance the development of its innovation by questioning underlying assumptions, particularly in relation to the use of Bitcoin and Ethereum blockchains which are criticised for being high-carbon emitters as a result of their energy requirements. It was shown that the ways in which Sun Exchange is influencing the energy system in South Africa include a contribution to lowering carbon emissions, distributing the ownership of energy projects, improving energy security, lowering electricity tariffs, and contributing to the development of renewable energy technologies. Despite these positive implications, the effects which the innovation is having in the broader sociotechnical energy regime are minimal and the innovation is unlikely to develop to a point where it becomes widely used and replaces the dominant ways in which electricity needs are met. One of the reasons for this is because of the legislative barriers relating to the scale of Sun Exchange projects which is capped at 10MW to avoid the need to apply for generation licences with the national energy regulator.

Chapter 6 explored the viability of blockchain-based electricity trading in South Africa using interview research with blockchain and energy experts as well as stakeholders in existing electricity trade models. It demonstrated that an application implemented by municipal distribution system operations has the most potential to become widely adopted and form part of the dominant energy regime. The following application features were proposed based on the research findings:

- the use of a private permissioned blockchain,
- a feature to manage wheeling,
- automated procurement and resale of small-scale electricity production,
- digital pre-paid wallets,
- an SSEG registration feature,
- automated dynamic pricing based on local demand and supply, and

- integration of renewable energy certificates.

An application development strategy was proposed using the SNM framework, suggesting that the innovation be developed within a microgrid, creating a collaborative development group made up of municipal representatives, a blockchain-energy software company, policy makers, and research organisations. Possible implications of the proposed application were identified based on combining the literature review with the primary research findings. It was shown how the application could, in part, contribute to a low-carbon energy transition in South Africa and that it could have several other beneficial implications including alleviating some of the challenges faced by municipalities resulting from the adoption of private generation. For the proposed application to be effectively developed and integrated, certain elements should be considered. These include legislative amendments which would recognise smart-contracts as legally binding PPAs and use-of-grid agreements, the establishment of an effective public private partnership, and careful consideration of the hardware requirements.

7.1 Focus Areas and Policy Recommendations

In order to effectively develop, nurture and integrate the researched blockchain innovations into the South African energy regime and unlock the benefits that they have the potential to provide, the focus areas and policy recommendations below should be considered.

7.1.1 Consensus Mechanism and Blockchain Architecture Use

As demonstrated in Chapter 3, one of the primary considerations when using blockchain relates to the consortium mechanism used since this can have profound implications for the energy requirements to run a given blockchain, and on the security, speed and scalability of the application (Andoni *et al.*, 2018). As suggested in Chapter 5, Sun Exchange should remain aware of developments relating to blockchain types so that their platform remains relevant and evolves with the evolving technology. The same applies to the development of the proposed electricity trading application. The developers should, where possible, design the application to be blockchain agnostic so that if new and improved blockchains develop, the application will be able to migrate to the new blockchain. The developers of both applications should ultimately remain flexible and adaptive and acknowledge the ever-changing nature of blockchain technology so that they are able to adapt the application when necessary.

7.1.2 Application Management and Development Costs

The development of blockchain applications can be expensive. Blockchain applications do however have the capacity to cut costs once implemented because of their ability to lower management and transaction costs. Considering this and the fact that many municipalities have capital constrains, it would be beneficial for the trading application to be developed in conjunction with private organisations for example software companies, research organisations such as CSIR and CRSES, and finance organisations like the Development Bank of South Africa. As suggested in Chapter 6 the development of such a public-private partnership would also be beneficial because many municipalities have capacity constraints preventing them from being able to effectively manage electricity trading.

7.1.3 Legislative Considerations

7.1.3.1 Smart Contract Integration

The literature review demonstrated that prerequisites to the integration of blockchain applications into energy systems are standardisation and supportive regulations which, for example, would recognise smart contracts as legally binding agreements (Christidis & Member, 2016; Weber *et al.*, 2016; Gustafsson, 2017). The issue was also raised in the primary research by De Lange (2019) who stated that digital smart contracts could facilitate power purchase agreements between producers and consumers and use-of-grid agreements with DSOs, but they first need to be legally recognised. It is therefore important that when developing an electricity trade application, policies and legislation are adapted to enable the application to function effectively.

7.1.3.2 Generation Licences and Feed-in-Tariffs

In a time when the need for transition to low-carbon systems has never been more pressing, it is essential to remove the barriers which prevent people from developing low-carbon technologies. Although the size at which an electricity generating technology is required to have a generation licence from NERSA, has been raised from 1MW to 10MW, Sun Exchange is still limited by the size of the projects they are able to develop. The start-up avoids projects larger than this because of the increased complexity and costs associated with building larger projects. It seems the energy system would benefit greatly if legislation could be changed in favour of encouraging the development of renewable energy technologies.

In many areas of South Africa, there are additional legislative barriers which prevent people from installing renewable energy technologies. For example only 42 of the 165 municipal utilities allow people to install grid-tied private generation (Bronkhorst *et al.*, 2019). Furthermore, only 25 offer feed-in-tariffs (Bronkhorst *et al.*, 2019). The literature review shows that the existing energy regime is failing in many ways, and that a potential solution which should be explored is for municipalities to allow private generation, feed-in-tariffs, and profit from electricity trading models which use the available local generation. The adoption of standardised and reliable feed-in-tariffs would give investors into private generation certainty regarding how long it will take them to pay off their systems. This would encourage the development of further private generation and provide municipalities with alternative revenue streams.

Another legislative topic not dealt with in this thesis, but which may be relevant, is that in South Africa, owners of SSEG who feed electricity into a network are generally required to be net consumers, meaning that they cannot feed more electricity into a network than that extract (City of Cape Town, 2015). If appropriate feed-in-tariffs are set which enable municipal DSOs to cover grid management costs while generating profit, it may be unnecessary to limit how much electricity private generators can provide to a network. If the requirement to be a net-consumer is removed, it would also have positive implications for Sun Exchange as they would be able to scale their projects larger than simply big enough to meet the energy demands of the customers they service because they would be able to generate profits for the owners of the projects by selling electricity into the grid. It would also be beneficial for the electricity trading application as people would be incentivised to install private generation systems larger than they require knowing that the installation would be an investment and could provide them with alternative revenue streams.

If designed appropriately, the removal of this requirement could provide municipalities with affordable low-carbon electricity which they can continue to profit from, consumers could further contribute to financing development renewable energy technologies, municipal distribution networks could become increasingly independent of Eskom, and the energy system would become increasingly decarbonised.

In order for the potential of the Sun Exchange application to be unlocked and for the benefits of an electricity trading application to be realised, the current legislation which hinders the energy system from transitioning, needs to be revised so that dependence on a failing monopoly can be removed and the energy system can reduce its reliance on fossil fuels.

7.1.4 Technological Complementarities

The literature review identified a key consideration for the integration of an electricity trading application, namely the development of technological complementarities such as smart meter hardware (Andoni *et al.*, 2018). This requirement was also raised in the interview with De Lange (2019), who noted that for a blockchain-based electricity trading application to be integrated, a given energy system would need to have the appropriate bi-directional four-quadrant smart meters able to interface with the application software. The development of the proposed application would therefore require that the municipality involved would be willing to either install the smart meters themselves or commission a private company to do so.

7.1.5 Blockchain and Energy System Structure Misalignment

The literature identified that there is a general misalignment between the structure of energy systems which are commonly centralised, and the structure of blockchain technology which is commonly decentralised (Orlov & Bjørndal, 2017; Zheng *et al.*, 2017). There is however opportunity to find common ground between the two because energy systems are becoming increasingly decentralised with the rise of distributed renewable energy generation, and because blockchains can be designed with varying levels of centralisation. It is therefore recommended that further research be conducted to establish how policies could be adapted to cater for decentralised applications, while simultaneously establishing which blockchain architectures would be most suitable for the level of centralisation present in the South African energy system.

7.1.6 Lack of Expertise that Combines Blockchain and Energy

The research identified that there is a lack of individuals who are knowledgeable about both blockchain and energy systems. It is therefore recommended that for the development of legislation and a supportive environment for blockchain-based innovations in the energy sector to occur, individuals and organisations with appropriate knowledge and skills should be identified, engaged with, and supported to ensure that informed and educated decisions are made. This could be achieved through prioritising investments in SMEs using blockchain for energy related applications. It could also become a focus for finance development institutions like the Development Bank of South Africa.

7.1.7 Public Private Partnership Development

Considering the scarcity of knowledge about the blockchain-energy nexus topic, it is suggested that for the development of policies, for a supportive environment for blockchain related application in the energy sector to be established, and for the development of the proposed blockchain-based electricity trade application, research organisations consisting of individuals knowledgeable about blockchain and the South African energy sector, should be developed. This could be initiated by organisations like the CSIR, the CRSES and the Department of Trade and Industry, and financially supported by organisations like the Development Bank of South Africa. It has been demonstrated that the possibilities of integrating blockchain into the energy system are potentially very beneficial but that a barrier to these benefits being realised is an energy regime which is slow to adapt to the changing way in which energy is generated and consumed. Effective communication and planning between relevant parties could help to overcome many of the obstacles preventing these innovations from advancing the energy system.

7.2 The Role of Blockchain in South Africa's Energy Transition

This research has explored the way in which the Sun Exchange innovation has developed and concludes it is unlikely that this innovation will form part of a transformed energy regime if legislative barriers are not overcome. The research also established that there is potential for a blockchain-based electricity trading application to be integrated into the South African energy regime. The potential effects of integrating this application have been identified.

The research has provided insights into existing blockchain energy applications and how they affect energy systems. It explored an existing blockchain application in South Africa and uncovered which elements have contributed to its successful development, and which strategies could be further leveraged to enhance its development. It has also provided insights into the viability and prospects of blockchain-based electricity trading in South Africa.

The energy regime in South Africa is experiencing significant pressures. The failing state utility, Eskom, and the threatened profitability of municipal utilities calls for a restructuring of the energy system. The increased uptake of private renewable energy technologies and the potential for municipalities to profit off electricity trade models which use and encourage these energy resources, shows that municipal adoption of electricity trading models are possible pathways to contributing towards the restructuring of a transformed sociotechnical energy regime. As is the nature of sociotechnical transitions, this process is likely to be contested, messy and challenging. The researched on blockchain-based innovations suggests that they might positively contribute towards a transformed energy system structure made up of distributed low-carbon technologies. Their development and integration into the South African energy system should therefore be encouraged and further researched.

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