Concentrating Solar Power (CSP) technology adoption in South Africa

By

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Declaration

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December 2018

Abstract

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South Africa (SA) aims to generate 42 per cent of its electricity from renewable energy technology sources by 2030. To achieve this target, the government started the Renewable Energy Independent Power Producer Procurement Programme (REI4P) to allow easy integration of renewable energy technologies into the existing energy mix. The country has an abundant solar resource, and the potential to harvest this resource through concentrating solar power (CSP) has been proven. In 2010, concentrating solar power (CSP) was one of the major renewable energy technologies that was prioritised by SA, and as a result 600 MW of CSP have been bought in the REI4P, and this includes seven plants that have been, or are being, built. Conversely, recent events have shown that the future of CSP in South Africa looks bleak, as the government's recent Integrated Resource Plan (IRP) updates gave no allocation to new CSP plants beyond 2030. Several factors have contributed to the chasm in the adoption of CSP technology in the country. Very few CSP plants are connected to the grid, and there is limited research and literature on its learning effect and economics of scale. Also, the impacts of this technology on South Africa's trade and the local manufacturing industries, as well as on the local research, development, and innovation community, have not been investigated to date.

This research presents a detailed analysis of the CSP technologies in South Africa in terms of the existing technology adoption models and diffusion strategies, used by government and its agencies, to improve the development and deployment of these technologies. The study also analyses the state of CSP, concerns, and complex issues limiting the deployment of the technology in the country. The study then uses mathematical relationship to determine the progress ratio, the learning effect, and the likely future of CSP in the country. The impact of the CSP technology on economics and trade were then quantified and a technology specific roadmap was developed.

The innovation analysis carried out on CSP technologies in South Africa shows that its tariff is currently higher than that of other major RETs (wind and PV), and that the innovation

experience of the CSP technology is incremental, as each subsequent plant was an improvement on previous facilities elsewhere. The development of research into innovation, and eventually into market products of CSP systems, is improving with a closer relationship and working together of the stakeholders. This progress, however, is slow, because of the limited knowledge in identifying and understanding the important activities and policy instruments that can aid the prioritisation of important actions to forge better relationships among stakeholders, and fast track the deployment of CSP.

The expert elicitation analysis on the impact of RD&D funding on the present and future cost of electricity from CSP presents a RD&D investment strategy that will foster technological improvement and adoption of CSP in the country. Three RD&D funding scenarios are presented and analysed, and an allocation procedure was developed. The results show that strategic policies, laws and the right funding can help South Africa to fully maximize its CSP resources potential to foster cost reduction and market viability of its solar innovations.

The result from the systems dynamics analysis shows that improved support for research is the most effective way to open new methods and ways in which the CSP technologies can be deployed, which will foster further CSP adoption in in the country. Further analysis, based on the data from literature and existing plants, highlights the current state of CSP in South Africa for capacity and costs. The economic indicators of CSP, which include LCOE, LPOE, DNI, and specific costs, are discussed, and the most realistic future cost of CSP in SA is presented. Limitations to the learning effect of CSP in SA are identified; existing principles were used with limited data to develop the learning rate, progress ratio, and cost reduction rate of CSP. The study shows that there are no existing patterns in the capital costs of the existing CSP plants in SA for technology, size, solar multiple, site location, or storage capacity; this makes the experience curve analysis of the CSP industry difficult. The solar field cost, which is the most significant capital cost, was analysed independently to give an idea of what the CSP experience curve might look like. The CSP learning rate in SA was calculated, the future of capital costs was then determined, and the likely experience curve for CSP in SA was presented. The assessment of the SA local manufacturing capabilities for CSP related services identified strength and the challenges of the sector. It further estimated the economic and social benefits of improvements, including the employment opportunities, and the overall impacts on trade and economy. A technology specific roadmap was developed in this study to present a framework for the medium term CSP adoption outlook in South Africa.

Uittreksel

Suid Afrika (SA) beoog om 42 persent elektrieiteit deur middel van herwinbare energie tegnologie te produseer teen 2030. Om hierdie doelwit te bereik het die regering 'n program: "Renewable Energy Independent Power Producer Programme (REI4P)" van stapel gestuur om die integrasie van herwinbare energie met huidige bronne te vergemaklik. Die land het oorvloedige sonkrag en die potensiaal om dit te benut vir energie deur middel van konsentrasie van sonenergie "concentrating solar power" (CSP) is reeds bewys. In 2010 was CSP een van die hoof geprioritiseerde herwinbare tegnologieë in Suid Afrika en is 600 MW deur die REI4P aangekoop. Dit sluit sewe aanlegte wat gebou, of in aanbou is, in. Teenstrydig daarmee lyk die toekoms van CSP in Suid Afrika swak, aangesien die onlangese opdatering van die regering se "Integrated Resource Plan" (IRP) geen toekenning vir 'n nuwe CSP aanleg na 2030 insluit nie. Verskeie faktore het aanleiding gegee tot hierdie gaping in aanvaarding van die CSP tegnologie. Baie min CSP aanlegte is gekoppel aan die nasionale rooster en daar is beperkte navorsing en inligting beskikbaar wat die effek en skaalvoordele bespreek. Die impak van hierdie tegnologie op Suid Afrika se handel en plaaslike vervaardigings industrie, asook die plaaslike navorsing, ontwikkeling en innovasie was tot op datum nie ondersoek nie.

Die navorsing verskaf 'n noukeurige ontleding van die CSP tegnologieë in Suid Afrika in terme van die bestaande tegnologie aanvaardingsmodelle en diffusie strategieë wat deur die regering en agente gebruik word om die ontwikkeling en uitrol van die tegnologieë te verbeter. Die studie ontleed ook die huidige stand van CSP, bekommernisse, en komplekse twispunte wat die uitrol van die tegnologie vehinder. Die studie maak gebruik van wiskundige verhoudings om die vooruitgangsveverdeling, leereffekte, en die moontlike toekoms van CSP in die land te bepaal. Die ekonomiese- en handels effek van CSP tegnologie is bereken en 'n spesifieke plan vir die tegnologie ontwikkel.

Die innovasie-ontleding van CSP tegnologieê in Suid Afrika dui daarop dat die tariewe huidiglik hoër is as die ander hoof hernubare energie tegnologie (wind en son fotovoltaïese) en dat die innovering en ondervinding van CSP tegnologie inkrementeel is, deurdat elke nuwe aanleg 'n vebetering was op ander fasiliteite. Die ontwikkeling van navorsing in innovasie en uiteindelike mark produkte van CSP stelsels verbeter as gevolg van die sterker verhoudings en samewerking van alle betrokke partye. Hierdie vooruitgang is stadig as gevolg van die beperkte kennis van identifikasie en verstaan van die belangrike aktiwiteite

en beleidsinstrumente wat sal help met die prioritisering van die belangrike aksies om beter verhoudings tussen betrokke partye te smee, wat die uitrol van CSP sal verhaas.

Die kundigheidseliseteringsontleding van die impak van RD&D befondsing van die huidige- en toekomstige koste van elektrisiteit deur CSP verskaf 'n RD&D belegginstrategie wat tegnologiese verbetering en aanvaarding in die land sal bevorder. Drie befondsingsmoontlikhede was ontleed, word geskets en aangebied. 'n Prosedure om dit toe te deel was ontwikkel. Die resultate toon dat strategiese beleide, wette en die regte befondsing Suid Afrika kan help om die CSP bronne ten volle te benut wat verlaagde koste en bemarkbaarheid van sonenergie innovering sal bevorder.

Die resultate van die stelsel-dinamiese ontleding toon dat verbeterde ondersteuning vir navorsing die mees effektiewe manier is om nuwe metodes en maniere van implementering van CSP tegnologieë te bevorder wat sal lei tot groter aanvaarding van CSP in die land. Verdere ontleding gebaseer op die data van bestaande leesstof en aanlegte, lig die huidige status van CSP in Suid Afrika uit in terme van kapasiteit en koste. Die ekonomiese aanwysers van CSP, wat LCOE, LPOE, DNI en spesifieke koste insluit, word bespreek en die mees realistiese toekomstige koste van CSP in Suid Afrika aangebied. Beperkings van die leereffek van CSP in Suid Afrika word geïdentifiseer. Bestaande beginsels was gebruik met beperkte data om die leertempo, vooruitgangsverhouding en koste verminderings tempo van CSP te bepaal.

Die studie toon dat daar geen koste patrone vir die kapitale uitleg van CSP aanlegte in Suid Afrika ten opsigte van tegnologie, grootte, spieël veldkapasiteit, posisie, of stoorkapasiteit bestaan nie. Dit bemoeilik die ondervindingskurwe ontleding van die CSP industrie. Die koste van die sonarea, wat die grootste kapitale uitleg is, was onafhanklik ontleed om 'n aanduiding van wat die ondervindingskurwe mag voorstel te bekom.

Die CSP leertempo in Suid Afrika was bereken, die toekomstige kapitaal uitgawes bepaal, en die bes moontlike ondervindingskurwe vir CSP in Suid Afrika aangebied. Die assesering van die plaaslike vervaardigingsvermoeëns vir CSP verwante dienste het sterkpunte en uitdagings van die sektor ge-identifiseer. Dit het verder die ekonomiese en sosiale voordele van verbeterings, insluitend werksgeleenthede, en oorkoepelende effek op die handel en ekonomie geskat. 'n Tegnologie-spesifieke plan was in die studie ontwikkel om 'n raamwerk vir die medium termyn CSP aanvaardingsvooruitskatting in Suid Afrika daar te stel en aan te bied.

List of publications

Peer reviewed journal articles

1. Craig, O. O., Brent, A. C. and Dinter, F. 2018. System Analysis of Concentrating Solar Power (CSP) technology in South Africa. American Institute of Physics Conf. Proceedings 6(01):1–13.
2. Craig, O. O., Brent, A. C. and Dinter, F. 2017. Concentrated Solar Power (CSP) Innovation Analysis in South Africa. *South African Journal of Industrial Engineering*, 28(2):14–27.
3. Craig, O. O., Brent, A. C. and Dinter, F. 2017. The current and future economics Concentrating Solar Power (CSP) in South Africa. 28(3):1-14

Conference presentations

1. Craig, O. O., Brent, A. C. and Dinter, F. 2018. Analysis of local manufacturing capacity, economic and trade impact of CSP in South Africa. *Solar Paces Conference*. Casablanca, Morocco.
2. Craig, O. O., Brent, A. C. and Dinter, F. 2018. Expert elicitation of the Impact Of R&D Budget On (CSP) in South Africa. *Southern Africa Solar Energy Conference (SASEC)*. Durban, South Africa.
3. Craig, O. O., Brent, A. C. and Dinter, F. 2017. System analysis of Concentrating Solar Power (CSP) technology in South Africa. *Solar Paces Conference*. Santiago. Chile

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Nomenclature

BP	British Petroleum
CRSES	Centre for Renewable and Sustainable Energy Studies
CSP	Concentrating Solar Power
DoE	Department of Energy
ESTELA	European Solar Thermal Electricity Association
ETP	Energy Technology Perspective
EPC	Engineering, Procurement, and Construction
FS-UNEP	Frankfurt School United Nations Environment Programme
IEA	International Energy Agency
IRP	Integrated Resource Plan
IPP	Independent Power Producers
NPV	Net Present Value
NSI	National System of Innovation
PV	Photovoltaic
RD&D	Research, Development and Demonstration
REI4P	Renewable Energy Independent Power Producer Procurement Programme
REN21	Renewable Energy Policy Network for the 21st Century
RETs	Renewable Energy Technologies
SAIREC	South Africa International Renewable Energy Conference
SARi	South African Renewables initiative
SASEC	Southern African Solar Energy Conference
StatsSA	National Statistical Service of South Africa
STERG	Solar Thermal Energy Research Group
WWF	World Wide Fund for Nature

1. Introduction

1.1 Background information

The technology adoption lifecycle (TAL) of a new product or technology, often follows a bell-shaped curve (see Figure 1-1). Moore (1991) divided the TAL cycle into 5 groups of stakeholders with respect to their motivations and characteristics as: innovators, early adopters, early majority, late majority, and the laggards; as displayed across the bell-shaped curve below.

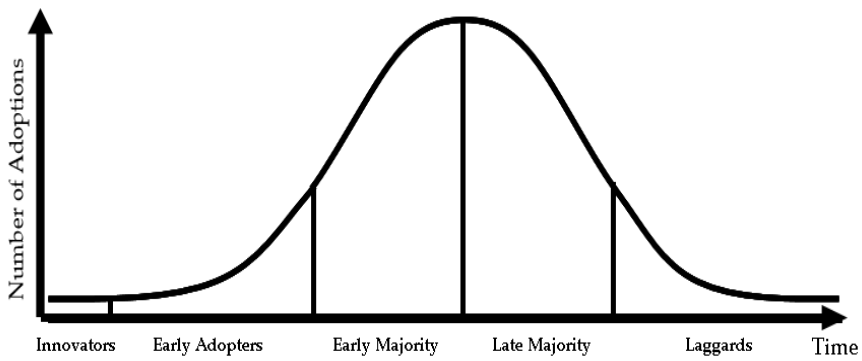


Figure 1-1: Technology Adoption Lifecycle (Moore, 1991)

In TALs, the valley of death (VoD) refers to a chasm or gap that exists between the early adopters and early majority group, as illustrated in Figure 1-2.

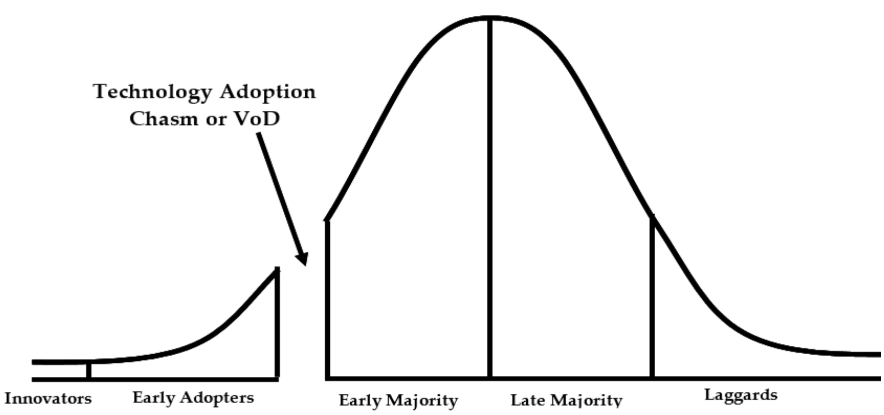


Figure 1-2: Technology adoption Chasm or VoD in the TAL

The VoD represents the constraint that limits the advancement of new technologies from early adopters, to early majority groups. Coughlan, Dew and Gates (2008) observed that the VoD situation often occurs when policy- and decision-makers cannot distinguish between the specific motivations and characteristics of the two groups involved. These two groups are the early adopters and the early majority.

Since its emergence, renewable energy technologies (RETs) have caught the attention of many researchers, industries and policy-makers; because it has been identified as a possible solution to halt global carbon emissions that are on the rise (Pfeiffer & Mulder, 2013). Despite the promises offered by various RET types, many of them still face the challenge of crossing the VoD. Therefore, various measures are being developed to help RETs deployment, adoption, as well as diffusion into the market (Haas *et al.*, 2004).

Presently, ample number of policies exist, which serve as instruments to support renewable energy technology advancement around the world. These policies are categorised as either, price driven or capacity driven, and investment based or generation based (Haas *et al.*, 2004). Another existing policy that has been used to encourage the diffusion of RET and its adoption, is the provision of funds or grants that can be used to set up stand-alone or individual-sited renewable plants. These policy have been successful with solar PV and small wind farms (Bozeman, 2000). Moreover, they have been found to encourage the early adoption of RETs (Shum & Watanabe, 2007).

Solar energy is believed to be the most promising of the RET types, especially in South Africa (SA), because of the good solar resources available in the country (NREL GIS, 2015; Kim *et al.*, 2014). There are two types of technologies through which solar energy has been deployed to generate electricity in South Africa: solar photovoltaic (PV) and concentrating solar power (CSP) technologies. While the former operates at low temperature using global horizontal irradiance (GHI), the latter functions well at high temperature - using direct normal irradiance (DNI) (Stine & Geyer, 2001). However, despite the available solar resources in South Africa, electricity generated from solar energy is only a small percentage of the overall power energy produced (Silinga *et al.*, 2015).

Various technology adoption frameworks have been developed to support policy-makers and help solar energy systems break-through and address carbon lock-in[1] effects. Thus, allowing

[1] Carbon lock-in: a term used to describe systems and markets that are carbon intensive and are driven by fossil fuel

it to cross its VoDs. Nevertheless, most of the technology and economic models, deployment and diffusion models found in literature are specific. These models were developed for solar PV, with none found for CSP (Faiers & Neame, 2006; Zhang & Datta, 2006; Shum & Watanabe, 2007, 2008, 2009; Rao & Kishore, 2010; Kim *et al.*, 2014).

The effects of applications of these frameworks or models, are evident in the rapid fall in the PV module price, as shown in the NREL report of Feldman *et al.,* (2012). To this end, Figure 1-3 shows the global annual module prices of PV, with the residential PV price becoming USD $3.21/W in 2014, a 7 % reduction from the fourth quarter of 2013 and the price of commercial PV reducing by 19 % reduction in plant during the same period.

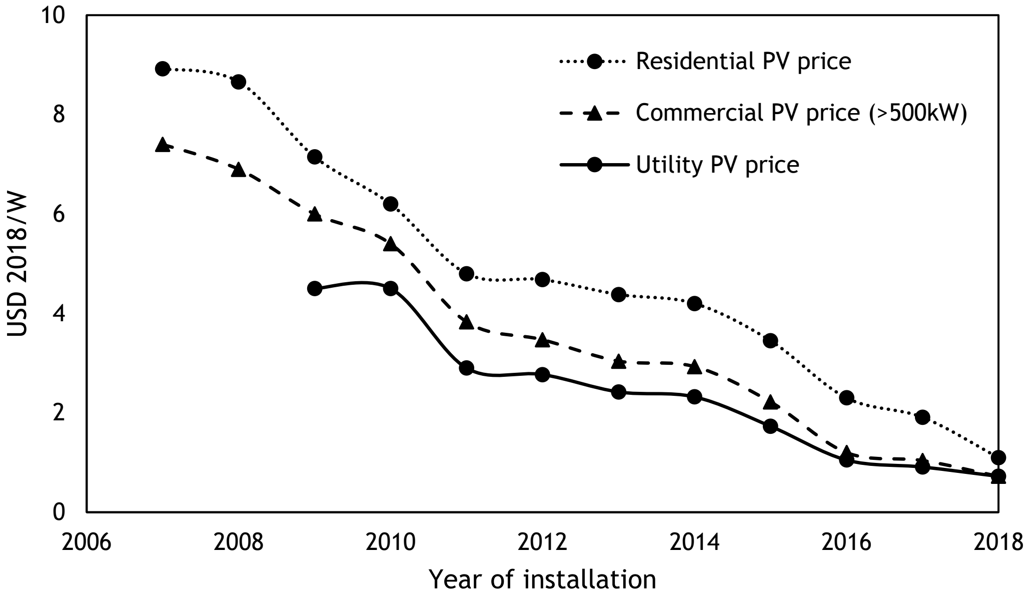
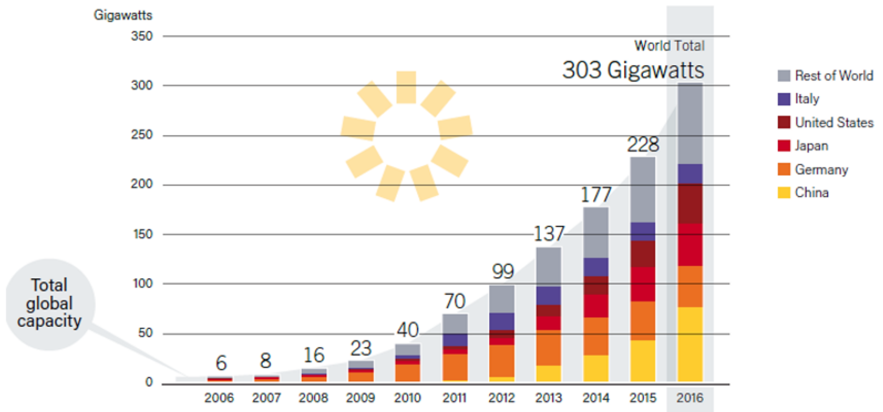


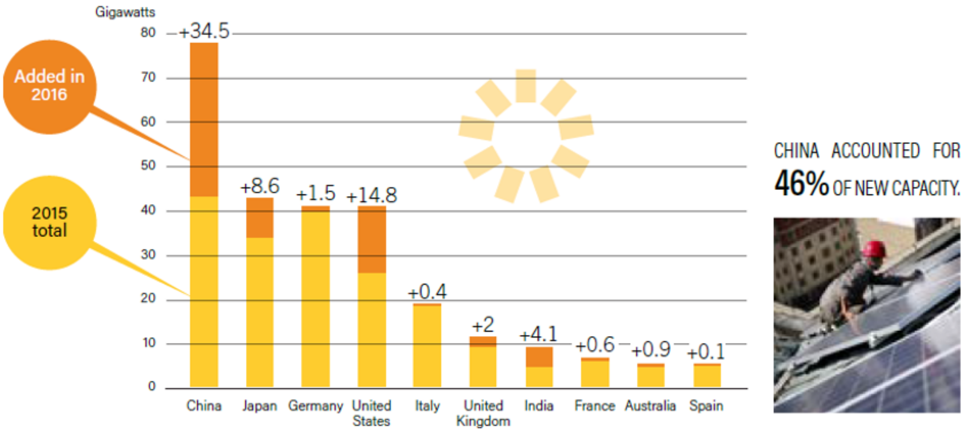
Figure 1-3: Installed price of residential and commercial PV systems (Adapted from (IRENA, 2018) and (Feldman *et al.*, 2014))

The absence, or limited literature on technology adoption and deployment for CSP technology is understandable, as the first fully operational plant was only installed in the mid-1980s in California (Kalogirou, 2009). Further installations were implemented later in Spain and around the world, making it a young technology as compared to other renewable energy types. In 2015, CSP growth activities and installation shifted from Spain to United States. Then, in 2016 it shifted to China and other emerging economies, with South Africa taking the lead globally in terms of the newly added CSP capacities and market. It was shortly followed by Morocco and China. This trend suggests the current and future deployment of CSP outside its initial home markets in Spain and the USA. Although there are numerous promises offered by CSP, it still faces various barriers like a high tariff, overcoming effects of carbon lock-in, some unique technical limitations and several non-technical barriers (CSP Today Markets Reports -South Africa, 2015).

The global energy report of 2017 (REN21, 2017) shows that, on one hand, 303 GW of PV have been installed worldwide in the last decade and over 75 GW was added in 2016 alone, which meant that over 31 000 solar panels were installed per hour in 2016 alone (see Figure 1-4a and b); while on the other hand, the total CSP installed capacity worldwide stood at 4.8 GW at the end of 2016. There had been an increasing growth in the annual installed CSP capacity between 2010 and 2015. However, there was a relapse in this annual growth in 2016 (REN21, 2017), but activities in 2017 suggested a possible rebound for the technology (see Figure 1-4c and d).



a.)



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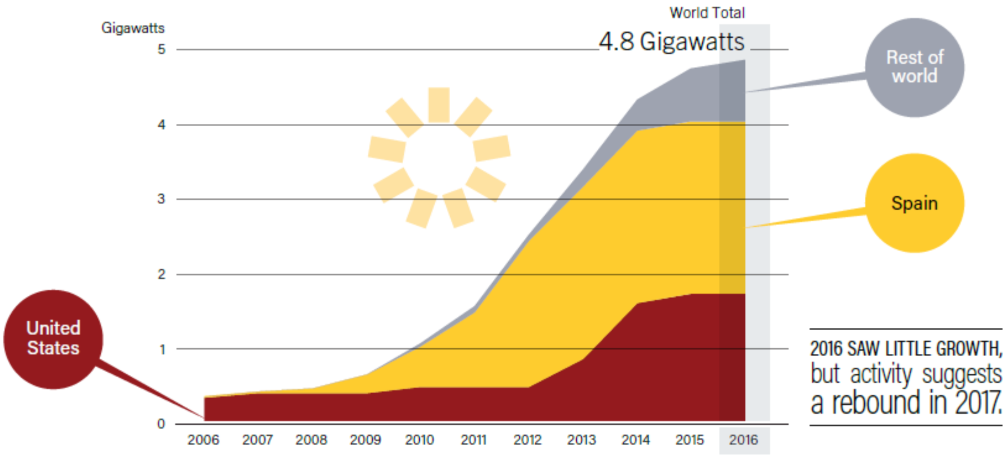

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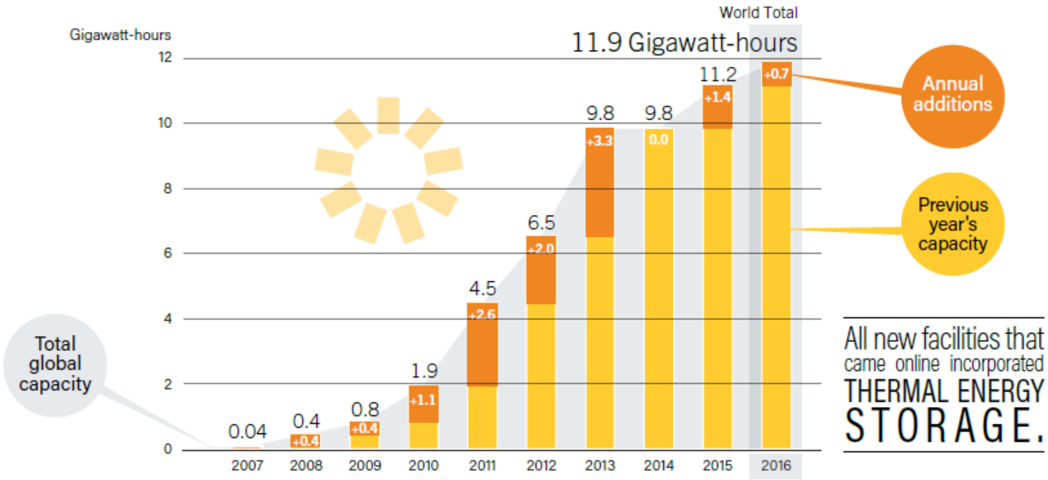


d.)

Figure 1-4: Global solar energy capacity. a.) Solar PV global capacity b.) Top countries with Solar PV Capacity addition in 2016 c.) CSP global capacity d.) Storage global capacity and annual Additions (REN21, 2017)

1.2 Research problem statement

There are many factors that may inhibit the growth of a new technology (Braun *et al.*, 2011). While these factors may work solely, they may also combine forces to result in the failure of an innovation, technology or product, as pointed out by Jacobsson and Johnson (2000). Some major factors identified in this regard are: markets, institutions, and networks. To influence the adoption of a technology, it is important to understand the central issues pertaining to its emergence and deployment. The CSP type of RET, although promising in terms of its potential, has not been widely distributed or adopted as compared to other RETs. Despite its storage ability, and its capability to supply uninterrupted power for 24 hours, electricity from CSP is still more expensive than other counterpart RETs. One of the reasons identified in this study is due to less installed capacity compared to other RETs, and limited adoption and deployment strategies.

This study therefore seeks to identify the key factors and forces that are pertinent to CSP technology deployment, and to present a technology adoption strategy/framework that will incorporate all the identified factors and externalities that affect CSP. The intent is for this framework to be able to analyse and explain the diffusion patterns observed in CSP technology and suggest a promising way forward.

1.3 Research aim

The aim of this research was to perform a technology adoption assessment that will provide a framework and strategy that can be used to accelerate the adoption of CSP technology in South Africa. A verified and validated adoption framework will aid in better understanding the roles of each stakeholder involved in CSP technology. It will identify the economic and innovation drivers and provide policy recommendations that will accelerate the deployment of CSP.

1.4 Research objectives

To achieve its aim to develop a technology adoption strategy that can be used to determine the drivers of economics, customisation, deployment, as well as provide the necessary framework to assist in policy-making of CSP technology, this research needed to:

1. Perform a detailed CSP innovation analysis;
2. Critically review technology adoption approaches and CSP technologies;
3. Identify critical factors affecting CSP adoption in South Africa as well as their impact;
4. Identify the current and future economics of CSP in South Africa; and
5. Develop an adoption framework for CSP in South Africa.

1.5 Motivation

To meet its future energy demand, the government of South Africa set up an Integrated Resource Plan (IRP) with the primary objective of determining its long-term electricity demand, indicating how this demand should be met in terms of generation type and timing. The IRP in 2010 presented the favoured energy generation techniques in South Africa and it allocated 17 800 MW (42 %) of the total energy mix in 2030 to renewable energy technologies (RETs). To achieve this target, the Renewable Energy Independent Power Producer Procurement Programme (REI4P) was launched and wind, solar photovoltaic (PV) and concentrating solar power (CSP) have been favoured mostly in the bids rolled out thus far (Eberhard et al., 2014; Craig *et al*., 2017). South Africa has been identified as one of the world's best destinations for CSP because of the available solar resources, and a total of 600 MW of CSP had been purchased in the REI4P bids.

However, the IRP update of 2016 threw CSP out of the future energy plans when it gave no share to new electricity generation from it until 2030. This has created growing uncertainty of the future of CSP in South Africa. There is therefore an urgent need for collective efforts to present a broad and detailed value proposition in terms of present and future prospects of CSP, and how it can be developed and deployed in the country to foster a lower tariff, encourage adoption and ensure its return to the IRP.

To identify the most effective way to open new methods and ways in which the CSP technologies can be deployed, which will foster further CSP adoption in South Africa. This study was carried out to analyse the unique, critical and complex factors that affect the deployment of CSP in South Africa, as identified by concerned policy-makers, CSP experts, and existing studies.

1.6 Significance of the research and unique contributions

Wind energy and solar PV promoters have developed various adoption analysis/models/frameworks/strategies that use related technical and economic variables to lead a significant global adoption, reduction in cost and improved general public's view of these technologies. Similar analysis, frameworks and strategies for CSP adoption in South Africa have also been developed in this study.

The overall aim of this study was to hasten the adoption of CSP technologies in South Africa, because of the available yearly solar irradiation, which is discussed in Section 3.1 of this study. Mass deployments of CSP will not only provide clean and supporting energy to the grid, it will boost the local manufacturing of CSP components, support job creation and can also create an avenue to export excess electricity and know-how to neighbouring countries.

This study presents a counter-argument to the prejudice, such as water consumption and loss of jobs, on the adoption of CSP technologies. It presents a method of research & development (R&D) funding for CSP by suggesting a healthy portfolio that will aid South Africa to be a global champion. The study presents the effects of various factors on the adoption and cost of CSP technology in South Africa. The study also presents a new approach to determining the future economics of CSP technology despite the limited data. The study presents the labour and trade benefits involved in its local deployments of CSP technology and presents an up to date technology roadmap. This study serves as a framework for the improvement and deployment of CSP technologies, which in the long run is expected to lead a reduction in cost and tariffs of CSP technologies and improve its competitiveness with other RETs. The study also developed a new CSP roadmap framework. The results from this study can also be used as a foundation to set up basic evaluation guidelines when the CSP technology is considered.

From the academic point of view, this study presents a better understanding of the system, quality, benefits, satisfaction, cost and other significant variables that affect CSP adoption. Knowing that only few studies have been conducted to aid CSP adoption, this study will contribute to the limited literature on CSP adoption and deployment strategies.

Shum (2013) stated that a deployment strategy or framework, which enhances existing competences, causes reduced disruption, as well as hastens new learning for stakeholders, has the highest chance of being successful. Thus, the framework developed in this study is complementary and supplementary to the existing RET models/frameworks. However, the study used a technology management approach, coupled with existing theories, to build a unique strategy that will provide reliable solutions to planning, development, distribution and deployment of CSP in South Africa. Also, this study addresses the knowledge gap, which is the absence of a technology adoption assessment for CSP technology; by developing a verified and validated adoption strategy that combined both technical and socio-economic variables to provide a framework that will aid CSP deployment in South Africa.

While Brent and Pretorious (2010), and Brent (2015) provided a general solar energy roadmap for South Africa, this study developed a technology-specific roadmap for CSP in South Africa with suggested implementation plans. This is expected to serve as a decision instrument for policy-makers, consultants and potential CSP adopters.

1.7 Limitations and research

CSP components and facilities often need to be at a large-scale before they can be highly efficient (Schmalensee, 2015). In South Africa and other parts of the world, the plants are few and are often built few units at a time. All the existing CSP facilities are near-unique, as they were developed right on site due to fragility, size and other complexities involved in moving CSP components. This uniqueness and unit constructions made it difficult to get the real cost information and other data needed for existing plants.

Access to CSP site cost and economic data was almost impossible and the few ones accessed were provided under strict non-disclosure agreement. The data analysed in this study were thus verified using credible global reports and validated by expert opinions.

1.8 Research strategy

To fulfil the aim of this research and answer its objectives, the research strategy used is presented in Figure 1-5. The first aspect performed a detail innovation analysis of CSP in South Africa, to understand the state of CSP in South Africa and the past and current efforts/actions that are being carried out to aid its adoption by all institutions. This effort also identified the innovation path that the technology has followed in South Africa. It then presents the accompanying challenges, impacts and the evolving research environment.

The next aspect performed a critical review of the technology adoption techniques in the literature and presents how they have helped other RET technologies break through the adoption chasm. The aim of this activity was to identify the uniqueness and limitations of the most relevant technology adoption methods and how they can inform the development of better and more applicable approaches for CSP adoption studies in South Africa. The gaps in the literature were identified and the best approach to helping CSP cross the adoption chasm was selected.

The last part performs five activities to present a value proposition and make a case for the need for the adoption of CSP technology in South Africa, as well as present the possible deployment path.

A system dynamics analysis was done to identify the most sensitive factors affecting CSP adoption, each of these factors, together with the other common ones found in the literature, were then analysed to understand the fears, challenges and limitations; to present a possible success path in overcoming them. The appropriate qualitative and quantitative approaches were deployed and the results of the analysis were used to create a roadmap for CSP technology in South Africa. The last aspect of the thesis presents detailed policy recommendations and suggestions based on the findings in the study.

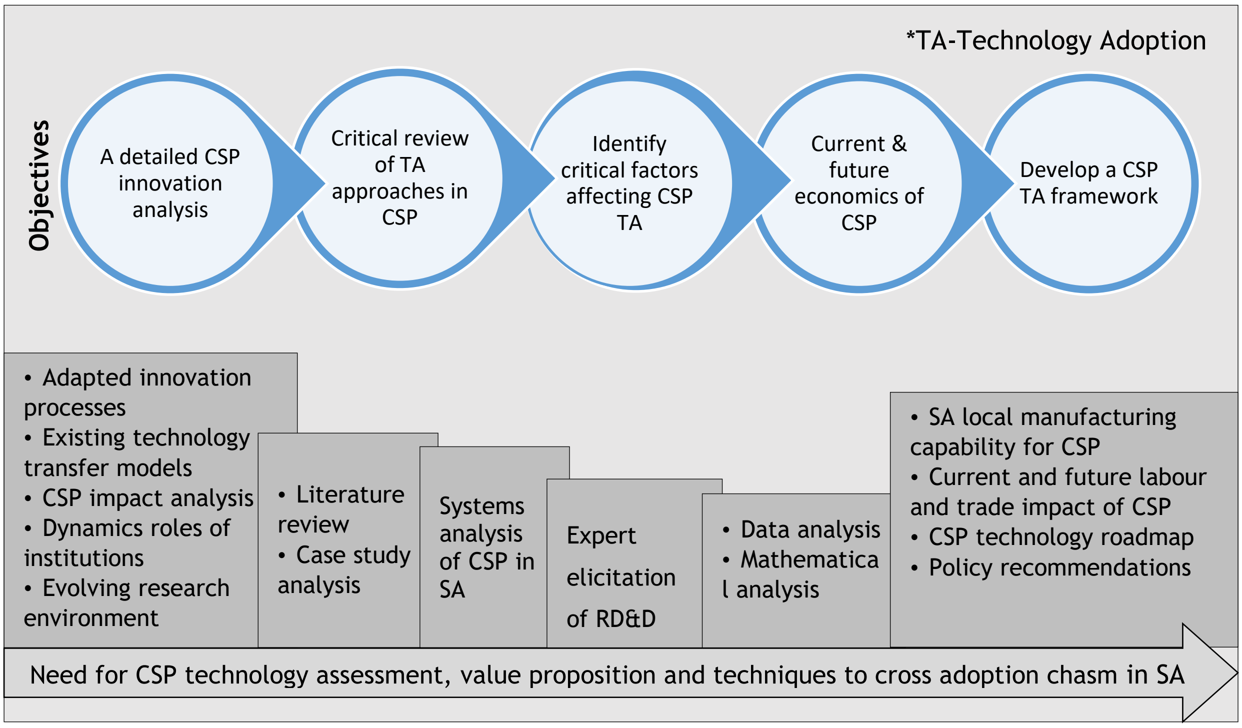
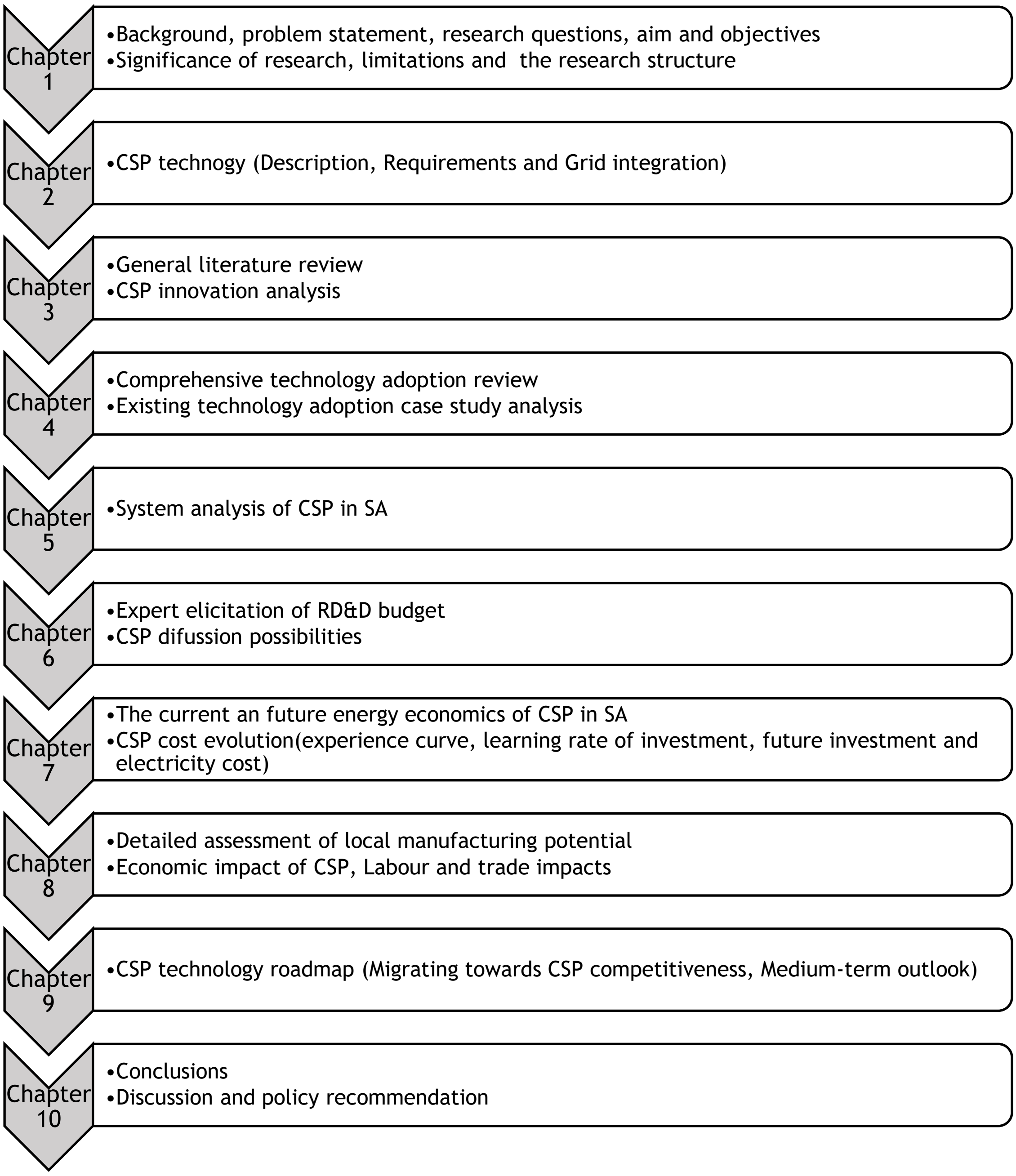


Figure 1-5: An overview of research design

1.9 Thesis layout



2. Concentrating solar power (CSP)

Viebahn *et al.* (2011) describe CSP as a RET with significant potential to meet part of the future energy demand. CSP systems are based on the conventional principles of driving a turbine and generator for electricity generation. The only difference, however, is the way steam is created. Here sunlight is concentrated using reflecting materials (mirrors) on a receiver to generate heat energy, and the heat is then used to create steam (Kalogirou, 2009). For example, in the CSP system configuration in Figure 2-1, the sun is focused on a receiver tube, and the heat generated is used to drive a turbine. The first successfully operated CSP plant was installed in California in the mid-1980s (Kalogirou, 2009), making CSP a young technology (in comparison with other power generation technologies) with many on-going innovations, as well as research and development (R&D) (Stine & Geyer, 2001).

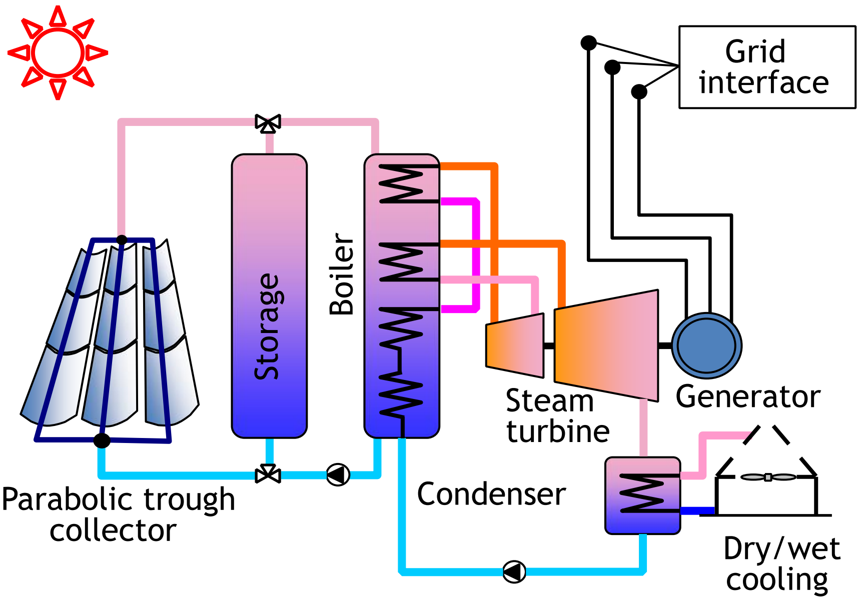


Figure 2-1: Operation cycle of a CSP plant (Bettter World, 2017; Gauche *et al. (2012)*)

In less than 40 years, CSP technology has shown a continuous viability both technically and economically with many promising features. In locations with high solar radiation, CSP offers intense heat and electricity opportunity because of the unlimited nature of its energy source - the sun.

CSP offers one of the best solutions to mitigating climate change, reducing dependence on fossil fuel and greenhouse gas emissions. CSP has a unique advantage over other RETs: it generates high heat energy, thus offering the option of thermal energy storage. This unique characteristic makes it possible for CSP to be flexible about when and how electricity can be supplied from it throughout a day. This value is important to the renewable energy portfolio (DoE, 2015).

Teske *et al* (2016) showed that 200 - 300 kg CO_2 are avoided by using a square meter of solar concentrators. With each CSP plant having hundreds to thousands of concentrators/collectors arranged in arrays or in other innovative styles, the amount of CO_2 emission prevented becomes highly significant. The CSP life cycle assessment shows that the plant pays back the energy used for its construction in less than 5 months after commission. Also, the minimum active lifetime of a plant is 30 years. This is because the first plants, which were constructed in the mid-1980s, are still running today. The components can be made from readily available materials which can be easily recycled and reused.

2.1 CSP technology description

Currently, there are four main types of CSP technology and they can be classified based on their solar radiation focussing techniques. Thus, a CSP system can either be classified as line focussed (Linear Fresnel and parabolic trough) or point focussed (parabolic dish and central receiver systems). The CSP classification as result of focus geometry (line or point), determines the type of collectors, the solar field configuration as well as overall system design.

In the line focus types, the parabolic troughs (see Table 1) use specially cut parabolic reflectors or curved mirrors to concentrate the sun's ray unto a linear receiver tube (covered with evacuator tube for insulation) to heat up the heat transfer fluid. Linear Fresnel (see Table 2) operates on the same line focus principle but uses flat mirrors for concentration. Some of the advantages of line focus technology include its simpler solar tracking techniques and its developed curved mirrors with very high reflective capacities (Gauché, 2016). However, CSP systems using line focus technologies have lower theoretical concentrating ratios as compared to point focus.

In point focus, heliostats (specially built solar tracking mirrors for central receiver technologies) concentrate the sun's rays unto a solar tower receiver (See Table 3), while in the parabolic dish technology, the reflecting dish concentrates the sun's rays onto a receiver placed at its focus (see Table 4).

Over 80 % of the existing CSP plants are parabolic troughs (Xu *et al.*, 2016), parabolic trough technology is referred to as the most matured of all the CSP technology types. However, most of the newly built large single unit CSP plants are central receiver systems and this is because of the promising future of heat to electricity conversion efficiencies of the technology and its ability to attain very high temperature.

Table 1-4 show an overview of the 4 types of CSP technology as adapted from the (Fichtner, 2010; Duffie &Beckman, 2013; Gauché, 2016; Craig *et al* , 2017).

Table 1: Overview of parabolic troughs type of CSP

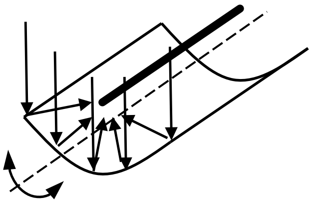
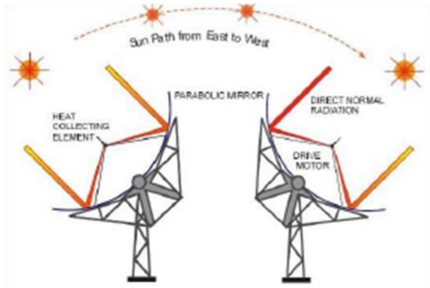
Collector design: 	
Principles/Characteristics	History and status
Tracking: Parabolic trough collectors track the sun on a single axis in North-South direction, and they reflect sunlight to an absorber tube (receiver tube) placed in its focus. Heat transfer fluid (HTF), molten salt or oil is then heated up in the receiver. The heated HTF is then transferred to power block to generate superheated steam by heating up a steam generator. Capacitor factor higher than 50 % can be achieved and the system can be hybridised with HTF heater, gas fired super heaters or back up boilers. Parabolic trough technology can work with conventional gas turbine power plant in an Integrated Solar Combined Cycle (ISCC).	The first parabolic trough collector was patented in Stuttgart in 1907, while the first plant was operated in Egypt in 1911 as a 55-kW pumping station. After the oil crisis in the early 1980, the first commercial plants, SEGS plants were built in California in mid 1980s (a 9-unit plant with unit capacities ranging from 14 MW to 80 MW, and a total combine capacity of 354 MW). The SEGS plants are still operational. There have been continuous innovations and development in troughs and collector design and technology. The first of the modern day parabolic trough plant is the Nevada Solar One, a 64 MW plant in U.S.A. This was followed by an attractive feed-in-tariff in Spain which led to the operation of CSP plants in Spain since 2009. It is the most matured out of all the CSP technology and this feature makes it the most supported in terms of credit facilities (most bankable).

Table 2: Overview of linear Fresnel type of CSP

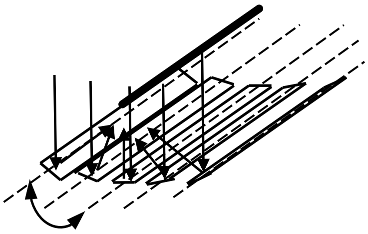
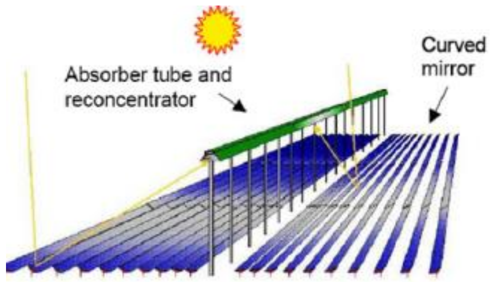
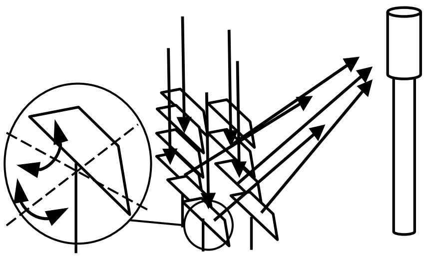
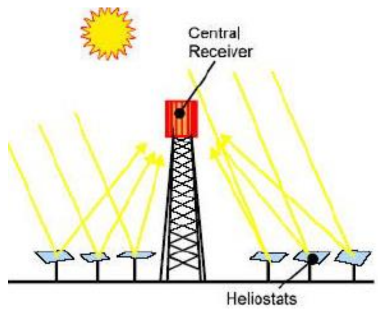
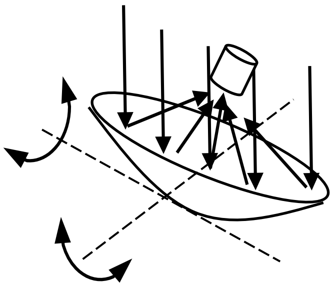
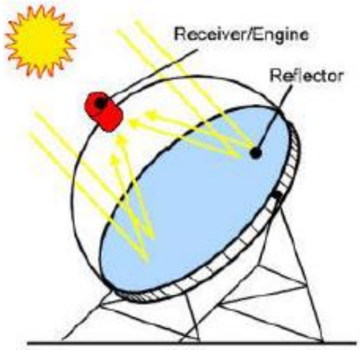
Collector design: 	
Principles/Characteristics	History and status
It has a large group of mirror fields that are fixed close to the ground, while there is a linear fixed receiver at a distance on top of the mirrors, with an option for secondary receivers. It has lower optical efficiency as compared to parabolic troughs but can generate direct superheated steam in the solar field. It is efficient in land usage because of its low specific land requirements, and the closeness of mirrors to the ground also reduces the wind load effects, thus, reduced materials. The concentrators are flat mirrors which are cheap and available; and simple tracking unit can be attached to each mirror facets. The receiver (often single absorber tube with secondary reflectors or multiple steel pipes) is fixed and requires no tracking.	It is a relatively recent technology, but there are few commercial plants and many demonstration projects that have proved the viability of the concept. In 2010 the construction of the first commercial Linear Fresnel plant (PE II) was started in Spain. The plant which has a generation capacity of 30 MW began operation in 2012. There have since been other plants with some having higher generation capacities. The largest single unit Linear Fresnel plant is a 125 MW capacity plant in India. The technology can also serve as an alternative to parabolic trough when there is need for a lower cost option.

Table 3: Overview of central receiver systems type of CSP

Collector design: 	
Principles/Characteristics	History and status
The solar field comprises of heliostats which are used to focus the rays of the sun unto the top of a tower receiver. The heliostats can track the sun in two axes. This point focus system allows a higher concentration rate which results in high operating temperature and thus higher efficiencies. The technology can work with diverse types of HTF, and the most used ones are molten salt, steam/water and atmospheric /pressurized air. It is cost effective, but this is a function of the type of HTF used. The capacity factor is also a function of the HTF and can vary from 25 % to more than 75 %. The molten salt type uses solar salt which is a combination of 60 % Sodium Nitrate ($NaNO_3$) and 40 % Potassium Nitrate (KNO_3). It has a high operating temperature up to 565ºC and has an effective reheat steam cycle. The molten salt can be used as direct storage and can reach a capacity factor higher than 50 %. The water/steam type of central receiver system can generate superheated steam up to 540ºC. It however has a low capacity factor between 25-30 % if there is no	It is also a relatively recent technology, as the first commercial plants began operation in 2007. There had since been many demonstration projects and several commercial plants that have proved the viability of the concept. The maturity varies for several types of this technology ant there are plants with unit generation capacity up to 640 MW.

initial gas firing. There is currently no commercial storage available for the accumulated steam. In the atmospheric air type of central receiver system, ambient air is drawn by a blower using a volumetric receiver and heated to 700ºC, and the heated air serves as the HTF. There is a possibility for thermal energy storage and the technology also allows hybridisation with duct burner. The capacity factors vary from 25-50%. The last type of central receiver plant uses pressurized air as its HTF. Pressurized air at approximately 15 bars is heated up to 1000ºC in a pressurized volumetric receiver (REFOS concept) and the heated air is used to drive a gas turbine. This concept supports co-firing of air with back up fuel to increase the temperature as a hybridized system and the capacity factors depend on the hybridisation techniques. There are few demonstration plants available to prove the viability of this concept.	

Table 4: Overview of Parabolic dish type of CSP

Collector design: 	
Principles/Characteristics	History and status
In technology, a group of mirror faces are combined to form a parabolic dish. The concentrator could also be a specially manufactured and well-cut mirror in form of a parabolic dish. The parabolic dish concentrates the rays of the sun on a receiver mounted at the focus of the dish. The point focus system to generate high temperature and to reach a very high solar to electric efficiencies (> 30 %). There are two types of this technology: the individual parabolic dish units (Stirling or Bryton engines); and the distributed parabolic dishes (where there is a transfer of heat from an array of parabolic dishes to a power block). It requires less water when compared to other types of technology and modular plant designs are possible. State of the art parabolic dish systems use Stirling engines with capacities ranging from 3- 25 kW. It has a low capacity factor of between 25-30 %.	It is a relatively recent technology, but there have been development of many dish generating plants and the test results have proved the viability of the system. Most of the developed plants are based on Stirling engine technology. The first large scale parabolic dish technology plant was a 1.5 MW dish Stirling energy system plant located at Peoria, Arizona in the United State. The plant was however, decommissioned in 2011 and was later bought by CondiSys China in the year 2012.

2.2 Basic requirements for CSP

There are two types of radiation from the sun: the beam/direct rays and the diffuse rays (see Figure 2-2). The types of solar radiation are important to solar energy processes because it is the reflection or absorption of these radiations that produces the needed heat or electricity. Understanding the direct and diffuse solar radiation resources available in a location makes it possible to identify the best kind of solar project that can be sited there and the amount of solar resource that will be available.

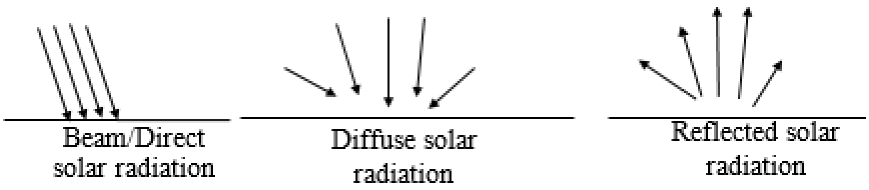


Figure 2-2: Solar energy fluxes/radiation

To achieve effective solar energy conversion, the two solar radiations are measured as Global Horizontal Irradiance (GHI) and Direct Normal Irradiation (DNI) on ground level in watt per unit area per unit time (Duffie and Beckman, 2013). GHI represent the total amount of shortwave radiation that a horizontal surface receives from the sun. GHI includes both the direct and the diffuse irradiation and it is of interest in Solar PV technology. The CSP technologies however, requires the direct radiation of the sun, DNI, to function.

DNI in CSP technologies refers to the rays of the sun that were not deviated either by clouds, dust or fumes and which reaches the earth surface in parallel beams. Teske *et al.* (2016) suggested that locations with at least DNI of 2 000 kWh are suitable sites for CSP while the locations with DNI of 2 800 kWh are the best sites for the technology. Teske *et al.* further stated that in locations with such high DNI, a square kilometre of land can generate between 100 to 130 GWh of electricity in one year with the use of CSP technology and this amount of DNI.

Figure 2-3 shows the global average DNI resources over the years. Some of the best locations include North and South Africa, Western part of the United States, Australia and the Middle East.

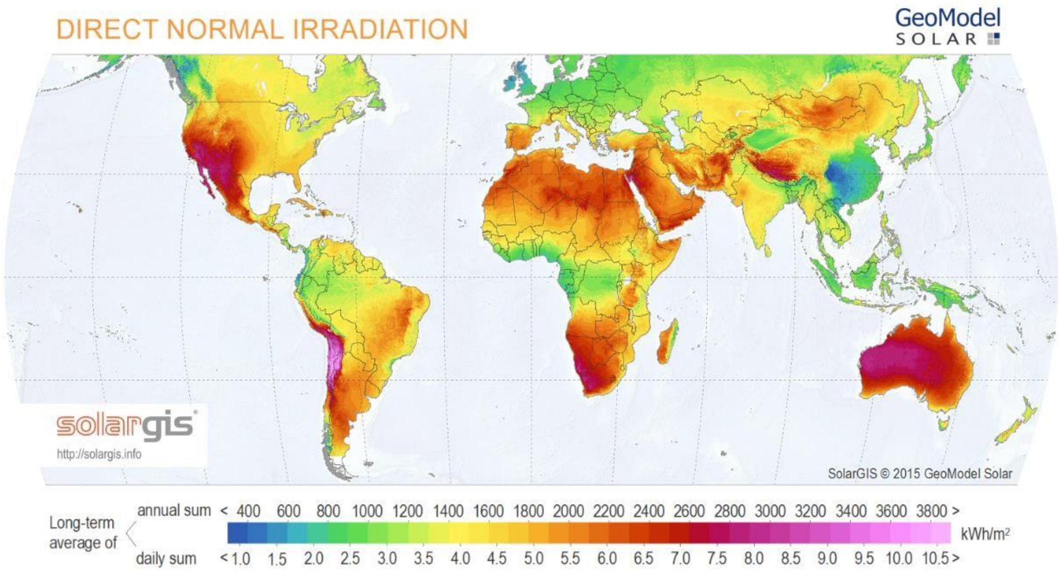


Figure 2-3: World map of DNI (SolarGIS © 2015 GeoModel Solar)

2.3 Dispatchability and CSP grid integration

Dispatchability is a characteristic of a power generation technology to be able to provide electricity on demand. All non-thermal RETs are not dispatchable, and therefore often require backup systems (such as gas turbines) to make up for their shortfall (EPRI-Tech DATA, EPRI, 2010). CSP electricity, on the other hand, is stable and dispatchable, thereby reducing the complexities involved in grid integration such as intermittency, ramping burdens, fluctuating power output etc. All the types of CSP technology can save heat for at least a brief period and thereby have the capacity to overcome short-time variation or solar intermittencies and can work without the need for any backup. These characteristics (thermal energy storage and dispatchability) make electricity from CSP able to meet base or peak demands and creates an opportunity for 24-hour energy supply.

Conversely, CSP sites are sometimes in places far from where the electricity they generate is needed, thus requiring grid supporting infrastructures and increasing the cost of investment. Grid constrains have been identified by several authors as a critical issue that needs to be considered before developing any CSP project in a location (Black & Veatch, 2012). Schmalensee (2015) suggested that it may be necessary to compromise best DNI site location to lower ones for grid location.

2.4 Global trend of CSP

For projects commissioned in the last decade, electricity costs from RET have continued to fall and according to the 2018 International Renewable Energy Agency (IRENA) report on power generation cost. Reductions in total cost of installations are driving the fall in Levelised Cost of Electricity (LCOE) and tariff for solar and wind power technologies to varying extents. This has been most notable for solar PV, CSP and onshore wind. Three major factors have been found to be the key cost reduction drivers, and these are: technology improvements; competitive procurement; and a large base of experienced, internationally active project developers (IRENA, 2018).

Despite the newness of CSP in terms of its global deployment, the technology has experienced a significant decrease between 2010 and 2017, with a global weighted average LCOE of USD 0.22/kWh for the plants commissioned in 2017. However, the recent auctions over the last 2 years suggests the possibility of this cost falling to USD 0.06/ kWh for CSP (see Figure 2-4)

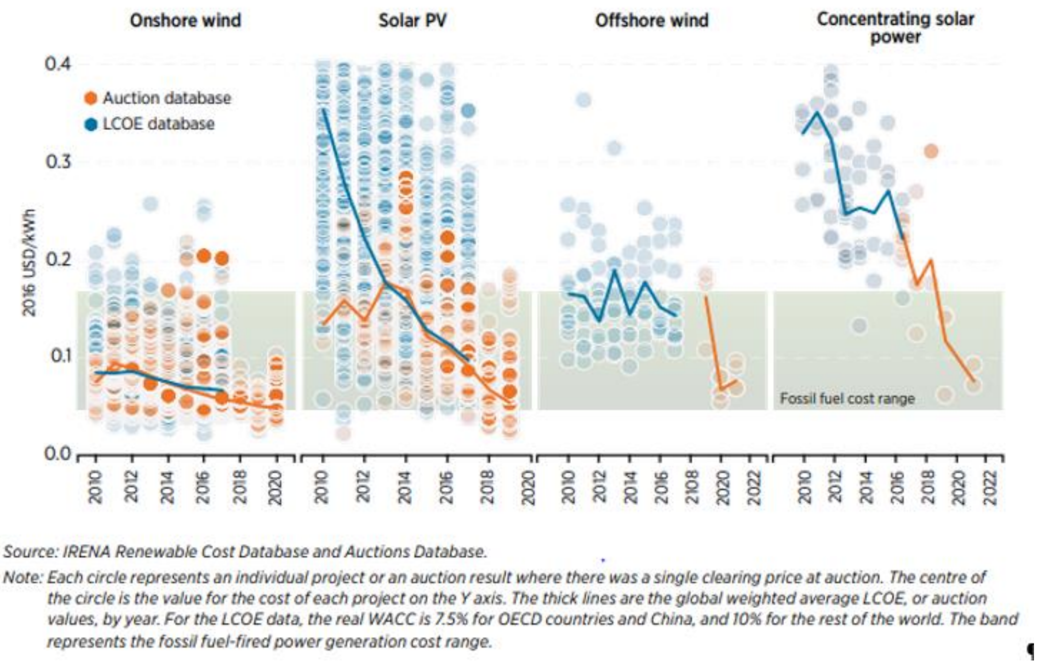


Figure 2-4: The levelised cost of electricity for projects and global weighted average values for CSP, solar PV, onshore and offshore wind, 2010-2022 (IRENA, 2018)

Between the years 2009 and 2011, the LCOE of projects varied from around USD 0.30 to USD 0.47/kWh because of several existing support policies which provided little incentive to drive down costs, although the installation costs remaining high. Since 2012, these have been falling, as deployment has shifted away from the traditional markets of Spain and the United States. Greater competitive pressures have reduced installed costs, with projects also benefitting from higher solar resources in new markets like Chile, Morocco and the United Arab Emirates. LCOEs ranged between USD 0.16 and USD 0.29/kWh in 2016-2017.

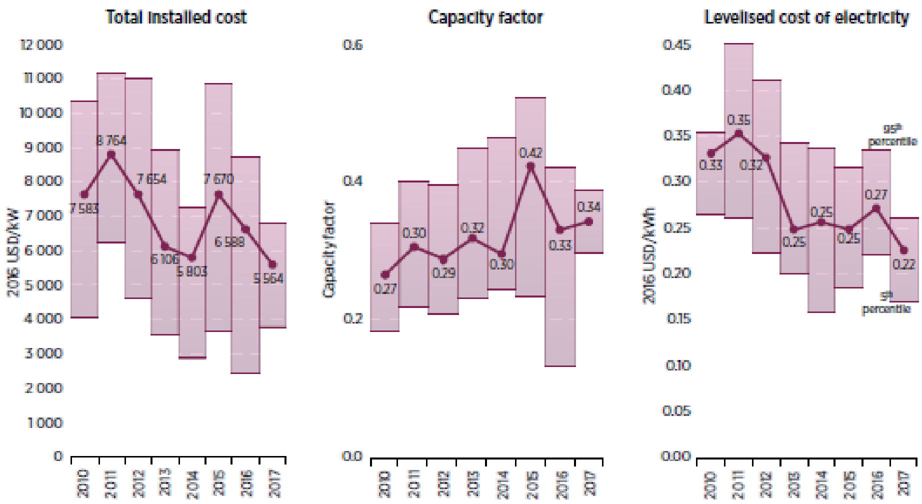


Figure 2-5: Global weighted average total installed costs, capacity factors and LCOE for CSP, 2010-2017 (IRENA, 2018)

Figure 2-5 shows the trend of the total installed cost, capacity factor and the LCOE for CSP globally. CSP had cumulative installed capacity at the end of 2016 of around 5 GW and have higher costs than the other more mature technologies. Costs are falling, however, and between 2010 and 2017 the cost of electricity of newly commissioned CSP projects fell by 33% to USD 0.22/kWh. The years 2016 and 2017 saw a breakthrough for CSP technologies, with auction results for projects to be commissioned from around 2020 onwards anticipated to have significantly lower LCOEs than in 2017.

Chapter conclusions

This chapter introduced the challenges faced by new innovations in terms of their acceptance or adoption. Furthermore, it showed that RETs especially CSP is a relatively new technology with the first plants only getting to be 30 years old when compared to several other technologies that have been around for centuries. The chapter established that there are several factors that inhibit the growth of new technology and thus presented a need to identify which factors are most important, or those that are specific to the adoption of the technology in an environment. It was also presented in this chapter that technological breakthrough is not the only exclusive factor that affects the adoption of any technology. As such, market readiness, institutional willingness, cost dynamics and related network strongly determine if a technology will cross the VoD or not.

The global trend of CSP in the world was presented, the urgent need for a support instrument for policy making for CSP adoption have been identified and the basic challenges limiting the competitiveness of the technology presented. Also, the opportunity that CSP offers to achieve global sustainable development goals and its potentials to function competitively in South Africa had been identified. To help CSP cross the VoD in TAL, a research strategy was developed to determine the drivers of economics, customisation, deployment, as well as provide the necessary framework to assist in policy-making of CSP technology.

The objectives that needed to be fulfilled to achieve this aim were clearly stated in Section 1.4. To fully understand the scope of CSP, its basic principles, requirements and applications, the next chapter presents an overview of the technology and its various types. This will build the foundation for the direction that this study will take in terms literature review and methodology approach, to achieve its aim and objectives.

3. General literature review [2]

South Africa aims to generate 42 per cent of its electricity from RET sources by 2030, and CSP is one of the major renewable energy technologies that were prioritised, given the abundant solar resources available in the region. Seven CSP plants have been, or are being, built; three of them are already connected to the national grid. In this chapter, the impacts of CSP technology on South African market, research, development and innovation to date have been investigated.

An innovation analysis of CSP technologies in South Africa is performed, in terms of the existing technology adoption models and diffusion strategies, used by government and its agencies, to improve the development and deployment of these technologies. This chapter starts by showing the state of CSP compared with other RETs in South Africa. It then discusses the impacts and challenges of CSP, along with its innovation analysis.

Furthermore, it highlights the efforts of the South African government to accelerate the deployment of CSP and discusses the evolving research environment by identifying the gap in CSP adoption in South Africa. The conclusion section presents a summary and the necessary recommendations for research approach.

3.1 Introduction

It has been established earlier (in the motivation) in this study that South Africa intends to achieve 17,800 MW of renewable energy by the year 2030. So, the South African Department of Energy (DoE) has prioritised some RETs in its Renewable Energy Independent Power Producer Procurement Programme (REI4P). These RETs include CSP, solar photovoltaic (PV), biomass, and onshore wind technologies (DoE, 2015). The reason for the inclusion of CSP technologies, which is a new and developing technology, is that South Africa receives an annual average direct normal irradiation (DNI) of 2,816 kWh/m^2 in the Northern Cape region (as shown in Figure 3-1). This amount is far higher than the DNI available in either Spain or the United States of America, where the best locations for CSP technologies only receive an

[2] This chapter is an expansion of an already published article titled: Concentrated solar power (CSP) innovation analysis in South Africa. Published in the South African Journal of Industrial Engineering. DOI: 10.7166/28-2-1640

annual average of approximately 2,100 and 2,700 kWh/m^2 respectively (Fluri, 2009), and both nations have CSP plants operating at full capacity.

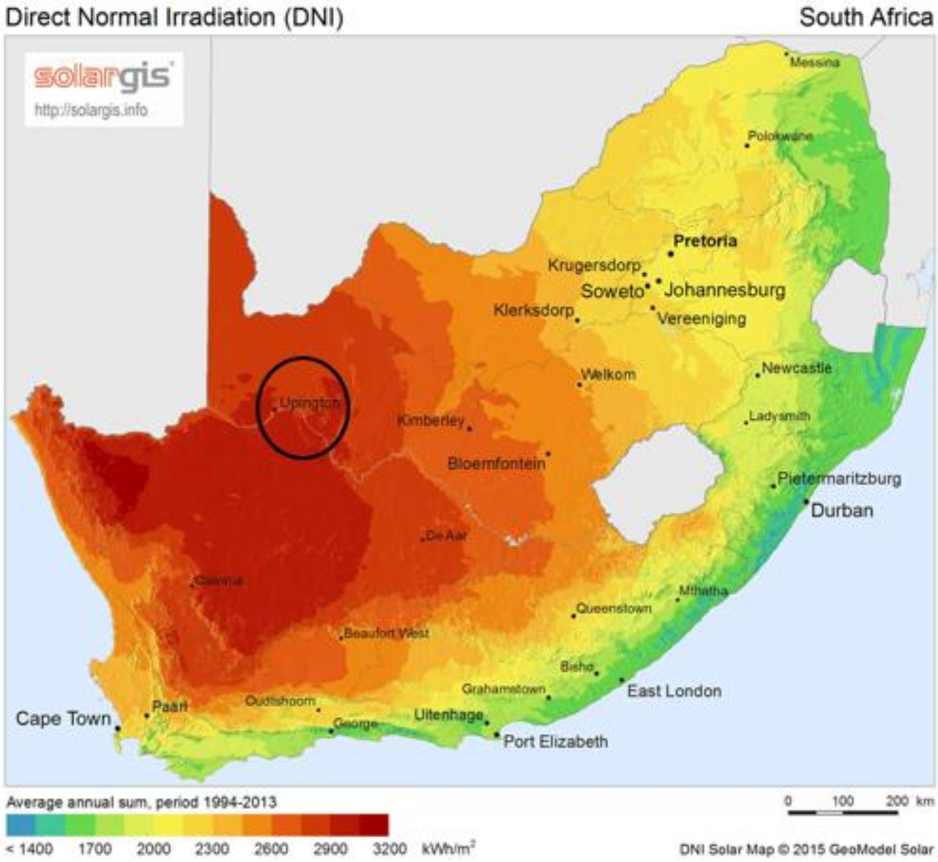


Figure 3-1: Average daily direct normal irradiation (DNI) for South Africa (Solar-GIS, 2015)

RETs, when connected to existing systems or grids, often have effects on the overall system, because these technologies have characteristics that are radically different from conventional generating systems with respect to intermittency (Tsoutsos &Stamboulis, 2005). Shum & Watanabe (2007) subsequently suggested that, as long as RETs seek either to complement or to challenge the existing technology status quo, they will have to compete with the existing complementary assets and infrastructures that accompany the established technologies.

This chapter presents an aspect of the literature review where an innovation analysis on CSP technology in South Africa was performed by examining the existing operations, establishing the impacts of this innovation on local research and development (R&D), and identifying possible improvement methods, thus answered the following research questions:

- What is the current state of CSP in South Africa?

- What are the impacts of CSP technology in South Africa with respect to research, development, and innovation?
- What role have the government and government agencies played in the development of CSP in South Africa?
- What is the way forward?

3.2 State of renewable energy in South Africa

In order to achieve its renewable energy target, the South Africa Department of Energy (DoE) has already rolled out bids in four successive windows for RET generation, through the REI4P (DoE, 2015). Solar PV, CSP, and wind RETs have dominated these bids, compared with other RETs (landfill gas, biogas, and biomass), as shown in Figure 3-2.

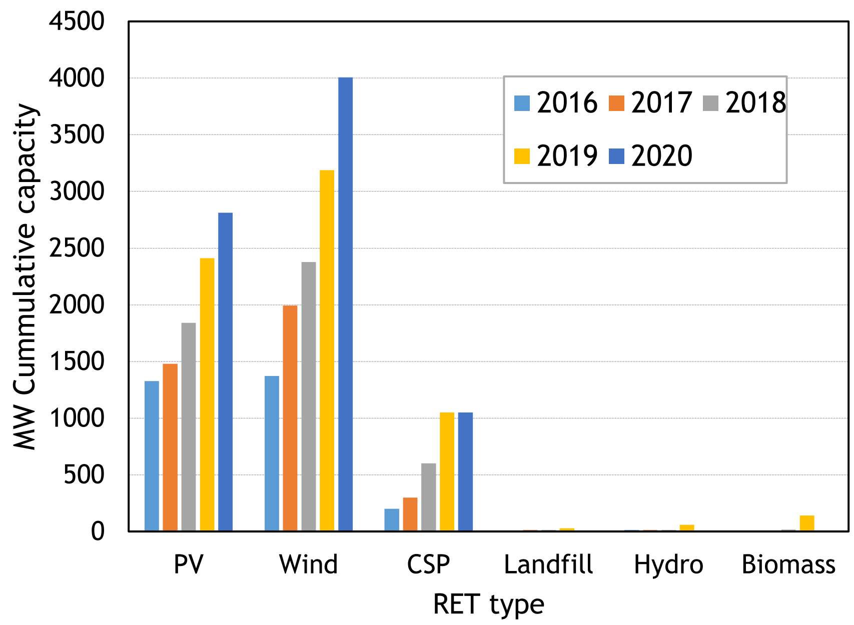
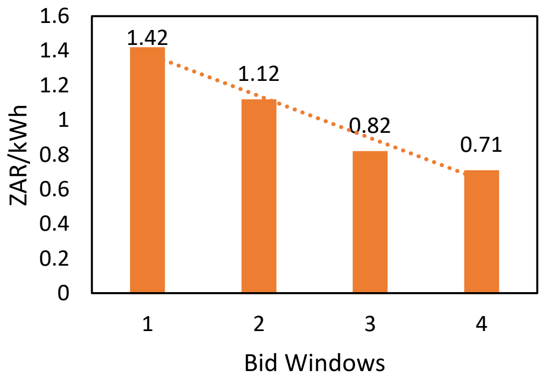


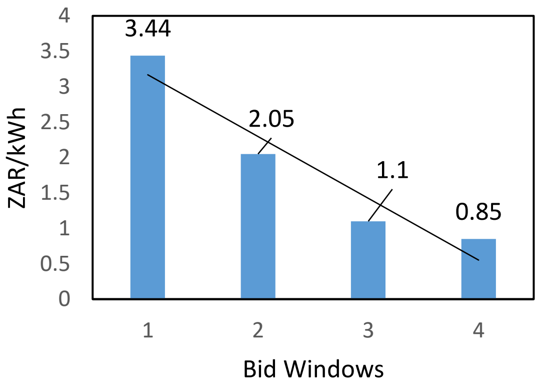
Figure 3-2: MW Cumulative RET mix in South Africa (excluding hydro) (DoE. 2016)

Out of the three dominating RETs, solar PV and wind contribute the most to the national grid, while CSP lags. Ibenholt (2002) identified that wind energy has established itself as a matured and global RET, and this has decreased the cost of that technology over the years. As at June 2015, a total of 790 MW of electricity in the South Africa power grid was supplied by wind energy (DoE, 2015). Figure 3-2 shows that 53 per cent of the procured RETs in South Africa's REI4P bids was for wind energy. The relatively low price of this RET has given it a competitive edge over other RETs, with an average tariff of 0.71 ZAR/kWh shows that the tariff has fallen by half since the first bid, as shown in Figure 3-3a.

In addition, by mid-2015, over 960 MW of electricity in the South Africa's power grid had been supplied by PV; thus, PV supplies more than one third (approximately 35 per cent) of the total energy generated from renewable energy sources in South Africa. Also, a total capacity of 2,290 MW of solar PV has been allocated in all the bid windows. This can be traced to the fact that PV experienced radical cost reductions and technical advancements over the previous decade, according to Feldman *et al.* (2012). In South Africa, the bid tariff for PV decreased more than three-quarters (75 percent) from the first to the fourth bid window, and it went as low as 0.82 ZAR/kWh, as shown in Figure 3-3b.



(a)



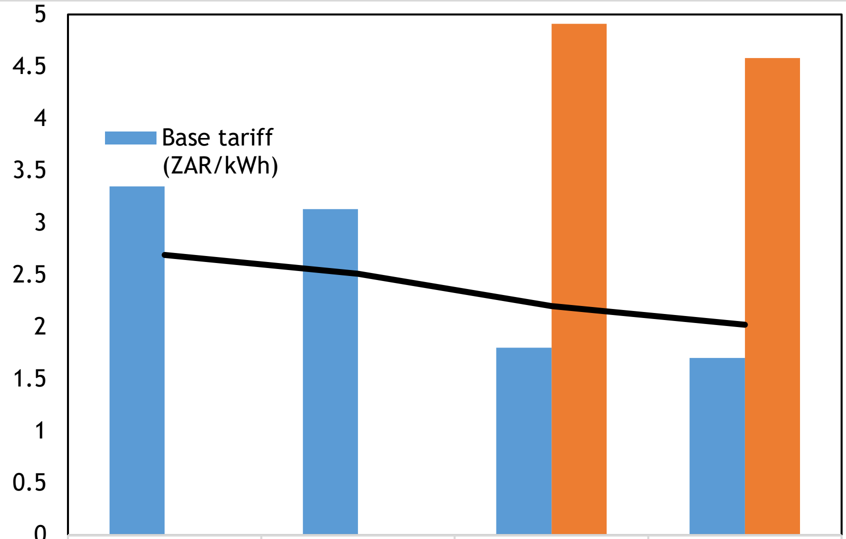
(b)

Figure 3-3: Average bid price: (a) wind energy, (b) solar PV (DoE, 2015)

3.3 CSP technology in South Africa

To encourage the competitiveness of CSP in the REI4P, the national DoE introduced a special two-tier tariff plan during bid windows 3 and 3.5. The two-tier tariff divided the initial single tariff plan into a base rate and a peak hour rate. The cost of electricity increases by around 270 percent of the base rate during peak hours (CSP Today Markets Reports -South Africa, 2015). This decision produced a positive result, as the single base rate during the first and second bid windows reduced by about six per cent, and later reduced by up to seven per cent from bid windows 3 and 4, as shown in Figure 3-4.

The bid window 3.5 was exclusive to CSP to encourage the two-tier tariff. At the end of bid window 3.5, only 50 per cent of the rolled-out bids of CSP had been procured, while wind energy procurement had exceeded its forecast. Solar PV is only 500 MW short of the DoE RET vision 2020.



	BW1	BW2	BW3	BW4
Base tariff (ZAR/kWh)	3.35	3.13	1.8	1.7
Peak tariff (ZAR/kWh)			4.91	4.58
Weighted average (ZAR/kWh)	2.69	2.51	2.2	2.02

Figure 3-4: Average bid price for CSP for bid windows (DoE, 2015; Energy.gov, 2016)

From the four sets of bid windows rolled out in the REI4P, the total existing CSP plants in South Africa 600 MW, which are either connected to the grid or in development phase (DoE, 2015). The locations of the plants are shown in Appendix B. The Khi, KaXU, Bokpoort and Xina plants are connected to the national grid. Kathu, and Ilangalethu 1 are under construction, and the Redstone plant is under development. The payback or tariff periods are also shown in Appendix B.

3.4 Adapted innovation process for CSP in South Africa

Innovations can be viewed with an integrated flow chart developed by Shum & Watanabe (2007), as shown in Figure 3-5. They considered a system/technology as an end-to-end process, rather than focusing on individual parts. This makes it easy to identify both the weakest and the strongest links in a technology under review. The first stage is idea generation, which begins in-house and grows until good partnerships are formed with other firms.

The second stage is the conversion of these ideas into the desired result. The initial innovation gap is crossed here, and the building and the development, as well as improvement, are done at this stage. The final stage is termed the 'diffusion' stage, in which the technology spreads across different organisations. Here, innovation is adopted by other existing systems, and diffuses into the norm, either by using the existing facilities or by developing a new one (Shum & Watanabe, 2007).

Analysing the innovation process adopted by companies that won CSP bids in South Africa and that used this end-to-end process of integrated flow innovation charts shows that CSP technology in South Africa is at the diffusion stage (see Figure 3-5), because the technologies used by these companies were developed (piloted) in their home countries; only the commercial scale of the technologies are built in South Africa.

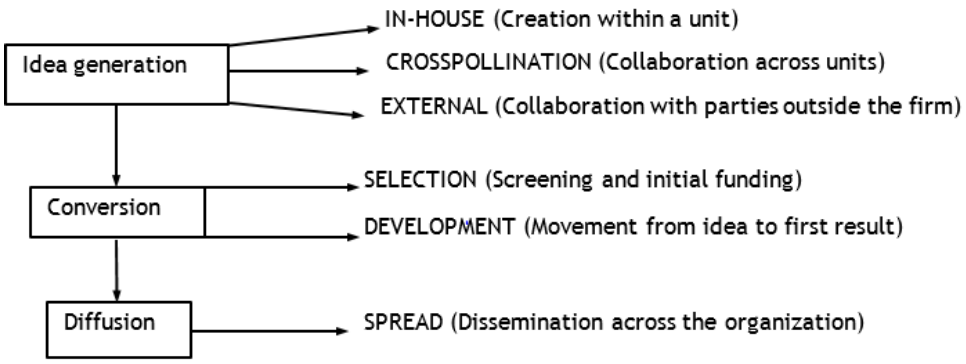


Figure 3-5: Innovation in a value chain

Abengoa, for example, owns three of the CSP plants; KaXU, Khi and Xina are already connected to the national grid, and the company provides the services and maintenance needed for the continuous running of the plants. The company claims to be making efforts to improve on each new plant in order to satisfy the consumers, who are the end-users of the electricity (Abengoa Solar, 2014). Due to continuous improvements through R&D, a systematic R&D type of innovation process is believed to have been adopted by pioneers of CSP technologies in South Africa.

3.5 Existing technology transfer models

Technology transfer can simply be defined as, a way of applying a known technology to new or novel product (Cetindamar *et al.*, 2010). Alternatively, technology transfer processes, is often hard to define despite the existing bulk of literature available - as different authors viewed it as different things because it differs from one sector to another.

While technology transfer is a popular policy in the first world countries, it is still an ongoing policy issue addressed by developing countries (that need it most) who import most of their technologies. Technology transfer was believed to follow a straight-line pattern till around twenty years ago and a linear model was often used to analyse these stages of technical change. Hudson & Khazragui (2013) described technology push version of the original linear model in the 1990s as shown in Figure 3-6:

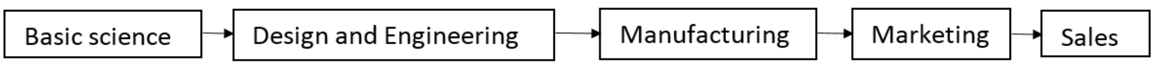


Figure 3-6: Linear model of technology transfer (Hudson and Khazragui, 2013)

The model described above had university research teams as a fundamental basis on which technology development was found. The model can be described to start with a known technology (basic science) and through some transmutation processes either new or existing (design and engineering, manufacturing and marketing) result in a new and novel product. This model was then viewed as the standard innovation process.

Tödtling & Trippl (2005) presented a new definition of innovation process as being characterised by systemic and interactive actions. Thus, Hudson & Khazragui (2013) suggested that innovation should be viewed as an evolving, non-linear and interactive process that requires high degree of communication and partnership among the stakeholders which include universities, funding organisations as well as government agencies.

A type of model that shows the interaction among these stake holders was developed by Etzkowitz & Leydesdorff (2000). They adapted the national systems and 'mode 2' model to develop a new updated model which they named the triple helix model in which the interaction between the university-industry-government relationship was shown. Another type of innovation model was developed by Nauwelaers & Wintjes (2003), as a new paradigm for innovation policy. This was reported by Hudson & Khazragui (2013) to be a more system-centred approach type of innovation model.

This shift in model development does not necessarily undermine the importance of basic research and technological innovations. However, it stresses the need for more inclusion and interrelation among all the aspects of innovation which include the organisations, finance, skills and commercialisation.

Funding has been a major constraint for the deployment of all types of renewable energy, innovation in CSP technology has often been halted by this constraint because there is a type of chasm that occurs in the form of a gap between the design and engineering stage of the linear model shown above. This gap prevents the relevant decision makers to adopt basic CSP research and develop them into industrial use.

Some of the major challenges faced by CSP that reduces its adoption chance is its costs and scalability as compared to the rapid cost cut experienced by Solar PV and PV's ability to supply energy cheaply in simple units as compared to CSP that is more efficient on large scale. Bosetti *et al.* (2012) identified that solar energy is indeed the energy solution of the future.

Other non-technical barriers that also affect the diffusion of CSP technologies are unfavourable power pricing rules and *ad hoc* policy interventions, an example of which is feed-in tariffs (Bosetti *et al.*, 2012). Despite the readiness of some developing countries (South Africa for example) to fund renewable energy technologies, there is a significant reluctance in their interest to fund the technologies that have not been proven over the years in their countries despite this technology having been used in major International Energy Agency (IEA) countries. CSP is an example.

Numerous other studies are available in the literature that address innovations, technology transfer, and diffusion. Amesse & Cohendet (2001) and Bozeman (2000) provide a general discussion on diffusion and deployment of technologies. The roles of different stakeholders and intermediaries in facilitating the processes of technology transfer and deployment are also presented by Lane (1999).

In summary, all the above challenges make it difficult to maximise the advancement in CSP technology as well as diffusion of the technologies developed especially by small research groups and their sister spin-off companies and thus preventing the innovations from crossing the technology adoption gaps.

3.6 Context and challenges of CSP technology in South Africa

3.6.1 Technological context

Most of the technological developments carried out by the foreign companies that won the CSP bids in South Africa were achieved through their own subsidiaries, which are also foreign companies. The demand for local CSP expertise motivated the appearance of some local companies. An example is Ilangalethu Solar Power Pty (Ltd), which is building a CSP plant, Ilangalethu 1, under the supervision of another local company, Emvelo. Other CSP technology needs are now being developed in South Africa.

In addition, GeoSun, a spin-off company from the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University, is involved in solar resource mapping and instrumentation for CSP plants under construction and during operations. Helio100 is another local setup; it is a 100 kW CSP research facility of the Solar Thermal Energy Research Group (STERG) at Stellenbosch University, which has been able to manufacture heliostats from locally made materials. The heliostats were built as intelligent, self-calibrating, modular-design systems.

Also, ACWA Power claims that during the construction of the recently commissioned Bookport CSP plant, materials and components worth well over ZAR 2 billion were purchased from local companies, which shows the increase in development of the CSP market in South Africa (ACWA Power, 2016a).

The development of CSP in South Africa has attracted global interest. South Africa hosted Solar Paces 2015, the most referred-to academic and industrial conference on CSP technologies in the world. The conference brought together world leaders (in both industry and academia) in CSP technologies and the local companies were able to meet global leaders in their respective sectors.

3.6.2 Socio-economic context

When all the CSP plants in South Africa become operational, combined they will eliminate annual carbon emission more than 1.3 million tonnes. It is estimated that 563,000 households in South Africa will have access to a clean energy supply. The existing CSP plants, together with the new ones to be built, will contribute immensely to the DoE vision for the year 2030, which is the desire to generate 17,800 MW of the total South Africa electricity from renewable energy sources (DoE, 2015). Around 10,000 jobs, from construction through to the operations of the plants, will be created, both temporary and permanent.

In addition, Abengoa Solar and ACWA Power have started development activities, including youth empowerment through small and medium-scale entrepreneurship support, in the local communities that are hosts to their CSP plants. Also, the presence of CSP plants has opened these communities to industrialisation, new markets, and new business opportunities (Abengoa Solar, 2014; ACWA Power, 2016a).

CSP systems attain very high temperatures during operations and require water for cooling, especially when the system is not dry-cooled (Harris & Lenz, 1985). The largest portion of water used at a CSP plant is steam cycle cooling (in the case of wet-cooling) (US Department of Energy, 2009). This however, is not specific to CSP technology, as it is a major concern when it comes to water usage at any thermal power plant including coal plants. The reason being the condensing and cooling of the steam exiting the low-pressure turbine is critical to plant efficiency and operation (US Department of Energy, 2009). There are two major methods used for cooling at CSP plants: recirculating (evaporative) wet-cooling and dry-cooling. (see (Duvenhage, Brent and Stafford, 2019).

Based on Meldrum et al. (2013) and Macknick et al. (2014) estimates, the lifecycle water consumption for a parabolic trough plant is approximately 4.5 m^3/MWh which makes CSP the highest water consuming RET technology (See Figure 3-7). Most of the CSP plants are in the Northern Cape Province, where there is a shortage of water. Consequently, the water requirements and consumption of CSP can create more drought pressures in the region. This impact was considered in the subsequent REI4P and dry cooling was stated as one of the selecting criteria for bid winner selection. Nonetheless, CSP plants require water for cooling and thus, if not properly managed, could affect the available water in the host communities. Khi, for example, uses an air-cooled technology to reduce water usage by two-thirds.

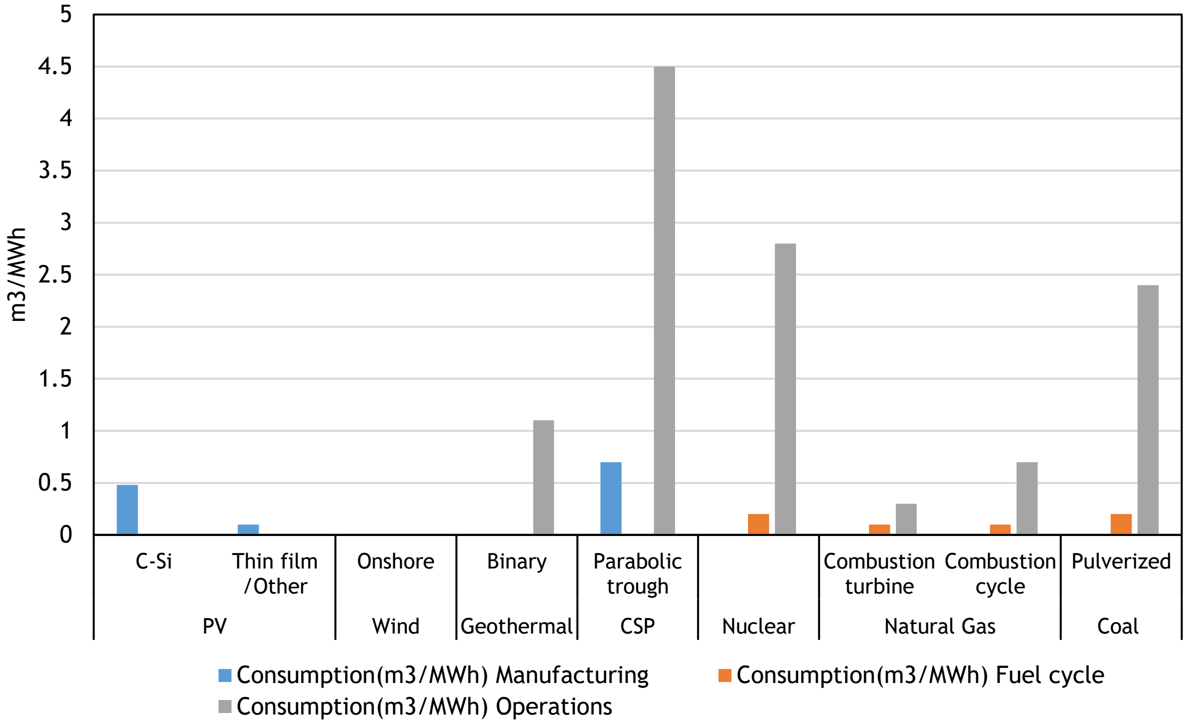


Figure 3-7. Life cycle water consumption values (m3/MWh) or RETs. Adapted from Meldrum et al. (2013) and Macknick et al. (2014)

3.7 CSP challenges

The challenges faced by CSP technologies based on innovation analysis can be summed up as having three aspects: cost and funding, market and political will and technology. Using the example of KaXU Solar One, which is connected to the grid, the following challenges are identified:

3.7.1 Cost and funding

There is wide gap between the design stage and the manufacturing stage of RETs, as identified by Tsoutsos & Stamboulis (2005). One of the causes of this gap is the expensive nature of RETs. In addition, while there are several funds available for RETs, the bankability of the offtakers and currency risks have become been a major constraint on the deployment of all types of RETs. The quality of manufactured systems is sometimes compromised by the low availability of funds, or by expensive raw materials, hence making it less attractive, and often having only limited applications (Tödtling & Trippl, 2005). This makes the relevant decision-makers less interested in adopting basic renewable energy research outputs, and thus limits its diffusion into industries. The overall adoption of RETs innovations has been slow, mainly because of these constraints.

Private financial institutions rarely support developing technologies. They have not been tested over time because they are often capital-intensive, and investment is a considerable risk. This makes accessing clean technology loans from the World Bank difficult for local companies, because of their lack of experience in CSP technology and the risk associated with the investment.

KaXU Solar One had a capital investment of about USD 860 million, and Khi Solar One was estimated at USD 445 million (Abengoa CSP SA, 2010). To cover these estimated costs, Abengoa Solar, the Industrial Development Corporation (IDC), and the local South Africa Community Trust Fund formed a consortium, in which Abengoa Solar (a foreign company with much experience) held most of the shares. This consortium was able to leverage loans of USD 160 million and USD 30 million from the World Bank's International Finance Corporation (IFC) for the KaXU and Khi plants respectively (CSP-World, 2012). This amount was around 12 per cent of the total capital investment, which meant that the consortium had to raise the remaining funding through other means.

3.7.2 Market and political will

Electricity is the same, regardless of how it is generated. However, the cost of electricity per kWh differs according to the various methods of generation. The average current price of electricity from Eskom, South Africa's utility company, is ZAR 1.2/kWh. That equates to about USD 8 c/kWh (Eskom, 2014), while the cost of electricity generated by KaXU is ZAR 2.69/kWh or USD 22 c/kWh (CSP Today Markets Reports -South Africa, 2015). This shows that, even though the energy generated is clean, the price is high. This is a major challenge, as the technology may not be successful if the government is not committed to the advancement of CSP as they can resolve to sticking with other RETs with cheaper cost of generation.

As discussed above, the DoE, through the REI4P, introduced a two-tier tariff plan – base and peak periods – in bid windows 3 and beyond. Bid window 3.5 was won by a consortium formed by Solar Reserve (a United States-based company) and ACWA Power (a Saudi Arabian company) to build the Redstone plant. This project is currently under development and will use the two-tier tariff plan. The electricity cost will be USD 14 c/kWh (ZAR 1.65/kWh) for the base price, rising by up to 270 per cent in peak periods. In this plant, however, no electricity is produced between 10:30 pm and 5:00 am (CSP Today Markets Reports -South Africa, 2015).

3.7.3 Technological challenges

The CSP technologies are high-tech innovations and need various levels of technology transfer for a company to begin production. In South Africa, the existing CSP plants were largely built by foreign companies, most of which are experienced in the sector and have running plants around the globe. For example, the tower system of Abengoa's Khi Solar One is an evolution of their previous tower plants in Spain. Khi's tower system uses superheated steam receiver instead of the previous saturated and dry cooling with an updraft cooling ventilation which were used in PS10 and PS20 plants in Spain. This proves the continuous improvement in Abengoa's R&D in Spain, because the technology was developed there and only built om commercial scale in South Africa. Despite the ongoing research in the National System of Innovation, very few local industries are involved in CSP technology in South Africa.

CSP technologies have storage capability, which is a unique feature that can help its adoption. This storage ranges from few hours to several hours depending on design (see Appendix B). On 26 April 2016, it was reported that Bokpoort CSP plant recorded six days of 24 hours full-load operation, a new African record for the continuous, round the clock supply of electricity from CSP (ACWA Power Media Reports, 2016). The record proves the viability of CSP to produce uninterrupted electricity round the year. However increasing the storage capacities of CSP plants increase the CAPEX and thus electricity tariff price per kWh (Faiers & Neame, 2006). There is a need, therefore, for more research into storage techniques that will be less expensive and more effective.

3.7.4 'Valley of death' (VoD) faced by spin-off companies

The 'valley of death' (VoD), in this context, is when a demonstrated technology cannot reach the market because it is unable to scale up through the commercialisation phase. This occurs when an innovator of a technology has shown that the technology is viable and realistic but cannot obtain the resources needed for mass production of the product or technology.

Some of the CSP technology resources and component designs have now been developed by local companies, as discussed in section 3.1. The strength of new research facilities like Helio100 is yet to be confirmed, as they have only recently started. Although they have immense potential, their innovations are yet to cross the VoD of technology adoption.

Some barriers faced by young developing companies, such the ones involved in CSP in South Africa, limit the commercialisation of their technologies. These were identified by Frank *et al.* (1996), and confirmed by Bosetti *et al.* (2012):

- The tedious process involved in contracting/procurement;
- potential liability exposure for developers;
- the inability to transfer technological development into technology deployment efforts; and
- insufficient fund to acquire state-of-the-art technology and limited available cost data.

A major challenge faced by CSP that reduces its adoption is its limited scalability. CSP is more efficient on large scales. It is almost impossible to use on very small scales, for example, in off-grid applications. The rapid cost cuts experienced by solar PV are a result of PV's scalability – that is, its ability to supply energy cheaply in simple units.

Some of the reasons for the limitations faced by CSP in South Africa were presented in a SAGEN report (SAGEN, 2013):

- Local R&D in CSP seems to be under-funded;
- local companies are unable to compete with international companies in labour cost and productivity;
- it is difficult to secure funding assistance because financial institutions tend to favour more accepted and proven technologies (e.g., solar PV) over a younger technology like CSP;
- the future cost reduction of competing renewable energy methods might occur faster than with CSP;
- transportation of imported materials from the ports to the CSP plants is expensive; and
- CSP operations requires high water usage (4.5 m^3/MWh), when compared to a conventional coal plant that uses 2.4 m^3/MWh and the shortage of water supply in South Africa might discourage CSP growth.

The above challenges make it difficult to maximise the global advancement in CSP technology in South Africa, and they also hinder the diffusion of the technologies developed, especially by small research groups and their sister spin-off companies, and thus prevent the innovations from crossing the VoDs.

The next section presents how some players in South Africa have approached the challenge of overcoming the identified limitations to massive deployment of CSP in the country.

3.8 The dynamic roles of organisations, universities, and government in the CSP industry

Universities and organisations, such as industries and institutes, conduct innovative research into CSP. There is the possibility of more interaction when these stakeholders work together. This interaction had been successful in various scenarios in the past, because technology champions are carried along throughout the innovation process in this research approach (Etzkowitz & Leydesdorff, 2000).

The roles of each of the stakeholders in the cycle of innovation were defined by Bozeman (2000) as complementary, not competing, in his market failure technology paradigm. The role of government is to break the market barrier for innovations by enacting favourable laws, regulations, free trade agreements, and neutral impact taxation. Universities are the knowledge providers, educators, and suppliers of public domain research, while industries (although they prefer to keep their innovations secret from competitors) can work together with the universities and government in this cycle for better results.

In South Africa, strategies to cross the CSP technology VoD have generally been deployed with other renewable energy systems (which can be a limiting factor, as each type of renewable energy has its own challenges). Various agencies and government entities have been set up to fund, direct, regulate, or actively participate in the R&D of RETs in South Africa. Three of these organisations are discussed in the sections below. Their roles in the development and deployment of RETs are presented and an overview of the impact on the economy is highlighted.

3.8.1 National Research Foundation (NRF)

The National Research Foundation (NRF) is a South Africa government body that is responsible for promoting and supporting research through funding. The NRF also facilitates the creation of knowledge and innovation that improves the quality of life of South Africans. Table 5 shows the 2014/2015 annual report of this organisation and the various programmes it funded, with their impact on the South African economy.

Table 5: NRF statement of financial performance for non-exchange transactions (NRF Reports, 2015)

		2015	2014
		ZAR '000	ZAR '000
Programme 1	Corporate	67 249	64 028
Programme 2	Science Engagement	134 756	129 015
Programme 3	Research and Innovation Support and Advancement	1 877 163	1 930 890
Programme 4	Nuclear, Biodiversity, Environmental & Conservation Sciences	378 005	342 852
Programme 5	National Research Facilities of Astro- Geosciences	359 706	303 398
Total expenditure		2 816 879	2 770 183

Through its 'Programme 3' – Research and Innovation Support Advancement (RISA) – the NRF collaborates with industrial stakeholders to champion the shift to RETs. The funds available for this programme were channelled in two ways: through the Energy Human Capacity Development and Knowledge Generation (EHCD&KG) programme; and through the Centre for Renewable and Sustainable Energy Studies at Stellenbosch University (SU).

- The Energy Human Capacity Development and Knowledge Generation (EHCD&KG) programme: This is a consortium of several programmes and funding boards that include the South African Nuclear, Human Asset and Research Programme (SANHARP); the Renewable and Sustainable Energy Scholarships (RSES); the Masters in Accelerator and Nuclear Science (MANUS); the Masters in Material Science (MatSci); and the Doctoral Studies in Energy Efficiency (DSEE).
- The Centre for Renewable and Sustainable Energy Studies at SU: This is the hub of renewable and sustainable energy research in South African universities. It comprises several spokes, including the wind energy research group, hosted by SU and the University of Cape Town; the solar thermal energy research group (STERG), hosted by SU and the University of Pretoria; and the Solar Photovoltaic research groups, which have their base at the University of Fort Hare and Nelson Mandela Metropolitan University.

In this way, the NRF has been able to use an inclusive model in which all the stakeholders in the renewable energy sector of South Africa – experts and academics alike – work together to achieve the goal of RET advancement in South Africa.

3.8.2 SANEDI tax incentives

Tax incentives have been identified as a major impact factor in accelerating the deployment of renewable energies (Mendonca, 2009). South Africa recently reviewed its tariff law under Income Tax Act No. 58 of 1962, with a new regulation published by the Minister of Finance under section 12L(5) in Government Notice No. 10080 (Republic of South Africa, 2013: Gazette No. 37136), and amended by Government Notice No. R.186 (Republic of South Africa, 2015: Gazette No. 38541 of 6 March 2015) (SANEDI Media Reports, 2016). The South African National Energy Development Institute (SANEDI), a state-owned entity, was formed because of this regulation. SANEDI was given the responsibility to issue certificates and coordinate tax returns for equivalent hours of energy saved. SANEDI has facilitated the increased deduction of the kilowatt hours equivalent of energy saved from 45 to 95 cents per kilowatt hour as tax incentives. This has been in effect since 1 March 2015 (SANEDI Media Reports, 2016).

The tax incentive is the amount paid to organisations or individuals that produce renewable electricity. It is often used to motivate more efficient energy usage and the development of more privately owned renewable energies. However, using the same base or standard tax incentive for all RETs is often not effective (Shum, 2013).

Shum (2013) reported that tax incentives can only be effective and lead to a rapid RET diffusion if the rate is scientifically calculated and differentiated for each type and size of RET. In the United States, for example, the tax credit rebate for RETs varies depending on the type of operation, size, and capacity (Energy.gov, 2015). They conveniently separated the tax incentives based on size into either residential or industrial (Energy.gov, 2015).

3.8.3 Renewable Energy Independent Power Producer Procurement Programme (REI4P)

The REI4P, an extension of the South African Department of Energy (DoE), has overseen the investment of over 168 billion Rands by various companies in the development of RETs in South Africa (DoE, 2015). It has rolled out four rounds of bid windows since 2011. This has led to the allocation of 79 different renewable energy projects nationwide with a total power capability of 6 000 MW. Most of these projects are concentrating solar power (CSP) plants, solar photovoltaic, and onshore wind technologies. REI4P also regulates the electricity tariffs using various innovative methods. For example, REI4P currently regulates the two-tier tariff payment options for CSP, discussed in section 3.3.

3.9 An evolving research environment

With the level of interest shown by the South African government in RETs development, there is a need for each type of RET to be analysed and developed as an individual entity to maximise its potential. As discussed before, CSP is a young technology, and only limited literature is available on the analysis of its feed-in tariffs, deployment, dispatchability, off-grid installation and adoption.

In the literature, several comprehensive assessments have been done for other RETs. For example, several technology adoption/diffusion models, have been developed for solar PV by Shum and Watanabe(2007, 2008; Shum, 2013). Information regarding other renewable energy sources, are provided by Breukers & Wolsink (2007), Wüstenhagen, Wolsink & Bürer (2007) and Zoellner, Schweizer-Ries & Wemheuer (2008) but there has been limited work in this field for CSP.

Technology diffusion or adoption is an important part of the cycle chain of invention-innovation-diffusion. Shum (2013) identified the direct link between innovation characteristics and technology diffusion, to make it necessary to adapt the available adoption models to the technology of interest, or to develop a new technology adoption framework for it.

3.10 Concluding remarks

The adoption of CSP in South Africa is having major positive effects on the supply of clean electricity. When all six CSP plants discussed in this paper are in full operation, 1.5 million tonnes of carbon emission will be prevented annually. The identified CSP consortiums are carrying out competence-enhancing activities, as the companies must train the newly employed operators, thus leading to local competence and skills development programmes.

The innovation analysis carried out on CSP technologies in South Africa also shows that its tariff is currently higher than that of other major RETs (wind and PV). Moreover, the innovation experience of South African CSP technology is incremental, as each subsequent plant was an improvement on previous facilities elsewhere. The development of research into innovation, and eventually into market products of CSP systems, is improving with a closer relationship and working together of the stakeholders.

This progress, however, is slow. There is limited knowledge in identifying and understanding the important activities and policy instruments that can aid the prioritisation of important actions, to forge better relationships among stakeholders and fast track the deployment of CSP. Some research facilities have been built to improve the technical R&D knowledge of CSP, while some independent and spin-off companies have begun operations in CSP technologies.

One of the steps to having a detailed adoption framework for CSP in South Africa, is to develop a comprehensive roadmap. There is an existing roadmap for the advancement of solar energy in South Africa, in which all the solar energy technologies in South Africa were harmonised as far as possible and treated as one (Brent, 2015). However, each solar technology faces specific technological and economic challenges, market dynamics, and deployment limitations, thus suggesting the need for roadmaps with high technical and economic specificity for CSP.

The two-tier tariff plans introduced by REI4P have reduced CSP tariffs up to seven per cent (CSP Today Markets Reports -South Africa, 2015). This attempt to support CSP adoption in South Africa is based on a dispatchability tariff plan (Gauché *et al.*, 2011; Gauché *et al.*, 2012; Silinga *et al.*, 2015). However, the development of technology adoption frameworks and models for other RETs such as PV have resulted in a reduction of over 75 per cent. It is therefore pertinent to develop a working adoption framework that can inform policy-makers of the right decisions to increase the uptake of CSP in South Africa. There is little or no literature available on CSP technology adoption and deployment models. For that reason, this chapter shows that an appropriate technology adoption/diffusion framework, which could incorporate the joint effects of learning and the necessary network externalities involved in CSP usage, should be developed. This will allow for easy diffusion of the technology into the economy.

The first step towards success in CSP deployment is to perform a critical review of the existing technology adoption methods and approaches and how it had been used for various technologies at various locations. This can inform a methodology or strategy that can be used to develop an effective technology adoption framework.

4. Technology adoption review

To fully understand technology adoption methods and how this knowledge can inform the development of the right adoption strategies for CSP, this chapter critically reviews the existing technology adoption approaches, its application in solar industries, and then presents an appropriate approach to develop a CSP technology adoption framework in South Africa.

Section 4.1 presents the various dimensions that adoption studies have followed in literature, and Section 4.2 explains the types of approaches to developing technology adoption models. To fully understand how these approaches are applicable to renewable energy technologies, two case studies on how the technology adoption approaches have been used for solar PV in different countries are presented in Section 4.3 and 4.4. The results, observations and limitations of these approaches are also discussed.

Section 4.5 presents the strategies, impact and effect of such adoption studies and a summary of few other cases from other sectors that were examined. Because CSP has been identified to be highly effective on large scale and not considered for individual adoption, it was impossible to use any of the existing technology adoption approaches. Therefore, Section 4.6 of this chapter proposes the use of a technology management approach, because it combines the elements of the existing approaches and the method that can be used to assess and develop adoption techniques and a framework for technologies that are only effective on large scales such as CSP.

4.1 Technology adoption studies

Coughlan *et al*. (2008) classified technology adoption assessments in the literature into five groups, based on the modalities and dimensions that were followed in performing the studies or building the frameworks/models:

I. Industry based - technology adoption have been proposed in literature with a focus on specific industrial sectors like agriculture, information technology, mining, health care, renewable energy and so on.
II. Interest based – these are technology adoption that focuses on the locus of interests involved in adoption processes, such as environmental characteristics,

individual/group adopter(s) characteristics, information dissemination methods and technology characteristics.

III. Type of innovation – here, adoption can be categorised based on the type of innovation path followed; radical versus incremental, administrative versus technical or backward versus forward integration and so forth.

IV. Analysis approach based – this is a grouping of relevant literature according to the methodology or the analytical approach used to develop the adoption model. Some of these methods are survey/questionnaire, case studies, cost/benefit analysis, econometric and techno-economic and so forth.

V. Stage of technology on the TAL cycle – here the technology assessments have been done based on current positions of the technology transfer processes in the TAL cycle (innovators, early adopters, early majority, late majority and laggards).

The above-classified methods have been used to study various technology and market trends, including computer, electric cars, bioinformatics, pharmaceutical drugs, television, camera, consumer goods and PV. These analyses have also been used to study major technological incidents and other occurrences like HIV/AIDS (Fisher & Pry, 1971; Meade & Islam, 1998). In the literature groups above, technology adoption was viewed as a diffusion process involving the 5 stages (awareness, interest, evaluation, trial and adoption) that corresponds to the TAL curve of Moore (1991), shown in Figure 1. The adoption of these technologies can be said to be dependent on three interrelated factors, similar to the triple helix innovation model of Etzkowitz & Leydesdorff (2000) that is, technological, socio-economic and institutional factors.

If the global sustainable development goals are going to be achieved, the diffusion of environmentally friendly technologies should be encouraged (Rao & Kishore, 2010) . Therefore, making adoption analysis of renewable energy important. However, the difference in the use of conventional methods, listed above for renewable energy technology (RET), is that as opposed to other matured and independent technologies, RET currently thrives on support policies, as well as a global desire to combat climate change (Rao & Kishore, 2010). Despite its obvious advantages and support from governments, RET adoption is still seen to be slow. Thus, developing adoption strategies for them is of high importance.

4.2 Existing adoption methods

Technology adoption is core to the cycle of invention, innovation and diffusion. It is a determining factor for the survival of technical changes or new products (Rogers, 1995). Some inherent characteristics of innovation have been identified by Rogers (1995) to affect technology adoption. These are the relative advantages, compatibility, and complexities of new technologies as compared to the existing ones. For a detailed analysis of the diffusion of RET as related to these characteristics see Jacobsson &Johnson (2000).

There are two methods to analytically study the pattern of technology adoption as identified by Geroski (2000) and these methods were confirmed by Shum (2013) as i) epidemic approach and ii) choice or equilibrium approach.

Epidemic approach

This is the earliest, most popular and most used analytical approach used in studying diffusion patterns. Here, the potential adopters of technology are assumed to be homogenous (Shum, 2013). Information about new product or innovation is disseminated through one-on-one interactions or based on current or potential adopters' location proximities. This model encourages direct marketing through communication of the economic and technical advantages of the technology to the end-users or adopters.

The shortfall of this approach is that it assumes that the adopters have the same intended use of the product, or that potential adopters have the same needs.

Equilibrium or choice approach

This approach assumes that potential adopters are heterogeneous in nature in contrast to the epidemic approach that considered adopters as homogeneous. Here, adopters are believed to have different values for cost and needs, and that technology adoption is only favoured when certain minimum expectations of individual adopters are met.

The spread of the minimum values or the differences in the minimum values of adopters are used to analyse the rate of technology adoption (Shum, 2013). This method proves that interested adopters will not all adopt an innovation at the same time and that the adoption rate can only be fast when more similar potential adopter's minimum values have been met. This is useful in analysing the diffusion of complex technology in which the innovation values may be hard to measure or communicated perfectly.

The two methods identified here explain the diffusion path using S-curve paradigm, which is often associated with change and innovation.

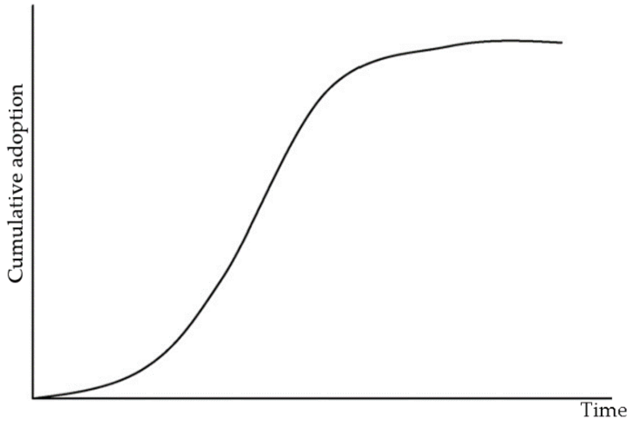


Figure 4-1: S-curve analysis

S-curve analysis as shown in Figure 4-1, presents a situation similar to the sigmoid shape cell growth in biology (Cetindamar *et al.*, 2010). The initial part represents low adoption and the adoption is limited to only the first two members of the group presented in Moore's model (the innovators and the early adopters) and then continues through an early majority to late majority, and finally ends with the laggards. These models have been effective, but Tidd *et al.* (2001) argued that these taxonomies are good and beneficial only if it is to analyse a developed or matured technology because it provides little suggestions on patterns of adoption in the future. Thus, these methods are not good enough for a new technology like CSP.

With the vast literature on technology transfer and VoD consulted, a few studies that focussed on how the epidemic and the equilibrium approach discussed above have been used to analyse adoption and de-adoption of technology similar to CSP, are discussed in the following sections. The aim is to identify and understand specific factors that affect technology diffusion as evident in CSP and to propose a methodology that can be used to develop an effective technology adoption model for CSP.

Using the two approaches discussed, technology adoption models have always been developed using quantitative, qualitative or technology management approaches.

4.3 Quantitative method: technology adoption model for PV under feed-in tariff policy in Germany

Shum (2013) used the principles of micro-economics to develop an adoption model for PV under a feed-in tariff. This model used an equilibrium, or choice, approach described above as it viewed the adopters as heterogeneous. The model incorporated learning effect with the network effects, based on suggestions from Cabra (2006).

Model Basis

A rational decision-maker was assumed, the main goal of whom is to balance the cost and benefit of adopting electricity generated by PV. A linear utility function was assumed to simplify the analysis of the diffusion of innovation using network effects.

The resulting equation is presented below

$$c_o\left[\int_{\theta}^{\infty} f(t)\,dt\right]^{-\alpha} = \theta - \lambda\left[\int_{\theta}^{\infty} tf(t)\,dt\right] \qquad [1]$$

A normal distribution f of the return from a feed-in tariff programme represents the heterogeneous nature of the PV adopting population, θ in the equation represents a type of adopter that will receive an income equivalent to θ after adopting or producing electricity using PV at a time t. Just like every other person who has adopted or generated electricity under the same grid, the adopter θ is expected to share in the volume of the feed-in tariff paid to that group.

In Equation 1 above, α is the learning elasticity to output volume of the PV system and can be determined using an expression, $\alpha = \frac{\ln(progressratio)}{\ln 2}$, c_o is the initial cost of generation equipment, λ represents strength of network externalities, and $f \sim N(\mu, \sigma^2)$ is the feed-in tariff income normal distribution of the adopter population.

Model analysis

A complete PV system comprises of the solar PV module and other attached systems, including inverters, switches, batteries and other mounting components, which all together referred to as the balance of system (BOS). Many studies have shown solar PV module and BOS are very different in terms of their learning effects (Shum & Watanabe, 2007; 2008). While BOS is driven by local conditions and institutional interests, solar PV modules are more globally driven and often affected by international spill overs. In this analysis Shum assumed a minimum spill over of production learning from other installed networks.

The left-hand side of Equation 1 represents the total amount invested in setting up a PV system (cost of investment). Learning effect can be measured in terms of cost learning over time or in terms of unit cost. This model was developed in terms of unit cost since it is often determined by the total volume of production. This formulation was used to aid the analysis of the size of existing installed PV base in the electricity network.

The right-hand side of the Equation, however, represents the establishment of an agent's utility. The formulated agents can be grouped by θ, or their interest to invest that is, their interest to adopt and generate electricity using solar PV, which eventually lead to feed-in tariff income.

Satisfying Equation 1 above will eventually lead to the adoption of PV technology.

Observations and conclusion of model

When the above adoption model was tested, with λ representing the network effect and income θ as the net present value (NPV), the assumed adopter or agent can observe the declining cost of equipment and an increasing feed-in tariff, and the following conclusions were made:

- There will be no adoption if the cost of generating electricity using PV is too high. Suggestions to overcome this include a low-interest loan and other subsidy programmes which will sustain the cost learning of the PV technology. An example of a successful implementation of this include buy-down programmes HTRP-PV roofing of 100 000 houses in Germany (Shum, 2013).
- The model also explained that the catastrophe effects of PV markets in Germany are because of the combined effects of feed-in tariff income, mild negative network externality [3] and cumulative volume-based cost learning.

[3] Negative network externality occurs when there is congestion on demand or when there is cost reduction because of increasing adopters

- The model identified that catastrophe happens in PV without network effects, although this is nullified by the fact that network effect is intrinsic characteristics of feed-in tariff policy. The advantage of this finding is that learning effect alone can lead to catastrophic effects.
- Learning elasticity and network effects were seen to be a major determinant in adoption dynamics of solar PV and thus can be maximised to cause a larger catastrophic effect on PV adoption.

4.4 Qualitative method: integrated solar energy adoption model in South Korea

A qualitative approach, coupled with statistical analysis, was used by Kim *et al.* (2014) to develop an adoption model for solar energy technology in South Korea.

Model basis

The study focussed directly on potential adopters, and the factors that influence their reasons for expected adoption were analysed. Solar energy in this section refers to PV technology as the study was carried out on PV alone. Kim *et al.* (2014) identified the key factors that most contribute to the willingness of the public to use solar energy, and then developed a model as shown in Figure 4-2.

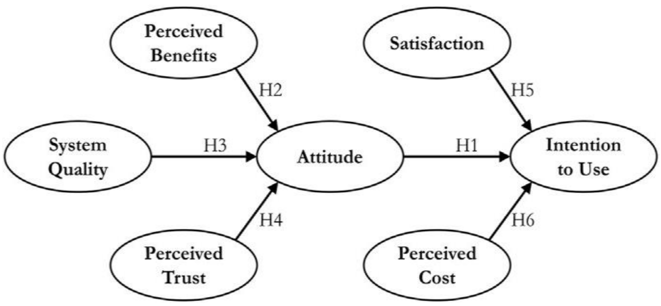


Figure 4-2. Solar energy adoption model (Kim *et al.*, 2014)

Model analysis

The trend and the current state of solar energy in South Korea were analysed and compared to other renewable energies in the world. The factors found to be significantly related to the intentions of adopters towards solar technology were used to propose the following hypotheses which are shown in Figure 4-2.

"H1 suggests that the attitude of anyone towards solar energy is significantly related to the intention of use while others, like H2 - the expected benefits, H3 - the system quality, H4 - the perceived trust, H5 - satisfaction, and H6 - the perceived cost of solar energy technology, are significantly related to the attitude towards the technology" (Kim *et al.*, 2014).

The proposed model was tested using a survey and the collection of data was done with the use of a questionnaire to identify the public behaviour regarding solar energy. The results of the survey were then used to develop a technology adoption model and framework. The results, as shown in Figure 4-3, suggested that three dominant factors affect the variance in the attitude of an adopter towards solar energy in South Korea. They include the quality of the system, its perceived/expected benefit, and its level of reliability/perceived trust.

The other three variables that affect the variance in the intention of an adopter include public attitude, satisfaction, and perceived cost; with the first two having a positive effect, and the last having a negative effect.

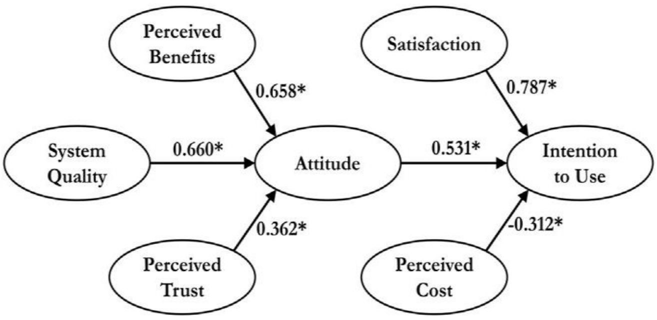


Figure 4-3: Summary of hypothesises from the research model

Model results and conclusions

The results from the survey and analyses by Kim *et al.* (2014) helped to understand the public perception of solar energy, as well as their intention and willingness to adopt the technology. The measured and research model quite agreed with limited deviation. While the study identified solar energy system quality and its expected/perceived benefits as the basic and dominant factors, it suggested that perceived trust is less dominant.

The results from this survey suggest that the attitude and psychology of a target populace must be considered before deploying the technology, as this will allow the development of a kind of technology that is needed and will help them to take full advantage of it.

The model also suggested the important need of specific policies that can help in the adoption of solar technology, with an intension of raising the positive variables (satisfaction and public attitude) and minimizing the negative variable (perceived/expected cost). Kim *et al.* (2014) also suggested that industrial engineers should find a way of minimising the cost of solar energy components, as well as its processes and installations, to reduce the overall cost of the technology.

The relationships between the variables were identified and a conceptual framework that can be used to improve the adoption of solar energy technologies was provided.

Model limitations

The results from this model cannot be generalised, as the survey was only conducted online in South Korea. It is expected that the result of any model would be different in different regions, as Venkatesh & Davis (2000) had identified that individual differences often affect choices when it comes to adopting new technologies or systems.

Many other important relationships among the variables were not identified in the model. They were overlooked for simplicity and the model only considered simple connections, while complex connections among variables were excluded. Only the mentioned six variables were considered, while other factors like individual differences, support policies, social influence, risks, location and available solar resources, were not considered. Thus, making the model not applicable to CSP.

The model only focussed on the users and neglected the technical circumstances, manufacturers' perspectives, and market dynamics.

4.5 Effects of adoption models in deployment strategies

Technology adoption models or frameworks are often used as policy instruments for decision-makers and potential adopters. They are sometimes used to propose deployment strategies that can facilitate the success of an innovation. The existing technology adoption models had been used by PV promoters to develop two distinct deployment strategies that have led to PV success in the last decade. Shum & Watanabe (2007) explained how these strategies have been used to deploy PV adoption in Germany, Japan and United States, as:

Information technology deployment strategy: this strategy is based on developing various new ways in which PV technologies can be used, making it diverse in application. It is also referred to as an open model. Diffusion using this strategy is aided by balancing the general purpose and self-propagating nature of PV technology with ease of customisation and user-specific designs.

Manufactured technology development strategy: here, PV systems are designed to function using existing infrastructures and equipment. This is a closed model, in which a major type of PV application is developed to fit into existing systems. An example is distributing electricity from a solar field through existing grid lines or incorporating it into existing house wiring. The previously existing systems, as well as their suppliers, however, dictate the success of PV diffusion using this model.

The two strategies described above use the same solar PV global cost dynamics although their implementation and success depend more on the existing policies in the home countries where they are deployed (Shum & Watanabe, 2007).

Diffusion and adoption techniques of other products, services and technologies were also consulted, with the intent of finding relevant adoption strategies applicable to CSP that can be used to achieve the objectives of this study. Some of them are as follows:

- Technology adoption models for the United States Department of Defence's technologies (Coughlan *et al.*, 2008)
- Electric cars and its deployment; the failure, lessons and the diffusion trend (Hensley *et al.*, 2011; Egbue & Long, 2012)
- Studies on the method used by successful medical drugs to cross the corresponding chasms, and the strategies adopted from research to innovation and successfully breaking through the policy barriers to market (Rao & Kishore, 2010; Hudson & Khazragui, 2013).

4.6 Technology management method: A strategic approach to CSP adoption studies

Technology management approach for performing adoption assessment and developing adoption framework, combines both the quantitative and the qualitative methods, using either the epidemic approach or the equilibrium approach (Cetindamar *et al.*, 2010), It considers both the adopters and the innovators. This research methodology is often based on any of the five popular research methodologies which include experiments, surveys, historical record analysis, computer-based analysis or case studies.

Several strategic methods have been used to develop adoption strategies for various product/technology in literature. However, majority have been found to follow the same pattern as understanding the current situation by performing innovation analysis on the technological trend, identifying the potential market for the technology, understanding the drivers and barriers to the adoption of the technology, and then building a better framework/model as shown in Figure 4-4.

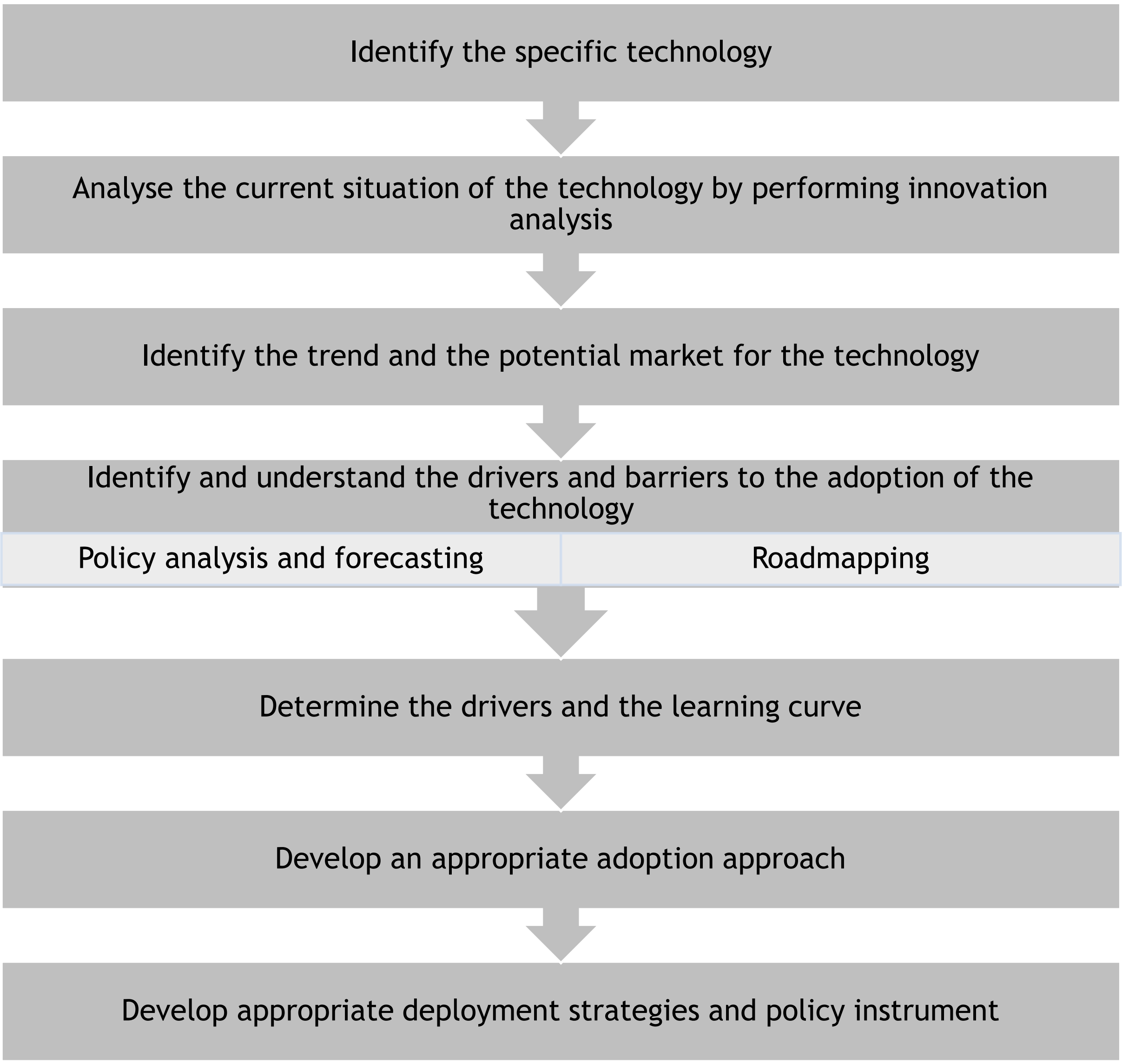


Figure 4-4: Technology management method to technology adoption process

Some authors in literature have attempted to aid the deployment of RETs using some of the activities stated in Figure 4-4, and a few of them are discussed further.

Analysis of the current situation of the RET by performing innovation analysis: Palgrave (2008) performed an innovation analysis of CSP and looked into previous efforts made to reduce the cost and suggested the likely trends. Palgrave (2008), however, focussed only on the technical aspect of CSP development and did not consider the other stakeholders identified in this proposal (institutions, policies). Also, the analysis was based only on the U.S. market trends; thereby suggesting that the results cannot be generalised and thus suggests the need for a detail innovation analysis of CSP in other locations like South Africa.

Road mapping: The International Energy Agency (IEA) designed a global technology roadmap for CSP with no specific focus on any country (IEA, 2014b). There was no detailed inclusion of specific government policies in the roadmap; an example is the two-tier tariff plan for CSP in South Africa. In order to improve on the roadmap, the IEA (2014a) provided a guide for the development and implementation of energy technology roadmaps, but with no specificity on any RET.

Brent (2015) on the other hand provided an overview of the solar energy RDI roadmap for South Africa, while Musango & Brent (2015) presented a roadmap framework for solar aided power generation in South Africa. These existing roadmaps tried as far as possible to harmonise all existing types of solar energy systems. Therefore, the activities and factors identified were tailored to follow similar innovation trends. However, each type of solar energy technology faces its own technical challenges, market dynamics, and societal acceptance and maturity issues. The need for a roadmap with high specificity, and which suggests implementation plans, is therefore identified.

Drivers and learning curves: Mondal *et al.* (2010) identified the drivers and barriers of RET in Bangladesh using an innovation system analysis, and then suggested strategies for adoption and implementation of the policies in the country. Kersten *et al.* (2011) on the other hand used historical information on cost and price of PV to derive a learning curve for PV modules, and to analyse the main factors. None of such analyses were found for CSP in literature.

The technology management approach is thus an effective way to develop an adoption strategy, framework or model for CSP, as it combines the innovators and potential adopters, and includes future trends and perspectives. This can be used to overcome most flaws identified in the existing studies.

4.7 Conclusions

The challenges faced by RETs often shift from technical, to economic and institutional (Shum & Watanabe, 2009). However, Unruh (2002) and Mattauch *et al.* (2015) identified government policies, solar resources and carbon lock-in as unique challenges facing RETs.

Gauché *et al.*,(2012, 2013) and Pierce *et al.*,(2013) presented a value proposition for CSP in South Africa, but there are no distinct CSP deployment studies/strategies found. Other related findings have been based on biddings and tariff plans. (Eberhard, Leigland & Kolker, 2014; DoE, 2015; CSP Today Markets Reports -South Africa, 2015; Silinga *et al.*, 2015). As a result, the factors that affect the deployment and economics of system integration and cost dynamics of CSP are poorly understood. Thus, there are limited policy instruments to improve the state of CSP. This has led to the technology's low adoption as a function of the available solar resources and when compared to other RETs.

The uniqueness of the barriers that limit the adoption of CSP justifies the need for a strategic approach to developing an adoption framework or recommendations, which addresses carbon lock-in, incorporates existing energy policies (tax credits, renewable energy portfolio and subsidies) and provides policy instruments to accelerate the use of the RET.

Technology adoption is core to the cycle of invention, innovation and diffusion. It is a determining factor for the survival of technical changes or new products (Rogers, 1995). Some inherent characteristics of innovation have been identified by Rogers (1995) as affecting technology adoption, its relative advantages, compatibility, and reduced complexities compared with the existing ones. A detailed analysis of the diffusion of RETs, as related to these characteristics, was presented by Jacobsson & Johnson (2000).

It is important to note here that, although the need for a technology adoption approach for CSP has been identified in this study, CSP must be treated uniquely. This is because currently the CSP electricity can only be very effective on a large scale and cannot be treated as consumer/unit-based technology. Therefore, there is a need for a systematic analysis approach to developing CSP adoption strategies.

5. Systems analysis of CSP in South Africa[4]

The RET sector in South Africa experienced significant investments in the last decade, with the sectoral asset finance increasing to 5.5 billion dollars in 2012, which was a 20,500 % raise when compared to that of 2011 (FS-UNEP, 2016). This progress led to a significant growth in various types of RET with wind energy, solar PV and CSP receiving the most attention in that order.

However, as discussed in previous chapters of this report, South Africa is not living up to its potential ability to lead the world in CSP. The deployment rate has been slow despite the available solar resources and technology's potential. As a result, the technology lags other RETs in terms of capacity and cost competitiveness and a number of limiting factors including technical and non-technical continue to exist (DoE, 2011).

The challenges facing CSP as identified in previous chapters make it difficult for potential adopters to apply for future funding for building CSP plants (Timilsina, Kurdgelashvili & Narbel, 2012) because banks and other financial institutions prefer to fund a matured and tested technology (Cetindamar, Phaal & Probert, 2010). This then has led to the inability of interested local companies in South Africa to compete with other companies from other countries with lower labour cost and higher labour productivity, for instance China and India. (CSP Today Markets Reports -South Africa, 2015).

The reduced megawatts (MW) allocation to CSP in REI4P had also contributed to the eventual reduction in local industry interest, thereby reducing the ability of the nation's manufacturing and energy sector to compete with other global counterparts (DoE, 2015). Electricity from CSP in South Africa is more expensive than other major RETs because of these and other challenges and had led to the removal of CSP from future energy mix of South Africa in the most recent South Africa IRP update of 2016 which is threatening to bring an end to the growth of the technology (Pierce *et al.*, 2013).

[4] This chapter is an expansion of a paper titled:" System analysis of Concentrating Solar Power (CSP) in South Africa" presented at SolarPaces conference held at Santiago, Chile in 2017 and published with the American Institute of Physics Conference Proceedings

With the several adoption models or deployment strategies already identified for various technologies, the exclusivity of the challenges facing RETs make it difficult for a one-fit-all strategy across RETs. While several deployment frameworks, strategies or models exist for other RETs, there are limited literature on the subject which address the same for CSP (Shum, 2013).

In this chapter, a basic system dynamics approach is used to analyse the unique, critical and complex factors that were identified to be affecting the deployment of CSP in South Africa, as identified by concerned policy-makers, CSP experts, and existing studies. A simple systems dynamic analysis was performed because the idea of the chapter was to know which factors should be given more attention and developed in the subsequent analysis.

The result from this study shows that improved support for research and local manufacturing is the most effective way to open new methods. Moreover, they show ways in which the CSP technologies can be deployed, which will foster further CSP adoption in South Africa.

5.1 Method

System dynamics is a field that uses mathematical analysis through modelling to solve complex issues. System dynamics concept was developed by Jay W. Forrester of the Massachusetts Institute of Technology (MIT) and it has evolved from a tool for corporate managers in the 1950's to becoming a policy analysis and design tool (Maani & Cavana, 2007). System dynamics approach is used to analyse complex interacting systems involving feedbacks, and it often presents several scenarios to understand the dynamic behaviour of the concept under review over a period.

The basic elements of system dynamics are causal interaction representations, analysis based on mathematical equations and simulation through a stock and flow system analysis. The identified actors are connected in feedback loops (Hsu, 2012).

The real impact of the actors/social system on a policy can be identified from the results of computer simulations in a laboratory to understand causal feedbacks (Forrester, 1991). This makes it possible to develop a policy laboratory in system dynamics. This serves as policy instruments to stakeholders or decision makers and gives them the freedom to develop various scenarios for an optimal decision regarding the subject under review.

System dynamics have been used in various sectors to solve complex problems and to quantify the effect of some social factors on a subject. There are several existing literatures where system dynamics have been used in policy analysis and organisational management. Gupta *et al.* (1989) developed a system dynamics model to analyse the productivity of the Just-in-time systems. While Lomi *et al.* (1997) developed a system dynamic model that showed the effect of an organisation's management policy on its growth, and how this interaction could be used to achieve maximum profits.

In the communications sector, Bui & Loebbecke (1996) used system dynamics to forecast the demand and supply of the mobile phone markets. Naill (1992) on the other hand, developed a system dynamics model which served as an instrument for energy policy planning in the United States. Also, Musango (2012), used system dynamics approach to perform a technology assessment of renewable energy sustainability in SA, in which she developed a model to present the possible outcomes from a proposed biodiesel production plant in the Eastern Cape region of SA, and the model was called Bioenergy Technology Sustainability Assessment (BIOTSA).

The cases presented in the previous paragraphs as well as many others existing in literature, show that system dynamics has been used satisfactorily to analyse or explain various social and organisational behaviours. Thus, making it suitable to access the most key factors affecting CSP deployment in SA as intended in this chapter.

Hence, to know which factors to analyse and improve on, to aid better CSP deployment, this chapter adopts a simple systems dynamics approach to construct an adoption model to simulate the effect of the identified key factors on CSP deployment in SA. The aim was to identify which factors to be worked on the subsequent chapters

The process followed in this study is based on the five systems thinking and modelling phases presented by Maani & Cavana (2007). These are: problem structuring, causal loop modelling, dynamic modelling, scenario planning and modelling, implementation and organisational learning, as shown in Figure 5-1.

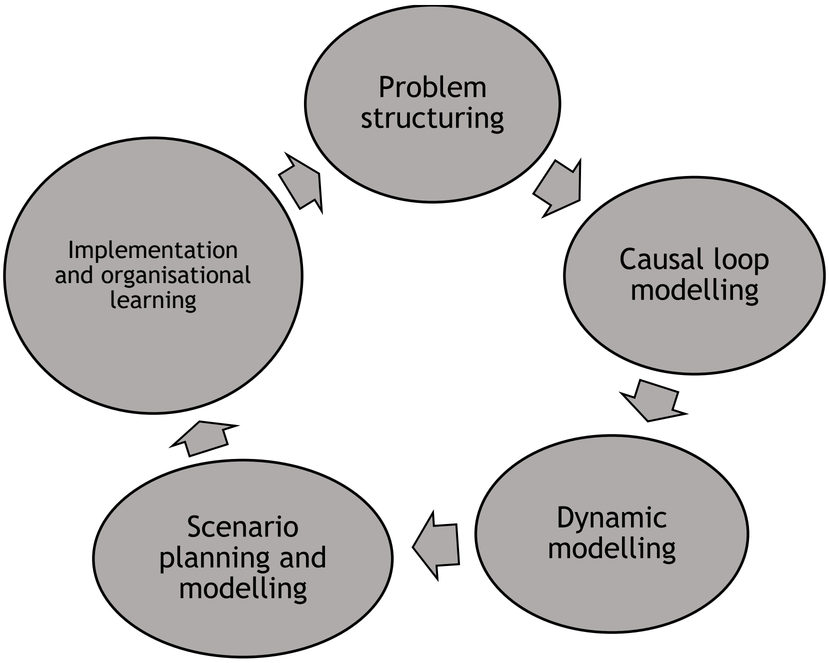


Figure 5-1: System thinking and modelling phases

MODEL FRAMEWORK

The objective of this chapter is to use system dynamics to develop a model to simulate the effects of a range of factors surrounding the adoption and deployment of CSP in SA. Moreover, the various concerns and challenges facing the adoption of CSP as one of the major energy sources in SA were assessed. The first step carried out here was the development of a causal loop diagram (see Figure 5-2) based on key levels and auxiliary parameters.

Figure 5-2 shows the interaction among various issues that affect CSP in SA, as identified using a causal loop diagram (CLD) in system dynamics. The implications of the identified loops are that they directly affect the competitiveness of CSP with other renewables or conventional energy sources, and they consist of the most important variables that attract and affect decisions on energy mix by policy makers.

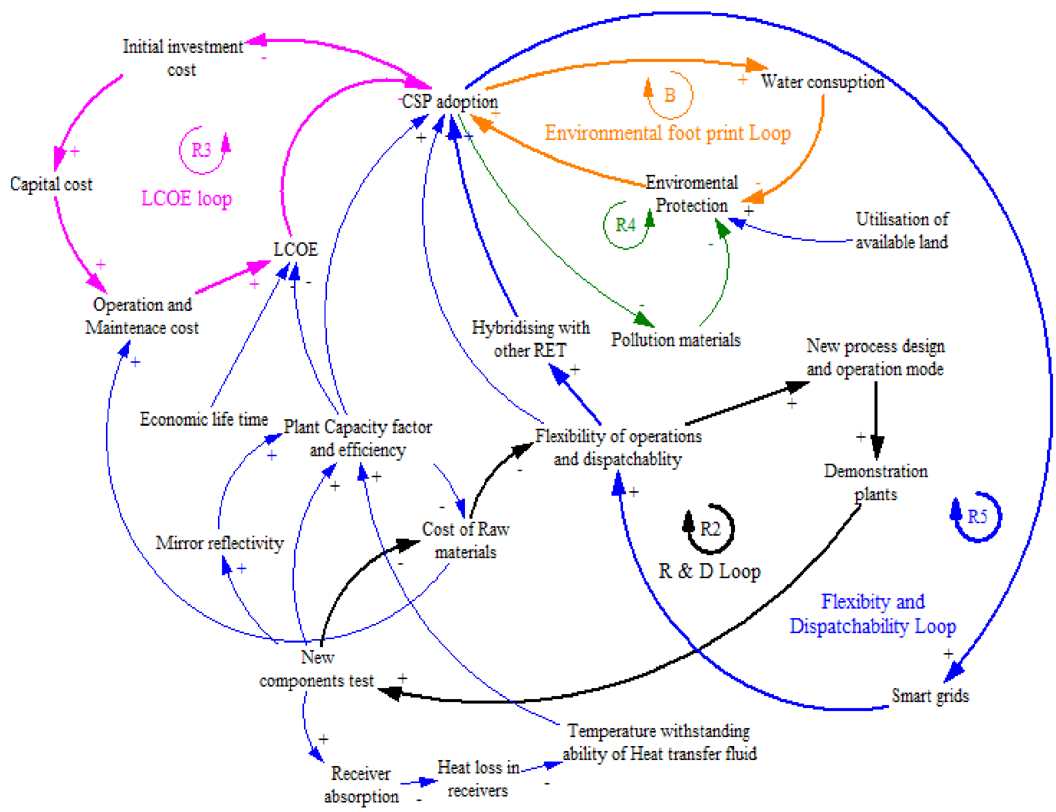


Figure 5-2. Causal loop diagram (CLD) of factors affecting CSP in South Africa

Because the use of CSP for electricity is currently not viable/profitable on a consumer based/small-scale level, the policies that promote CSP can be divided into two: those that encourage the allocation of MW in the IRP and those that limit the further development of other conventional/fossil fuel sources. The former was used as the CSP support policy in this study, hence the focus was on presenting value proposition for CSP adoption to the stakeholders involved in decision making such as bid windows and general IRP updates and those in the department of energy (DoE).

The total cost of building a CSP plant include the capital cost, cost of equity and loan financing operation and maintenance costs. The cost drivers include the cost of land, cost of the solar field, power block, transmission connection, storage and O&M costs. In Figure 5-2, LCOE was presented as a function of capital cost, O&M costs, the economic lifetime of the plant and the capacity factor. CSP adoption increases when it can compete favourably with other energy sources in terms of the environmental foot print, flexibility/dispatchability, electricity tariff cost, LCOE, storage capabilities, and hybridisation potential.

The current state of CSP in SA, as identified by experts and existing studies, were used to formulate a baseline scenario. Three other scenarios, based on the CLD, were developed:

- Improved local research, development and demonstration (RD&D) scenario;
- lower Direct Normal Irradiance (DNI) + improved RD&D scenario; and
- reduced water consumption scenario.

5.2 Modelling parameters and justification

The interactions generated in the CLD were used to create a dynamic model with a time reference to 2030, using Vensim PLE (system dynamics modelling software). The four scenarios were analysed within the same time horizons using a time step of 0.0625 years, and the fourth order Runge-Kutta method of integration.

The description of the developed model is as follows:

The interactions identified in the CLD were used to create a system dynamic model in Vensim PLE, in terms of stock and flow diagram as shown in Figure 5-3. The parameter input into the baseline scenarios was based on approximations from Fichtner (2010), Black &Veatch (2012) and publicly available technical documents for KaXu plant (KaXu is a parabolic trough plant and the first CSP plant to be connected to the grid in SA) (Abengoa Solar, 2014).

The fractions and approximations were made based on author's discretion and expert opinions through a survey. Flexibility of operations and rate of hybridisation were the author's approximation based on suggestions by Gauché *et al.*, (2012; 2013). The fraction of import levies was set to 0.8, as a majority of the technology used at the beginning of CSP in 2010 in SA were foreign. This value would decrease with increased local manufacturing capability.

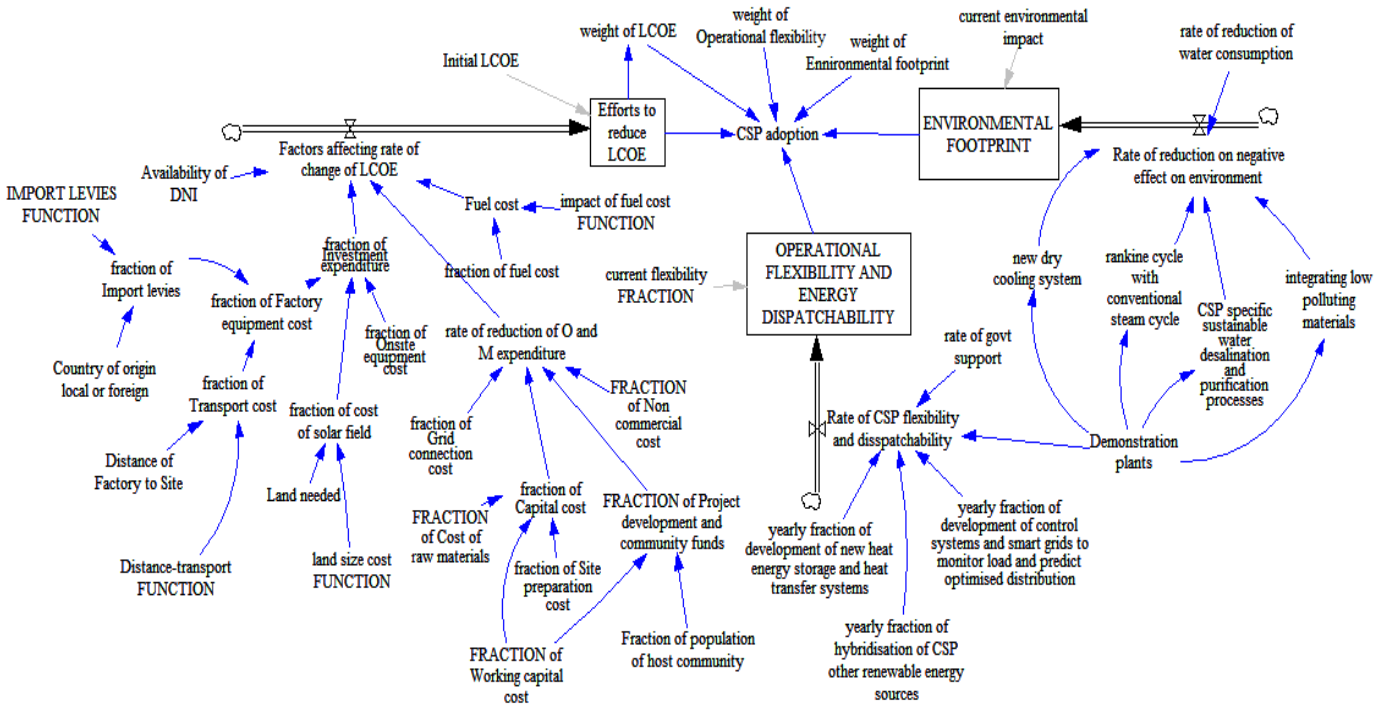


Figure 5-3. Stock and flow diagram screen shot from Vensim

The fraction of DNI availability in all scenarios (except the lower DNI + RD&D scenario) was set to 1 because all existing CSP plants in SA are currently in Northern Cape Province and they receive maximum solar irradiation. The value was reduced in the lower DNI + RD&D scenario to (<1) to check whether CSP adoption would be affected by setting up CSP plants in places with lower DNI resources with better grid facilities. The fraction of the population of host communities was done by calculating the population percentage of the host community to the size of land being used by the CSP plants based on available data from Statistics SA (Statsa, 2014).

5.3 Analysis and discussion

Baseline scenario

The baseline scenario in this chapter refers to the current situation of CSP in SA. The aim of the simulation was to check what the CSP adoption would look in the year 2030 based on the current policies and trends. The parameters used were in accordance with the values in Table C1 in Appendix C. The results from the analysis are presented in Figure 5-4 and it shows that CSP adoption in SA will only rise by 5.6 % in the year 2030 if the current status quo is maintained. With such adoption rate, electricity generation from CSP to the SA national mix may be heading towards extinction.

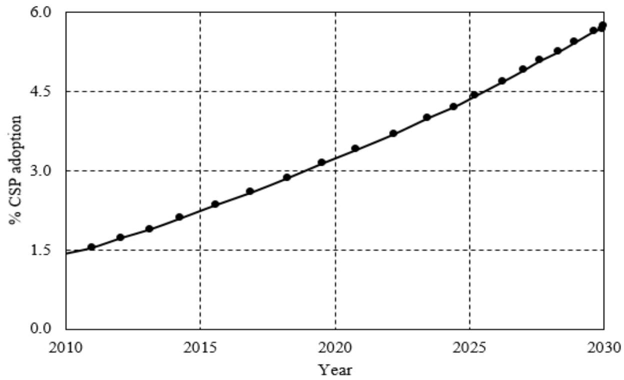


Figure 5-4. Rate of CSP adoption in SA: Baseline Scenario

Improved R&D

The R&D loop in the CLD as earlier shown in Figure 5-2 has a reinforcing effect on CSP adoption. Thus, in this scenario, factors that are directly linked to R&D were varied as shown in Table C1 in Appendix C, while other parameters in the existing model were left at baseline values.

The aim of this simulation was to check what the effect of developing R&D sector through demonstration plants and increased government support will be on CSP adoption. The building rate of demonstration plants was increased to 0.7 from 0.1 in the baseline scenario and the rate of hybridisation[5] with other RET changed to 0.5 from 0.3.

The simulation results shown in Figure 5-5 show that there is a significant increase in the operational flexibility and energy dispatchability of CSP technologies because of the changes made, and this led to a significant increase in the CSP adoption rate when compared to results from the baseline scenario. This result proves that improved support for research will open new methods and ways in which the CSP technologies can be deployed.

Improved R&D will also lead to better control mechanisms and smart grids which will eventually improve the electricity dispatchability strength of CSP. The rate of reduction of the environmental foot print (measured as a function of volume of water used per MW) also

[5] (RET hybridisation occurs when different types of RET are combined to form one plant. Here, the various types of RET complement each other in terms of dispatchability and uninterrupted power supply)

evidently increased as compared to baseline scenario. The rate of adoption of CSP in SA increased to 13 % in the improved R&D scenario by the year 2030 as shown in Figure 5-6.

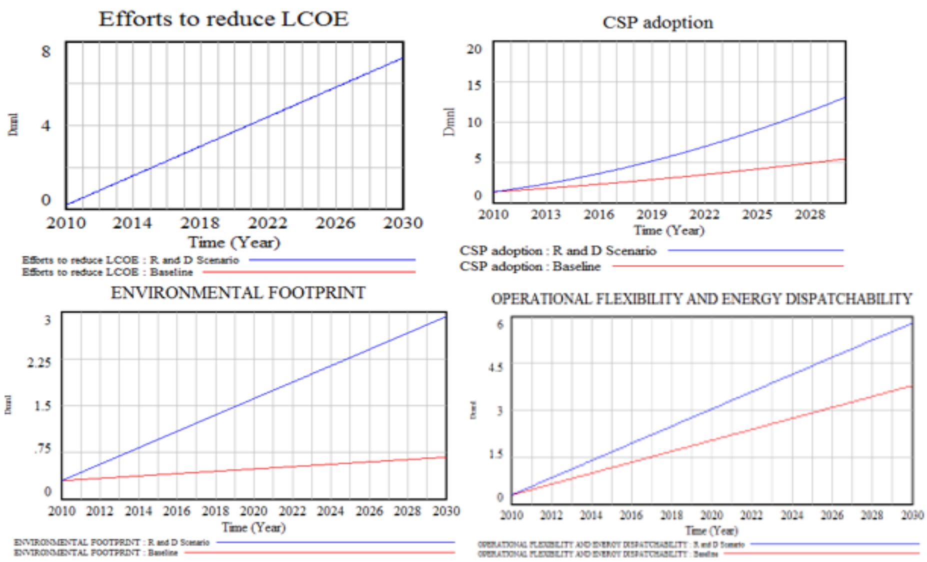


Figure 5-5. Simulation result of R&D Scenario (Blue: improved R &D scenario, Red: baseline scenario)

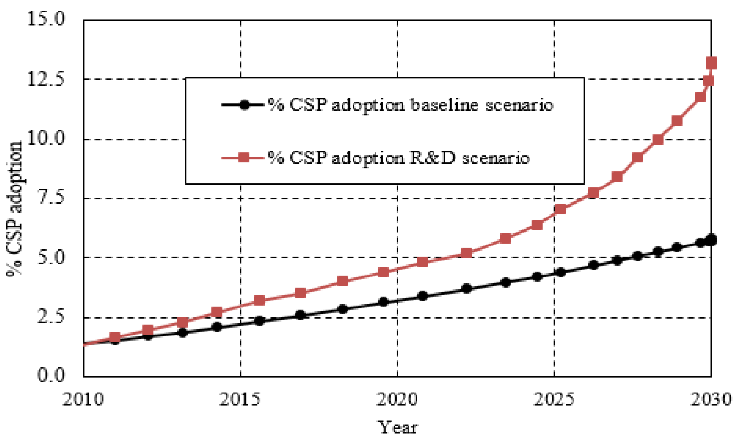


Figure 5-6. CSP adoption R&D scenario

Lower DNI plus Improved R&D scenario

With the established influence of R&D on energy dispatchability, flexibility of operations and CSP adoption, a scenario was developed to evaluate what CSP adoption in SA in the year 2030 would look like. The scenario is specifically based on CSP plants being sited in places with lower solar irradiation, but with improved R&D and better grid facilities.

To achieve this, the fractional impact of available DNI in the simulation analysis was reduced by half. The values for simulation of this scenario are in accordance the parameters in Table C1 in Appendix C. The rate of CSP adoption based on this scenario was compared to the previous scenario with improved R&D only and the baseline scenario and presented in Figure 5-7.

The rate of CSP adoption in places with lower DNI but very high R&D was higher with time than the value of adoption in the other scenarios.

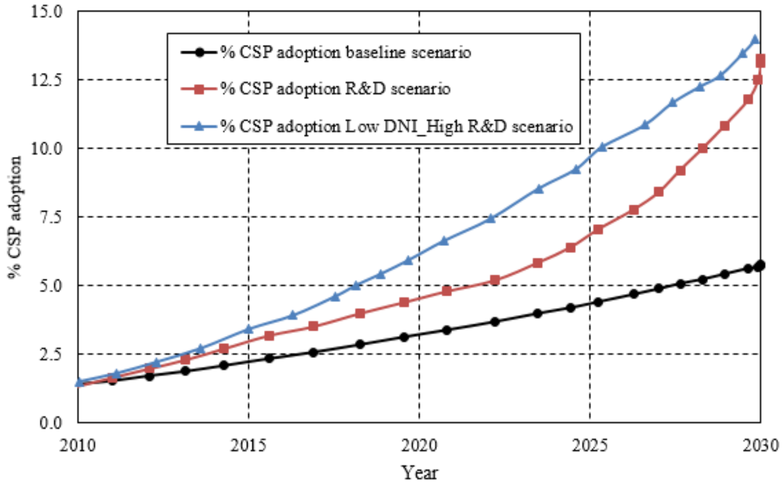


Figure 5-7. % CSP adoption comparison: Baseline, low DNI, and improved R&D scenario

If CSP plants are sited in other locations with lower DNI but better grid facilities, and a high R&D finance, there will be an increase in the technology learning rate and over time CSP will experience more adoption in these regions despite the lower solar resources (see Figure 5-7). There will be a greater increase in efficiency of the CSP technology because of the improved R&D and reduction in investment cost, as part of the capital cost which caters for new grid integration facilities, would be lowered or eliminated.

The result from this scenario explains why CSP thrives in Germany, Spain and United States, with lower solar resources as compared to SA, yet CSP plants are fully operational and large scale (NREL GIS, 2015).

In this scenario, the rate of reduction of LCOE over the years was lower than the first two scenarios. This is understandable as DNI has a direct impact on the LCOE calculation as it is a primary input function. The value of flexibility and dispatchability in this scenario was lower than the scenario with improved R&D and high DNI location, because of the impact of good solar irradiation on the rate of overcoming inertia and the hours of available sunshine.

Reduced water consumption scenario

One of the arguments that limited the adoption of CSP is its high level of water demand. The technology functions well at high temperatures, and wet cooling is frequently required.

There is often the need for high volume of water and this has habitually limited the adoption of CSP (Fluri, 2009). While CSP would function well in the desert and other hot regions because of the available solar resources, the fact that the technology will have to compete for the limited water resources limits the adoption.

Although, most manufacturers have developed dry cooled receiver systems to reduce water consumption (Gauché *et al.*, 2012; Brent, 2015; Xu *et al.*, 2016). The prejudice of the need for water still scare away many adopters, especially in regions with the challenge of drought like SA.

The effect of water consumption on CSP adoption in SA was analysed in this scenario, and this was achieved by increasing the rate at which new technologies use dry cooled components and by reducing the rate of change in the water usage by CSP plants based on experts' opinions. The input parameters are in accordance with the values in Table C1 in Appendix C. The expected CSP adoption based on this analysis is shown in Figure 5-8.

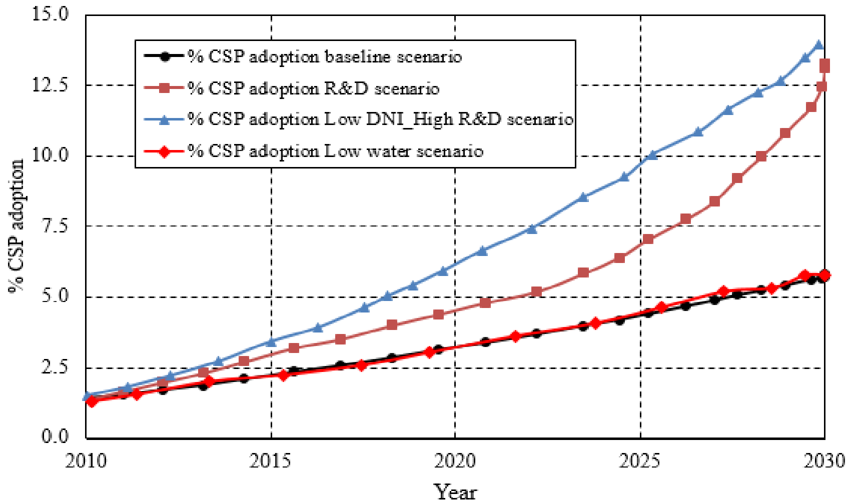


Figure 5-8. % CSP adoption reduced water usage by CSP scenario

5.4 Result summary and conclusions

The results of the various scenarios at a set time horizon are presented in Table 6.

Table 6: Overall result for policy decision for target year 2030 based on the scenario analyses

Scenario name	Factor by which LCOE will reduce	Factor by which environmental footprint will reduce	Factor by which operational flexibility and energy dispatchability will increase	% increase of CSP adoption
Baseline	2.2	0.67	3.8	5.4
Improved R&D	2.3	2.9	5.8	13.1
Lower DNI, High R&D	7.3	3.3	5.5	13.4
Reduced water usage	4.5	0.7	3.8	5.52

Table 6 shows that the improved R&D and the lower DNI with high R&D scenarios had highest CSP adoption. This means that, relying on the good solar resources alone without an improved local R&D and know-how may not accelerate the rate of CSP adoption. While natural minerals such as gold, platinum or crude oil may be profitable to an economy by just exporting them in their raw state, solar resources must be converted to electricity or heat for it to have a significant impact on the economy (Craig, 2015).

The overall results from the system dynamics analysis of CSP show the trends the technology is likely to take beyond 2030. Graphs, tables and a projection path with learning effects were developed. The chapter identified most important factors that can help achieve massive deployment of CSP and its components in SA. The study hence presents a policy decision instrument on the best approach to assist fostering large-scale adoption of CSP in SA.

The findings in this chapter identified the need to analyse the existing R&D budget and its impact on CSP technology and CSP related services in SA. However, because there are limited data in terms of R&D funding or its impact on CSP adoption as well as manufacturing capacity globally and in SA (Craig *et al*, 2017). The next chapter uses an expert elicitation approach to analyse the R&D budget in SA and to present a better portfolio of suggestions for CSP.

6. Expert elicitation of RD&D budget

The system dynamics analysis in the previous chapter shows the importance of R&D on CSP adoption. This chapter presents a detailed analysis of the state of R&D in SA and analyses the impact of improving it for future adoption of CSP. Various scenarios were considered, and the necessary policy recommendations presented.

6.1 Study justification

There are over 2,300 existing academic papers on expert elicitation in literature, based on SCOPUS search with key word *(TITLE-ABS-KEY: expert AND elicitation) and no boundary condition.* The search results showed that expert elicitation has been used in most sectors including, energy, agriculture, law, governance, health, SME's and many others. However, when the search result was modified, to get the existing expert elicitation studies that focused only on Africa with keywords: *TITLE-ABS-KEY (expert AND elicitation AND Africa)*, only 6 studies were found as shown in Table 7.

From this search, prominent authors like Bosetti *et al.* (2012), Fiorese *et al.* (2013a), Baker *et al.* (2009a; 2009b) and Chan *et al.* (2011) have used expert elicitation procedure, to determine the future of RET based on probabilistic information in Europe and in the United States of America. However, to our knowledge, none of this kind of research had been performed on RET in Africa. Thus, an expert elicitation among top CSP experts in SA will provide a much-needed insight into the impact of RD&D on CSP. This will be possible due to the solar resources available in SA and the progress in RET since 2010.

Table 7: Existing elicitation study in Africa

Authors	Title	Year	Source title	Document Type
Durbach, I., Merven, B., McCall, B.	Expert elicitation of autocorrelated time series with application to e3 (energy-environment-economic) forecasting models	2017	Environmental Modelling and Software	Article
Naicker, S.N., Richter, L., Stein, A., Campbell, L., Marston, J.	Development and pilot evaluation of a home-based palliative care training and support package for young children in southern Africa	2016	BMC Palliative Care	Article
Birol, E., Meenakshi, J., Oparinde, A., Perez, S., Tomlins, K.	Developing country consumers' acceptance of biofortified foods: a synthesis	2015	Food Security	Article
Williams, B.J., Cole, B.	Mining monitored data for decision-making with a Bayesian network model	2013	Ecological Modelling	Article
Whyte, G., Classen, S.	Using storytelling to elicit tacit knowledge from SMEs	2012	Journal of Knowledge Management	Review
Adams, F.K.	Risk perception and Bayesian analysis of international construction contract risks: The case of payment delays in a developing economy	2008	International Journal of Project Management	Article

6.2 Elicitation layout

This chapter focuses mainly on various types of CSP technology in SA. Moreover, it presents the comparison with other major countries in the CSP sectors, which were grouped as U.S.A, Europe, China, Chile, North Africa and others.

The study presents an elicitation of the opinions of CSP experts in SA. It considered the cost evolution and the state of the technology. It analysed the SA RET RD& D budget portfolio, and it identified existing technical and non- technical barriers to CSP cost and its adoption.

6.2.1 Expert elicitation procedure

All the individual responses to this survey were anonymously recorded, and the experts that participated in the study cut across academia, industry and national research groups. These groups are: the Centre for Renewable and Sustainable Energy Studies (CRSES), the Solar Thermal Energy Research Group (STERG), the Council for Scientific and Industrial Research (CSIR), and the South African National Energy Development Institute (SANEDI). The study was carried out between March and July 2017.

The survey was carried out via emails while the responses with inconsistencies were clarified through one-on-one discussions or via telephone calls. 70 emails and 9 web links were sent out, but only 14 experts responded. All the responses were analysed to ensure a wide range of opinions within the CSP community and to reflect the diversity of the experts' views.

6.2.2 Elicitation focus

For clarity in the questionnaire, the four types of CSP technology for generating electricity were sub-divided based on the existing types of Heat Transfer Fluid (HTF) technology as shown in Table 8.

CSP experts were then selected to participate in the survey to identify the impact of RD&D fund on CSP advancement, to determine the future cost of CSP electricity and to predict the future technical development.

The questionnaire had 6 sections:

1. Expert's background, bias, knowledge of CSP technologies and policies.
2. State of CSP, reference data and CSP technology evaluation.
3. The current stage of CSP type RD&D.
4. Optimal SA RD&D budget portfolio.
5. Technical and non-technical limitations to overall cost of investment and cost of CSP electricity.
6. Future cost of CSP electricity in SA based on various RD&D scenarios.

Table 8: Types of CSP technologies and their status

CSP technology type	Type of HTF technology
Parabolic trough	Parabolic trough (oil)
	Parabolic trough (molten salt)
Solar power towers	Solar power towers (steam)
	Solar power towers (molten salt)
linear fresnel reflectors	linear fresnel reflectors (steam)
	linear fresnel reflectors (molten salt)
Dish/Stirling system Technology	

An important limitation of elicitation studies is bias, which often affects the decisions of respondents. Bosetti *et al*. (2012) stated that all experts are also human and therefore can be affected by cognition and affiliations. Various strategies exist in the literature which has been used to overcome idea of bias and uncertainties in elicitation protocols (Morgan *et al.*, 1992; Van Der Sluijs *et al.*, 2005; Bosetti *et al.*, 2012; Fiorese *et al.*, 2013).

The major identified solutions involve making the survey questions as understandable as possible and to follow up with one to one interviews if there are any ambiguities or inconsistencies in responses. Also, it is necessary to notify the participating experts about the likelihood of bias judgment and to encourage a fair treatment of all matter under investigation.

To prevent underestimation or overestimation of values to the questions in the survey sections, options were provided based on data from reliable reports on the local and global state of CSP. However, additional spaces were provided for the experts to provide their own opinion if they disagree with any of the options in the survey.

6.2.3 Expert composition

In the first section of the survey, respondents were asked to evaluate their level of expertise on each of the various aspects of CSP technologies included in this questionnaire.

Figure 6-1 showed that 7 out of the 14 respondents identified themselves as among the top experts in CSP sector of SA, 6 claimed to have a very good knowledge and only one claimed to have the basic knowledge of the technology. The highest number of experts per sector was found in the solar power towers technology in which 4 of the respondents are among the top experts in SA. 12 of the respondents have good knowledge of SA CSP policies, but only 2 identified themselves among the top experts on linear Fresnel and SA CSP policies.

None of the respondents identified themselves as among the top experts in Dish/Stirling technology, but most of the respondents are highly specialised, and the degree of expertise was well spread through the various types of the technologies. Most experts in the academia showed high specialisation in the new or emerging CSP technologies (dish/stirling and linear Fresnel), while experts in other sectors showed a high degree of specialisation in policies and in parabolic trough and solar tower technologies, which are the most developed CSP technologies considered in the survey.

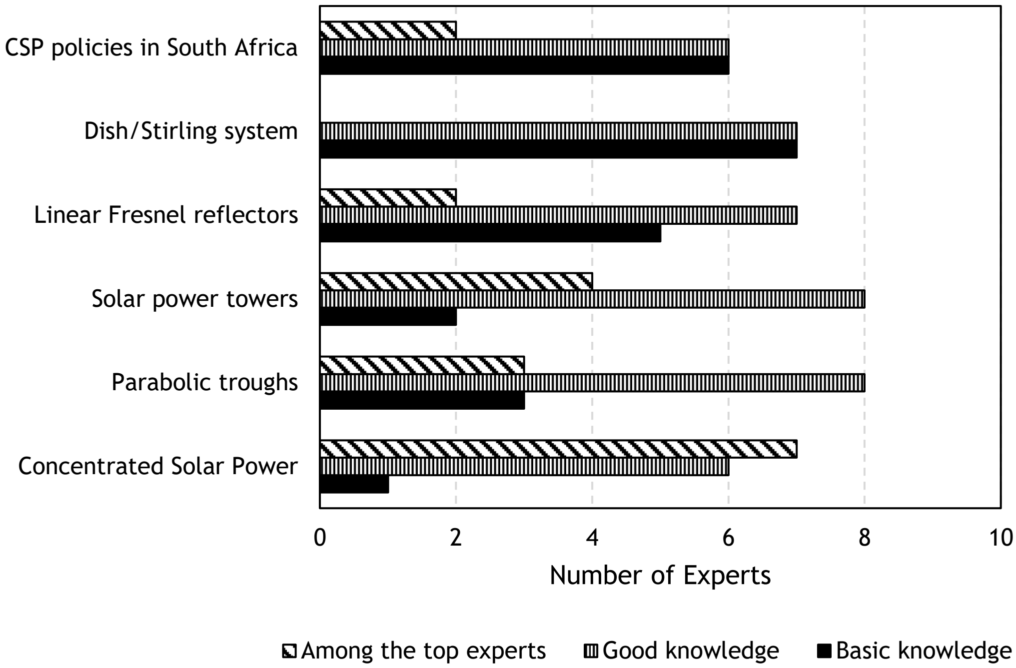


Figure 6-1: Expert compositions: The degree of expertise per technology

The expertise levels of the respondents based on their self-evaluation were also analysed using a weighting average of 4 as presented in Figure 6-2. Approximately 88 % (3.5 out 4) of the respondents have an expert knowledge in CSP, while the remaining claimed to have a general background in solar energy. The results show that the responses from each expert were somewhat biased based on their specialisation and interest. For example, some experts who were asked further questions about their knowledge of Dish/Stirling systems just said, since the technology doesn't look realistic, they never bothered to increase their knowledge of it.

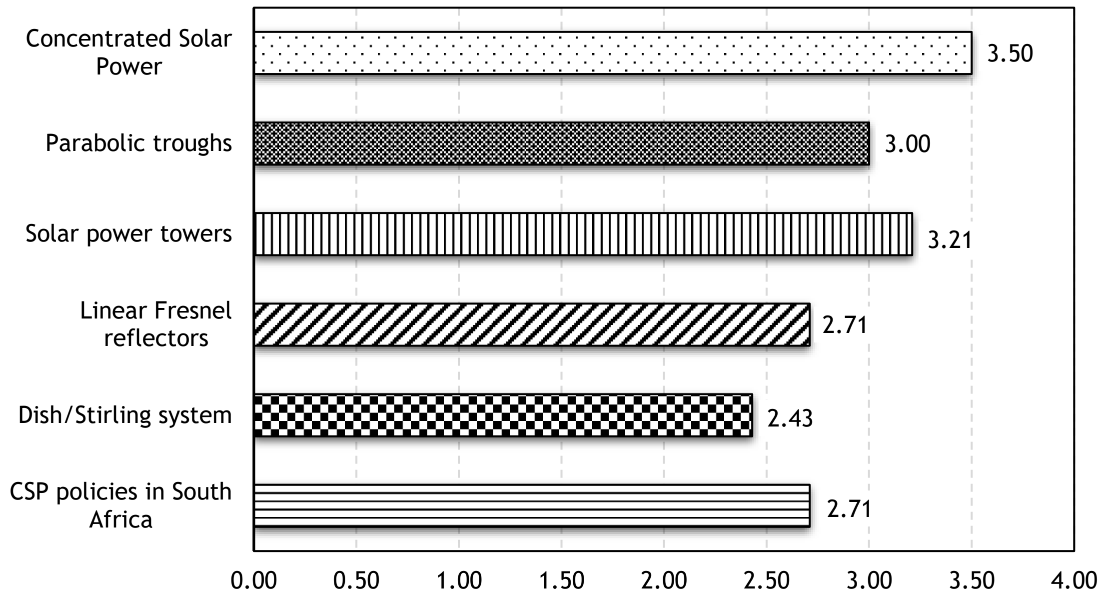


Figure 6-2: Rating average of the level of expertise of the respondents

(The rating presented in Figure 6-2 above shows the average level of expertise of respondents per each sector or type of CSP technologies considered in the study)

6.3 CSP technology evaluation

CSP technologies were further divided based on the HTF to increase the specificity of the evaluation. Experts were asked to evaluate the various types of CSP in SA based on their potentials, to identify the current maturity level of the technologies and to suggest the technological steps needed to make them achieve the identified potentials. The technologies were grouped from ones in early adoption stage to the ones in latter adoption stage.

Some technologies are new and may not be successful without significant advancement and other technologies are matured with no need for advancement. Fifteen per cent of the experts suggested that Dish/Stirling system and linear Fresnel (steam) might become unsuccessful if there are no urgent significant advancements in the technologies. While 22 % said the same for linear Fresnel (molten salt) (see Figure 6-3). Sixty-five per cent of the experts suggested that solar power tower technology (molten salt) and parabolic trough (molten salt) respectively have the highest chance of improvement. These technologies work and have room for development and advancement. They were therefore suggested as the most promising of all the technologies.

Fifty per cent of the experts identified Parabolic trough (oil) as a developed technology, with an excellent status and needing only slight advances, while 23 % of the experts identified that the same technology is fully matured and may require no further improvement.

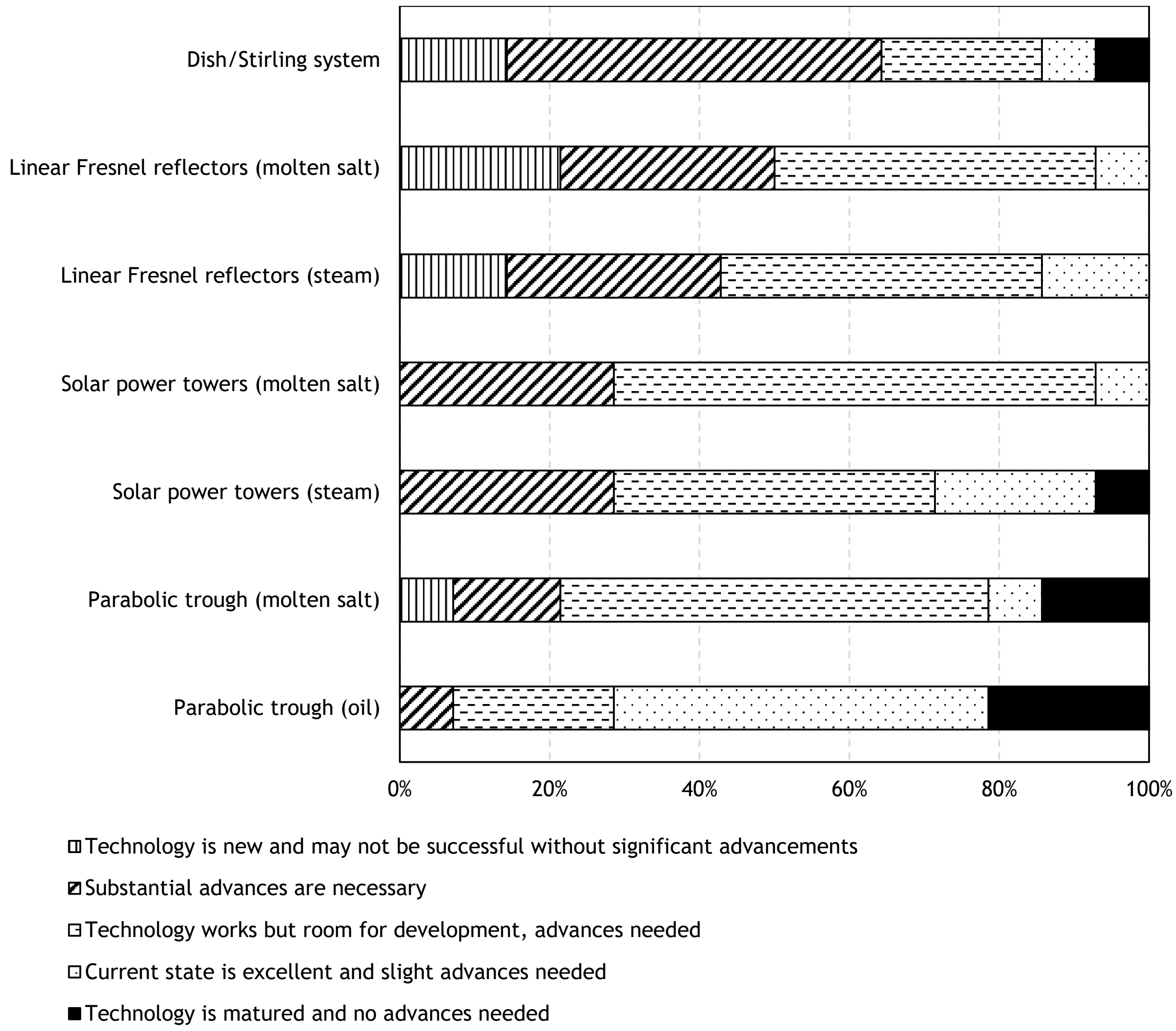


Figure 6-3: Current maturity stage of CSP technology types

Based on the results from Figure 6-3, experts were asked to specify the stage of research and development or demonstration (RD&D) that is needed to improve the types of CSP technologies considered in the survey. The RD&D was divided into stages as, basic research, engineering/applied research and demonstration. The definition of each stage of research was presented to the experts as shown in Figure 6-4.

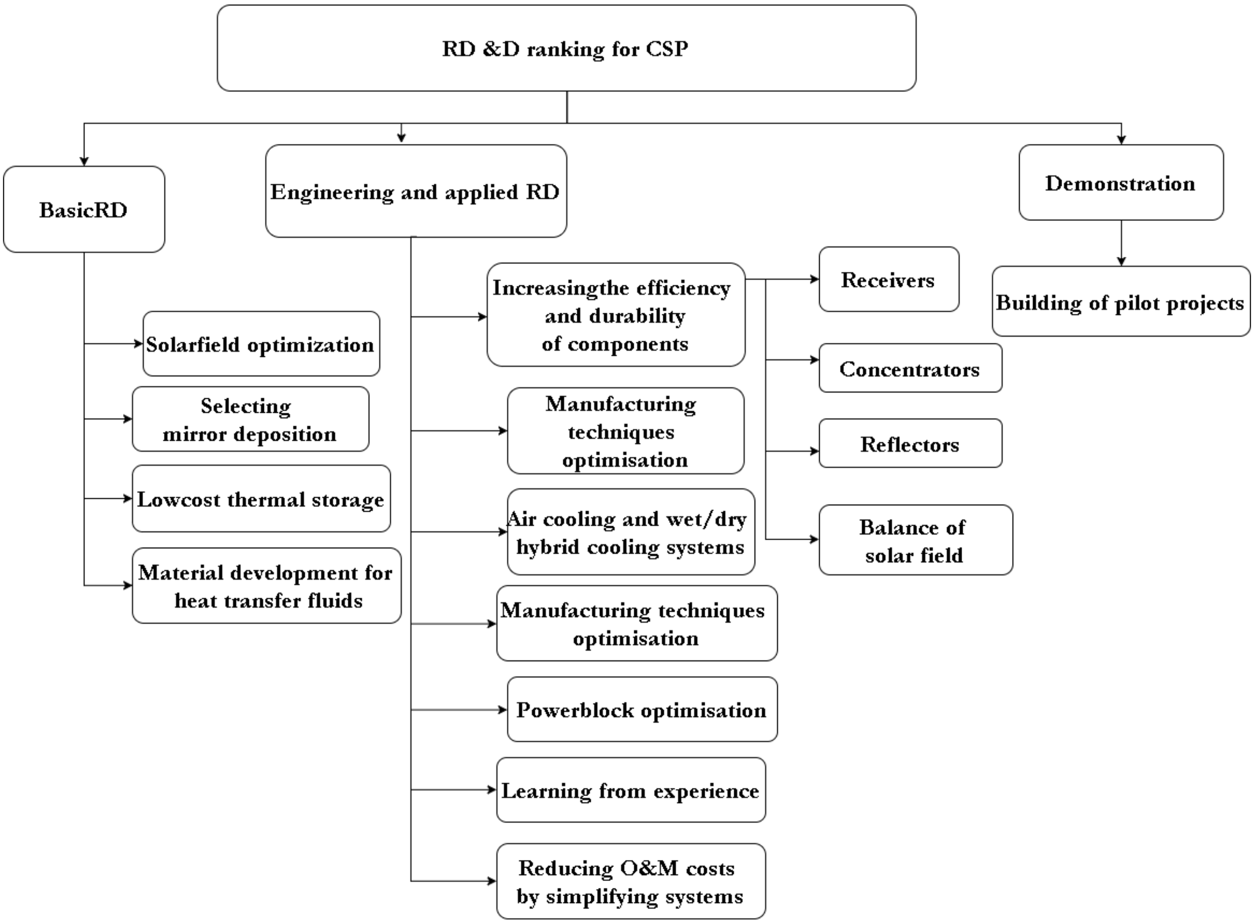


Figure 6-4: Classification of RD&D

Demonstration stage of RD&D in the study referred to the building of a test facility to prove the technology works and could be scaled up. Also, some aspects of any of the technologies could fall under the demonstration stage, if that aspect (subsystem) requires building of pilot projects before scaling up, and not necessary the whole technology.

The responses of the experts are shown in Figure 6-5, where they identified Dish/Stirling system as requiring a high-level of basic research to be successful. This response agrees with the level of maturity identified earlier. Other technologies on the other hand, require high-level engineering and applied RD, while most of the experts identified that solar power tower (steam) and parabolic trough (oil) need no further demonstration, as the technologies have been tested and are fully in use.

The molten salt-based technology for parabolic trough, solar tower power systems and linear Fresnel need some high-level demonstrations. Experts claim that although the technologies have been proved to work, some specific challenges needed to be overcome before scaling up. Linear Fresnel (molten salt) needs very little basic R&D, but requires demonstration sites and then high-level engineering, applied RD. Also, experts identified that linear Fresnel (steam) needs very little demonstration as the technology works, but it requires a lot of improvement in terms of in engineering and applied RD to break through.

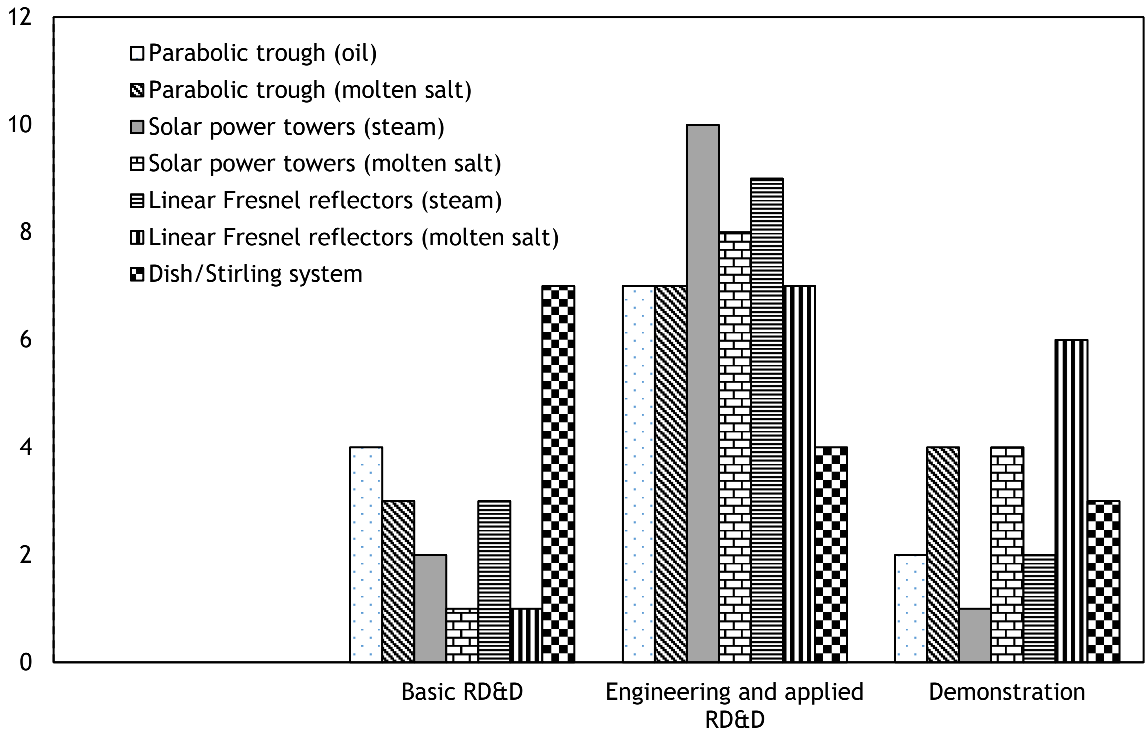


Figure 6-5: Stages of RD&D per technology

Most of the experts identified engineering and applied RD&D as the most important stage that should be concentrated on for CSP research in SA, followed by demonstration and basic research respectively (see Figure 6-5). Therefore, more attention needs to be given to outdoor research, which involves development and testing rather than basic in-house research.

The need to improve the learning effect by practical demonstration was identified and most of the experts suggested that specific CSP challenges be solved in applied research through development, demonstration, testing and optimisation, with the aim of commercialisation and patenting rather than simulation and paper writing.

The results from this section fairly disagree with the Wiesenthal *et al.* (2009) report that identified basic research as the driver of technologies. The results agree with the expert elicitation carried out among solar energy experts in Europe by Bosetti *et al.* (2012). They also identified that applied research would be the major driver of solar energy technology adoption rather than basic research.

6.4 Allocation of RD&D fund

To present a balanced mix of RD&D funding portfolio for CSP in SA, the constant sum survey approach was used. Experts were allocated 100 chips which represent the current public research budget/expenditure on CSP in SA. They were asked to allocate the chips among the types of CSP technologies in SA as identified in the survey. The individual budget allocation of each expert is represented by code numbers[6] on the x-axis, as illustrated in Figure 6-6.

Over 35 % of the experts allocated no chips (U-chips) to Dish/Stirling systems and suggested that further major research should not be done on this technology, as its chances of success are slim. Three of the experts in this category stated that Dish/Stirling engine is only good for academic demonstration purposes, and the system has little or no realistic promising feature in terms of large scale roll out or nationwide adoption. They also noted that further funding of this technology, with the aim of commercialisation, may yield no positive result and may harm the overall image of CSP.

Solar power towers received the highest chips allocation but with highest fluctuations across the budgets of all experts. While Expert 12 and 13 allocated 15 % to it, other experts gave it higher percentages. Experts 2 and 7 gave 70 % and 80 % of their budget to solar power tower respectively, thus having the largest share and the largest spread. Expert 11, on the other hand, believes so strongly that more RD&D will make parabolic trough compete favourably with existing conventional power generation techniques and thus allocated 80 % of his RD&D budget to parabolic trough technology.

[6] identities of each expert were replaced with code numbers in no particular order

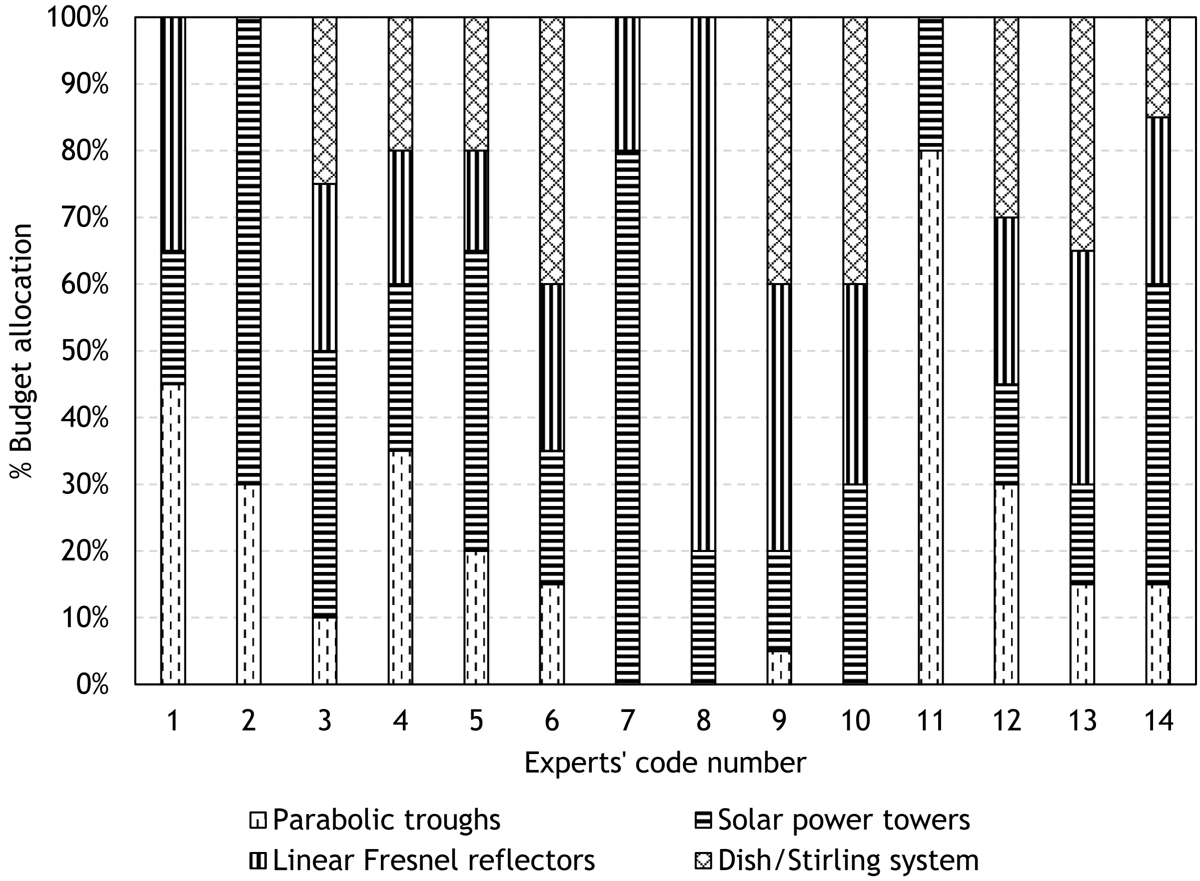


Figure 6-6: Percentage budget allocation by each expert

The fluctuations in the overall budget allocations show the diversity of the experts' opinion on CSP technology in SA and how RD&D can help its breakthrough and adoption.

For easy comparison of budget allocations among all the experts, the overall budget allocation by the experts per each type of technology considered, was calculated and presented in Figure 6-7.

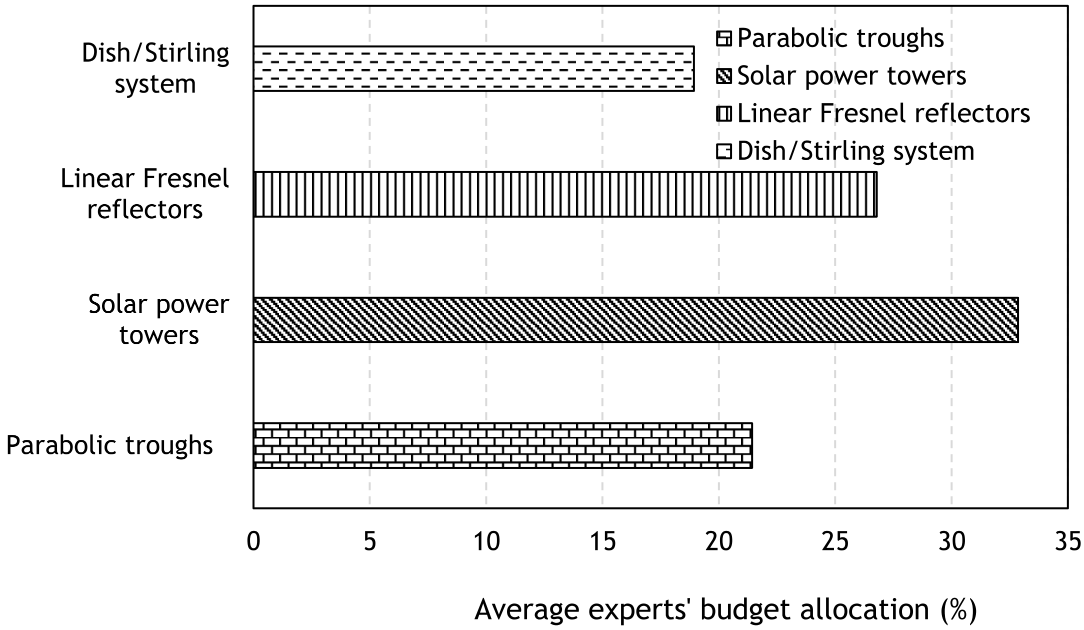


Figure 6-7: Average experts' budget allocation

In Figure 6-7, solar tower technology received approximately 33 % of the overall experts' budget in the survey. All the experts believed that the technology works and that it has the highest room for improvements, in terms of its storage, capacity factor, efficiency and levelised cost of electricity (LCOE). Linear Fresnel reflectors received 27 % of the experts' budgets, because of the reduced complexities that accompany it as compared to the solar towers.

Many of the experts believe that linear Fresnel has lower investment cost, and should this technology become successful in terms of scaling and storage. Thus, it could be the CSP champion in the future. Parabolic trough technology received 21 %, which comes third on the average experts' ranking.

The majority of the experts agree that parabolic trough is the backbone of CSP technology and that it is the most matured and currently the most competitive in terms of cost. However, some experts argued that since the learning rate of parabolic trough has not yielded any major reduction in cost over the years as compared to other RETs. Thus, it should not receive the highest RD&D funding.

Conversely, other experts stated that the potential of parabolic troughs have not been well harnessed. More RD&D needed to be done on various aspects of the technology including heat transfer materials, energy conversion and storage and that with a leap forward in such aspects, parabolic troughs will surely help CSP advance in the ongoing battle of RET electricity cost. Dish/Stirling technology, however, received the lowest budget allocation as expected based on the responses from the previous sections. Nineteen per cent of the total experts' budget allocation was given to Dish/Stirling, and most of the respondents who allocated chips to this technology are experts in the academia, who are idea and basic research enthusiasts. Some of them argued that not enough research had been done to prove that there are no feasible storage techniques for Dish/Stirling technology.

Overall, the experts gave a wide range of CSP RD&D portfolio by allocating chips to the various types of technologies presented to them. While solar power tower may have received the highest average, it cannot be generalised that it should receive the highest funding allocation in the CSP RD&D portfolio, because the average presented was based on the individual author's allocations.

However, it can be said that solar tower, parabolic trough, and linear Fresnel received good allocation among all the experts as they identified that they have very high potential and that more effort should be put in to improve their abilities and to identify their potential market.

6.5 Cost analysis: the future cost of CSP based on different RD&D Scenarios

This section aims to identify which scenario of RD&D funding would lead to the greatest reduction in CSP investment and electricity cost. In this section of the survey, experts were asked to estimate their expected cost of electricity produced with CSP technologies in 2040 under the following public RD&D investment:

- Scenario 1: Research in the field of CSP receives the current yearly amount of R&D (SA public RD&D expenditure).
- Scenario 2: The current yearly amount of R&D expenditure in CSP increases by 25 %.
- Scenario 3: The current yearly amount of R&D expenditure in CSP increases by 50 %.

Experts were given 4 ranges of cost options to estimate what the future cost of CSP electricity under the scenarios presented would be. An extra option was added to give the experts the freedom to suggest their expected cost if it does not fall within the ranges presented to them.

The results in Figure 6-8 show that 50 % of the experts agreed that the current cost of CSP in SA is likely to remain unchanged if the current budget allocation RD&D in CSP does not increase. Thirty per cent of the experts indicated that the current RD&D expenditure on CSP in SA will lead to a fair reduction in electricity tariff to around 8.6 c$/kWh (ZAR 1.2/kWh), which is still less than the present day solar PV price, in the year 2040. However, this will be through a slow reduction rate.

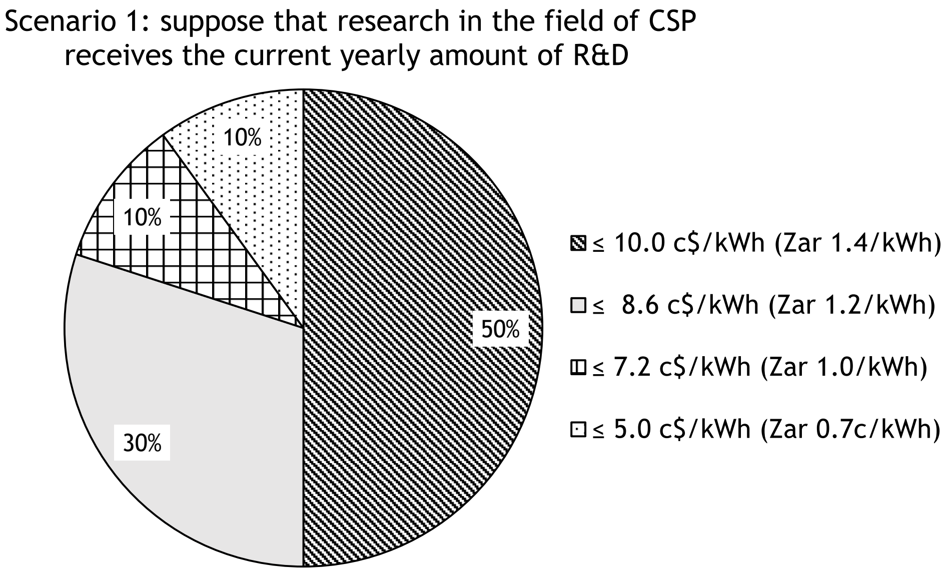


Figure 6-8: Future cost of CSP electricity in SA with current RD&D funding

The remaining 20 % of the experts stated that the current R&D will eventually lead to a low CSP cost of around 5.0 – 7.2 c$/kWh, claiming that effective utilisation of RD&D fund plus global market force could force down the CSP cost in SA.

Scenario 2 was set to analyse what the impact of a 25 % increase in the current public RD&D would be on the cost of CSP electricity in 2040. The same range of CSP electricity cost was presented as before in scenario 1. A drastic optimism was seen in the responses of the majority of experts as 47 % immediately proposed that the cost of CSP electricity in 2040 will be less than 7.2 c$/kWh (ZAR 1/kWh).

While 35 % proposed that the cost of CSP electricity will be less than 8.6 c$/kWh but not as low as the 7 c$/kWh mark. Six per cent of the experts remained pessimistic about the reduction in the future cost of CSP electricity in this scenario, while the other 12 % were very ambitious and suggested a 50% reduction in cost of CSP electricity could be achieved in this scenario, leading to CSP electricity cost of 5 c$/kWh in 2040 (see Figure 6-9).

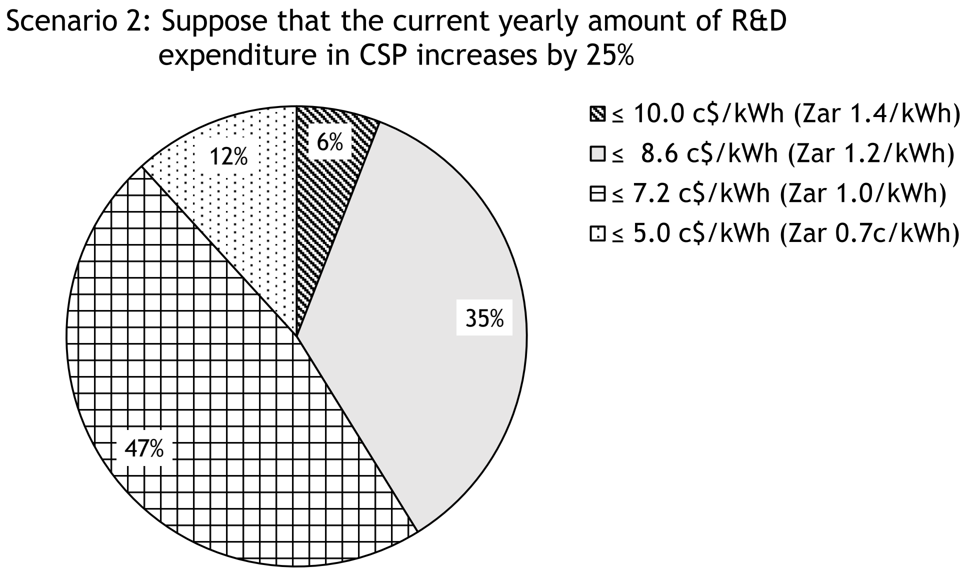


Figure 6-9: Future cost of CSP electricity in SA with 25 % increase to the current RD&D funding

The experts were provided with the third and most ambitious scenario, in which we aim to determine what the future cost of CSP electricity would be in the year 2040 - if the current CSP public RD&D expenditure is increased by 50 %. The majority of experts (61 %), as represented in Figure 6-10, said that the cost will be lower than 5 c$/kWh (ZAR 0.7c/kWh). Thus, will lead to maximum CSP adoption and competitiveness, while the remaining percentage was a fair mix among other costs.

However, three experts indicated that even if the CSP RD&D cost increases by 50 %, it is not likely to yield any effect on the cost of CSP electricity. Two of these experts identified local manufacturing capabilities as a major limitation while the other identified politics and the willingness on the on the part of the government as important actors in cost reduction of CSP technologies.

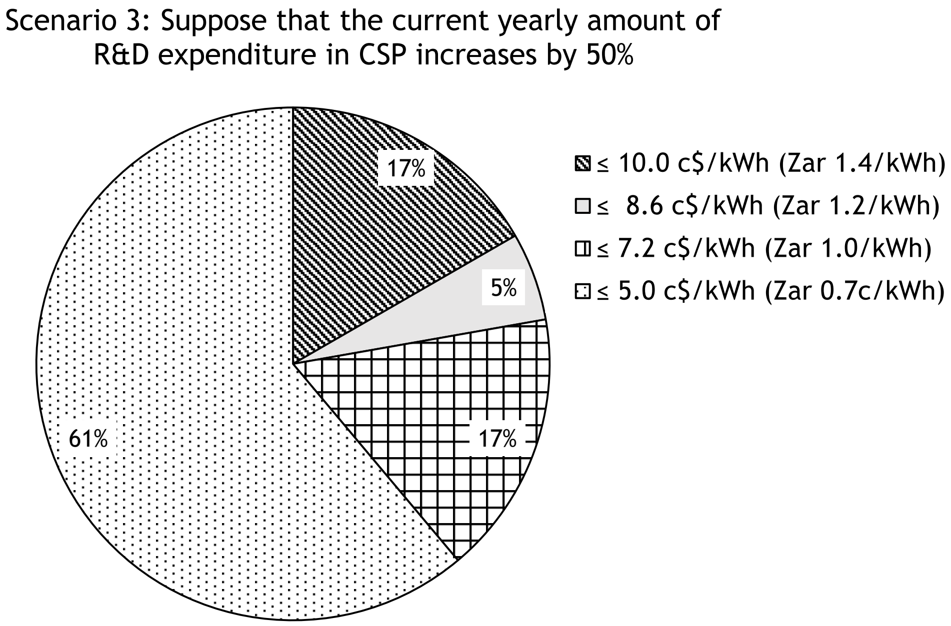


Figure 6-10: Future cost of CSP electricity in SA with 50 % increase to the current RD&D funding

This section showed that all experts in CSP in SA agreed that there is a direct link between RD&D and electricity cost of CSP. Moreover, the experts state that an increase in the RD&D expenditure will lead to a significant reduction in the investment and electricity cost of CSP.

However, there was a huge disparity in the exact quantification of the effect. Experts 8 and 12 (see Figure 6-11) explained that, if the current CSP RD&D expenditure does not increase by up to 50 % or more, there will be no momentous change in the electricity cost of CSP. They only gave answers to scenario 3. Experts 3, 7, and 9 suggested that depending on the priority of the research work, cost reduction in Scenario 2 could get as low as 7 c$/kWh, but they are very sure that the cost would be lower than 8.6 c$/kWh by 2040 in such scenario.

There were follow up interviews with experts whose chips were allocated inconsistently. They explained that only an increase of 100 % or more on the RD&D expenditure on CSP would lead to flexibility of research. In this instance, less matured technologies with higher uncertainties and matured technologies with huge potentials, can both be improved and developed to become better and more competitive systems. Experts state this would probably usher in an era of exponential cost reduction of CSP technologies.

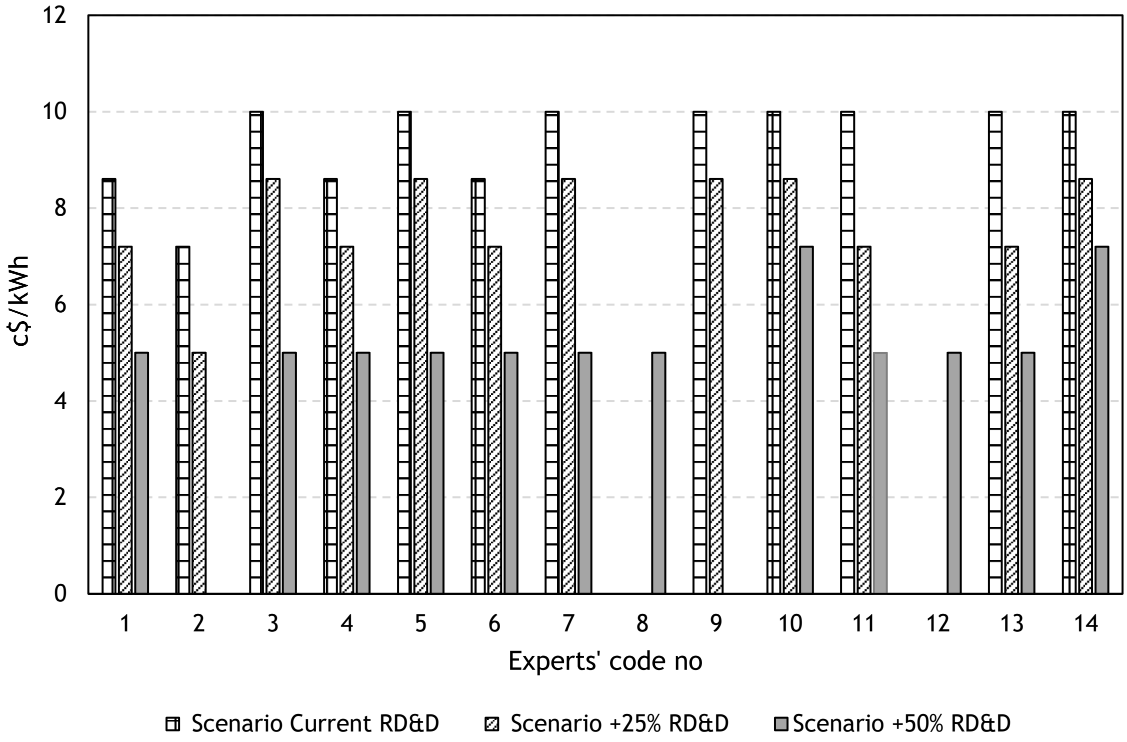


Figure 6-11: Variation in experts' responses

To regularise the identified inconsistencies in the experts' responses in this section, specific experts were asked what the minimum breakthrough cost of CSP in SA would be. On average, they suggested that any cost below the 7.0 c$/kWh (ZAR 1.0/kWh) would break through, therefore setting a threshold of ZAR 1/kWh. One specific expert said that, if these threshold costs were not achieved by year 2030, there would be no need to build newer CSP plants, as that could be the end of the technology in SA. The follow-up questions made it easy to eliminate ambiguity in the experts' answers. Those who gave more than one cost option per scenario as identified before, were asked to select their most preferred scenario (see Figure 6-11).

In summary, this section also confirms that all experts agree that the current RD&D budget may lead to no reduction in the future cost of CSP. An increase of 25 % on the current public RD&D expenditure in CSP could have a cost reduction effect. However, it may not lead to a competitive cost (threshold cost) as it can only achieve cost reduction to between 8.6 c$/kWh and 10 c$/kWh, which is higher than the present cost of some generation techniques. An increase of 50% or more on the RD&D budget could force a significant reduction in CSP cost which would further reduce the cost beyond the threshold to reach around 5.0 c$/kWh (ZAR 0.7 c/kWh).

6.6 RD &D specificity

There are several barriers limiting CSP development, hence its slow adoption. Having confirmed that RD&D expenditure has a significant effect on the future cost of CSP, it is necessary to understand the impact of overcoming some specific barriers in CSP subsystems on the overall cost of its electricity. These barriers were categorised into 3 groups, namely, technical barriers, non-technical barrier and other general indicators.

This section seeks to analyse how optimisation of the technical factors and improvement on the non-technical factors can lead to a reduction in the cost. Moreover, this section explains how other indicators affect the overall cost of CSP electricity.

6.6.1 Impact of technical factors

To analyse the technical factors affecting CSP in SA, the most relevant factors as identified by Kulichenko & Wirth (2012), WWF (2015) and REN21 (2016) were used as indicators, and efforts to overcome the barriers surrounding these sub-systems were analysed. The factors include:

- Balance of plant costs and other issues;
- thermal energy storage;
- heat transfer fluids;
- solar field: Mirrors, receivers and support structures; and
- increasing plant size.

It is important to identify the experts' expectations on which indicator would have the most effect on CSP electricity cost. To achieve this, weighted average was used, and experts were asked to rank the indicators in order of their influence on the reduction of CSP electricity cost in SA. The factor with the least influence received the lowest rank, while the factor with the highest influence received the highest rank.

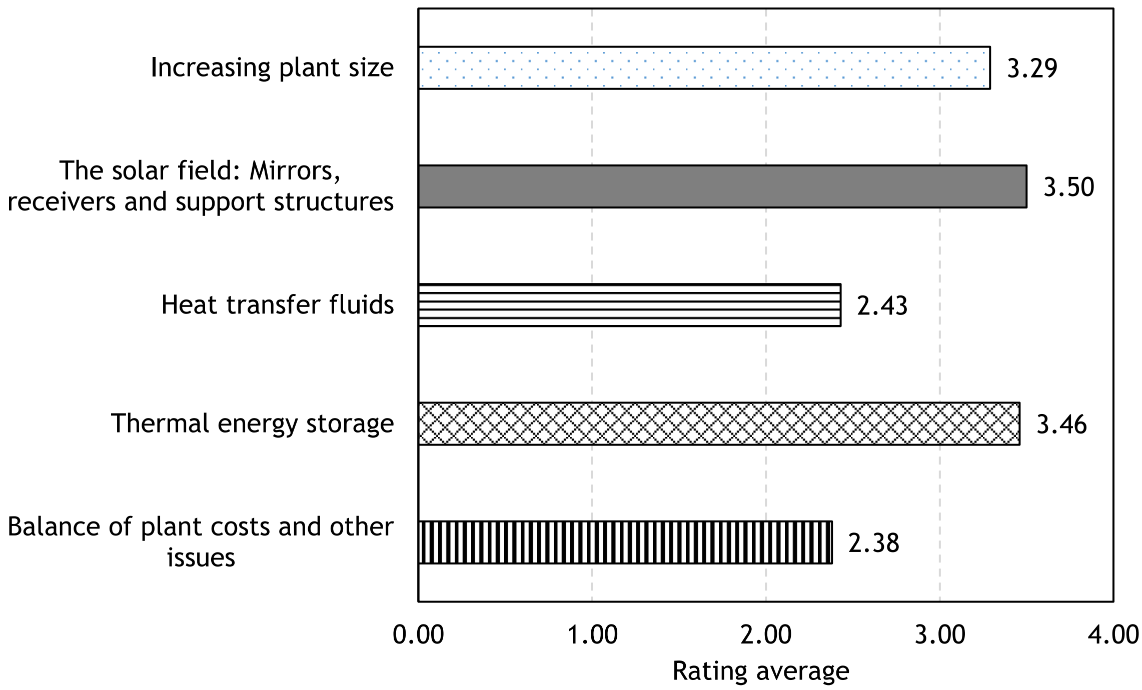


Figure 6-12: Rating average of CSP cost reduction Indicators

Experts identified that all five indicators have a very high influence on CSP electricity cost reduction (see Figure 6-12), as all the indicators received more than 50 % of the average rating. There is no limit to the amount of energy that can be harnessed from the sun. Therefore, the need to provide more efficient but cost effective solar mirrors and receivers was identified.

Solar field (including receiver and support structures) optimisation was ranked by the experts as having the highest impact on CSP cost of all the indicators identified. This also includes optimisation of the available land and the general layout of the solar field. Support structures, which will promote the security of plant against natural and human disasters. Thus, reducing the risks associated with the development of solar plants in areas with good solar resources.

The next important indicator as identified by experts is the development of cheaper and more efficient thermal energy storage systems. The CSP's ability to store energy allows for easy electricity dispatchability and thus can supply electricity throughout a day or when it is needed. Consequently, development of better storage will increase the capacity factor of the technology, which will lead to a reduction in investment cost and boost the confidence of funding organisations.

The third indicator, according to the ranking, is the plant size. Experts identified that increasing the plant size of CSP, which also includes allocation of more megawatts of electricity to CSP during bid rounds, will lead to better learning effect. Consequently, reduced cost. Most existing CSP plants have been built-in units with each layout and components unique, thereby making the process of learning by doing complicated (Schmalensee, 2015). It is therefore important that a large roll out of CSP technology be encouraged to force down the cost.

Heat transfer fluid is very important in CSP technology and one of the major determinants of the system's overall performance. The HTF does the work of transferring fluid from the heat receiver to the power block and also performs the function of heat storage (Kalogirou, 2009; Duffie & Beckman, 2013). Experts suggested that significant reduction in the cost of HTF would lead to a reduction in the overall cost of CSP electricity (see Figure 6-12). In addition, some experts suggested some specific features, which upcoming RD&D on HTF must target to achieve an overall CSP electricity cost reduction as:

- HTF with higher heat capacity for energy storage;
- HTF with reduced viscosity; and
- HTF with higher thermal conductivity.

The above factors identified by the experts in this study are in accordance with the existing and ongoing studies on ways of improving the performance of HTF in CSP technologies (Cordaro, Rubin and Bradshaw, 2011; Vignarooban *et al.*, 2015; Pacio & Wetzel, 2017). This section thus confirms that an improvement in the characteristics of HTF with an accompanying cost reduction will contribute immensely to the overall reduction of CSP electricity cost.

Several other systems and external costs relate to CSP. The balance of plant cost and other issues like grid connection systems, electricity transmission and availability of local experts are among other technical issues which need to be identified and improved upon to reduce the CSP electricity cost. Experts in this study identified that there are still many uncertainties around these factors, which give room for improvement.

6.6.2 Non –technical factors

There are several non-technical factors affecting CSP cost and adoption, some of which vary depending on the location of the plant or the state of the nation. The major non-technical barriers limiting massive adoption of CSP from existing studies were analysed (Charles, *et al.*, 2005; Trieb, 2005; SAGEN, 2013; IEA, 2014b; Brent, 2015; CSP Today Markets Reports - South Africa, 2015). The most relevant factors to CSP electricity in SA were determined and set as indicators to understand the impact of non-technical barriers on CSP cost and its overall adoption. To achieve this, experts were asked to assess the importance of each of the following non-technical factors limiting the further adoption of CSP technologies:

- Long-lived capital stock and turnover of power plants;
- long range transmission;
- geographical constraints;
- unfavourable power pricing rules;
- water usage;
- land availability;
- politics; and
- other energy sources (e.g. nuclear deal).

Weighted average was used, and experts were asked to rank the selected barrier indicators in order of their influence on the reduction of CSP electricity cost. In their response, the majority of the experts ranked politics, government's interest on other energy sources and unfavourable power pricing rules as having highest impact of all the non-technical barriers on the cost reduction of CSP electricity (see Figure 6-13). These, however, are in agreement with the major concerns raised in the activities carried out in this section on CSP in SA (Pierce *et al.*, 2017).

Breukers & Wolsink (2007) had shown how government interest can foster a boost in RET and how a lack of sense of urgency in terms of energy and environmental sustainability can limit its progress. For example, in 1985, the German government decided to develop large scale wind turbines, an effort which failed. However, their interest in RET got stronger and in 1988, they diverted the remaining RD&D budget to small scale wind turbine development. This effort encouraged the participation of many research and academic institutions.

By the end of 1995, North Rhine-Westphalia (NRW) province in Germany solely produced 97 MW wind turbines locally (Borchers & Landesoberbergamt NRW, 2009). That was the beginning of a massive roll out of wind turbines, its adoption and eventual cost reduction that occurred in the following decades. This confirms that government interest and investment can foster massive deployment of CSP.

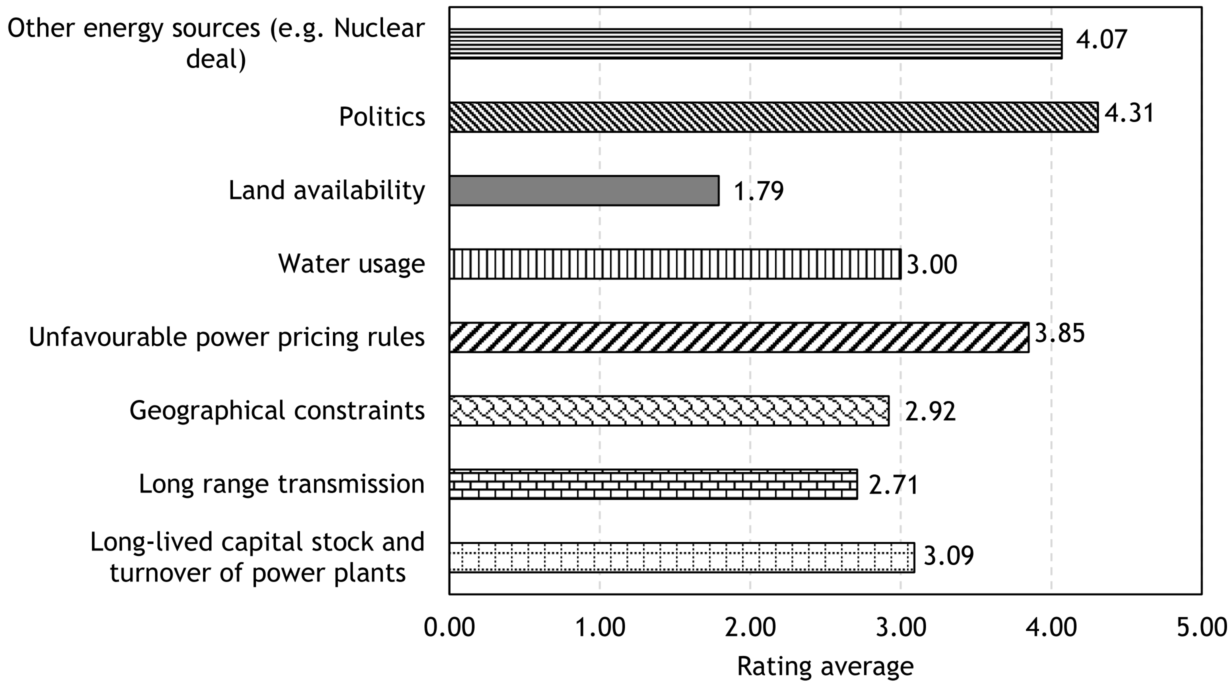


Figure 6-13: Average rating of non-technical barriers to CSP in SA

Experts also identified that inconsistency in power pricing rules (see Figure 6-13) and the cases of failed promises, may harm the progress of RETs. An example of this is Redstone, a 100 MW solar tower power plant in the Northern Cape of SA. The project is yet to reach its financial closure and still waiting for ESKOM's purchasing agreement to secure debt.

This has not been achieved for over a year, despite the promises of immediate sign off (SAIREC, 2015). Cases like this could contribute to future reluctance by stakeholders to contribute to RET development in SA. Experts also pointed out that the SA government's interest in using nuclear, as the next major source of electricity has led to the marginalisation of new clean and sustainable power generation methods like CSP.

Unfavourable power-pricing rules make it difficult for CSP to compete with other matured and existing power generation methods when placed in the same bid and under the same electricity cost cap. Experts pointed out that only technology specific and strategic power pricing rules can help develop various types of alternative power generation methods. An example of this is the cost reduction witnessed in CSP electricity in SA after the power pricing tariff was optimized for CSP. The optimisation includes a two-tier tariff plan used to replace the initial single tariff plan in the SA REI4P latter bid windows (BW 3 and BW 4) (earlier presented in Figure 3-3). This confirms that there is a direct relationship between power pricing rules and the cost of CSP.

CSP plants are often sited in arid environments and they require water for cooling. These locations are often characterised with limited water supply, thus making CSP a possible contributor to water shortage. This is a major limitation in the usage of wet cooled CSP systems. To reduce water usage by CSP, there have been recent developments in which dry cooled technologies are used instead of the wet cooled ones (Gauché, Backström & Brent, 2011, 2012).

Other techniques that have been used to save or reduce water usage include the re-use of waste water and the use of machines with higher thermal efficiencies that require less water. In plant locations with high ambient temperature (which sometimes prevent the use of dry cooling), hybrid cooling has been used in which dry cooling is used until the ambient temperature rises to a level where the technology is ineffective and the system switches to wet cooling, thereby reducing the overall water consumption (IRENA, 2012).

Experts in this study identified the prejudice of CSP, as a competitor for insufficient water as a negative contributor to the adoption perspective of CSP. This will be especially effective in areas where water is expensive, improved systems with reduced water usage will reduce the overall cost of CSP. Sixty per cent of the experts agree that a reduction in water usage will surely lead to a major reduction in the cost of CSP electricity and with the on-going research, the water usage barrier will soon be overcome. The majority of experts suggested that more information needs to be made available on the water usage of CSP plants, so the prejudice of CSP as a contributor to drought could be overcome. CSP technology can help in solar desalination in coastal regions which could also help countries overcome the challenge of drought (Trieb, 2005; Kalogirou, 2009; Braun *et al.*, 2011).

Most CSP plants are in the Northern Cape region of SA, and therefore require long-range transmission to other areas. This is a major concern as there is variability in the DNI received in the country at various locations. Experts in this study were asked to determine the effect of geographical constrains and long-range transmission on CSP electricity cost.

While some of the experts pointed out that these are minor barriers, over 40 % believe that these two factors contribute effectively to the overall cost of CSP electricity. In follow-up interviews, some of the experts suggested that the DNI received in some locations in SA give the country a fantastic opportunity to develop local capacities to manufacture some CSP equipment, which can be exported to other countries.

Although recent developments in CSP in SA had led to the localisation of some companies, most CSP technical components are manufactured abroad and majority of the systems are imported, hence, increasing the investment cost of CSP technology. For complex engineering systems like CSP, there is often a need for localisation of structural designs and technology, in order to suit the local use and environment (Tödtling & Trippl, 2005).

In this section, three of the experts suggested that SA should articulate her CSP value proposition to attract foreign investors to build local capability on CSP components. The responses of the experts agree with the GIZ SAGEN report (SAGEN, 2013) which suggested that SA should develop specific strategies to attract foreign investment. Thus, leading to the overall development of local capability, export markets and the RET sector.

Land characteristics like cost, slope and availability also affect the cost of CSP electricity (SAGEN, 2013). Experts were asked here to analyse these effects, and from the result shown in Figure 6-13, challenges of land availability were ranked lowest out of all the non-technical barriers by a majority of the experts. Some experts suggested that the relationship between host communities and CSP companies is very crucial to security of the plants, and some concerns were raised that CSP sites are often located far from where the electricity is needed.

Therefore, experts suggest the use of better grid connection strategies including the use of a smart grid. The expert responses in this section agree with Bosetti *et al.* (2012), in which European experts ranked land availability as the lowest of all factors affecting solar energy advancement.

6.6.3 Other general indicators

To check bias and inconsistencies in the experts' responses to the technical and non-technical indicators, a list of expenses and subsystems of CSP was provided. Experts were asked to rate the impact of these items on the overall cost of CSP plant and electricity.

The items/expenses are not comparable, therefore rating average from the expert rankings was used to present a radar chat, in which values of the individual effect was presented as relative to a centre point (see Figure 6-14). The values are presented in descending order of their impact starting from DNI with the highest impact to waste water cost which has the lowest impact on CSP cost of investment and electricity in SA.

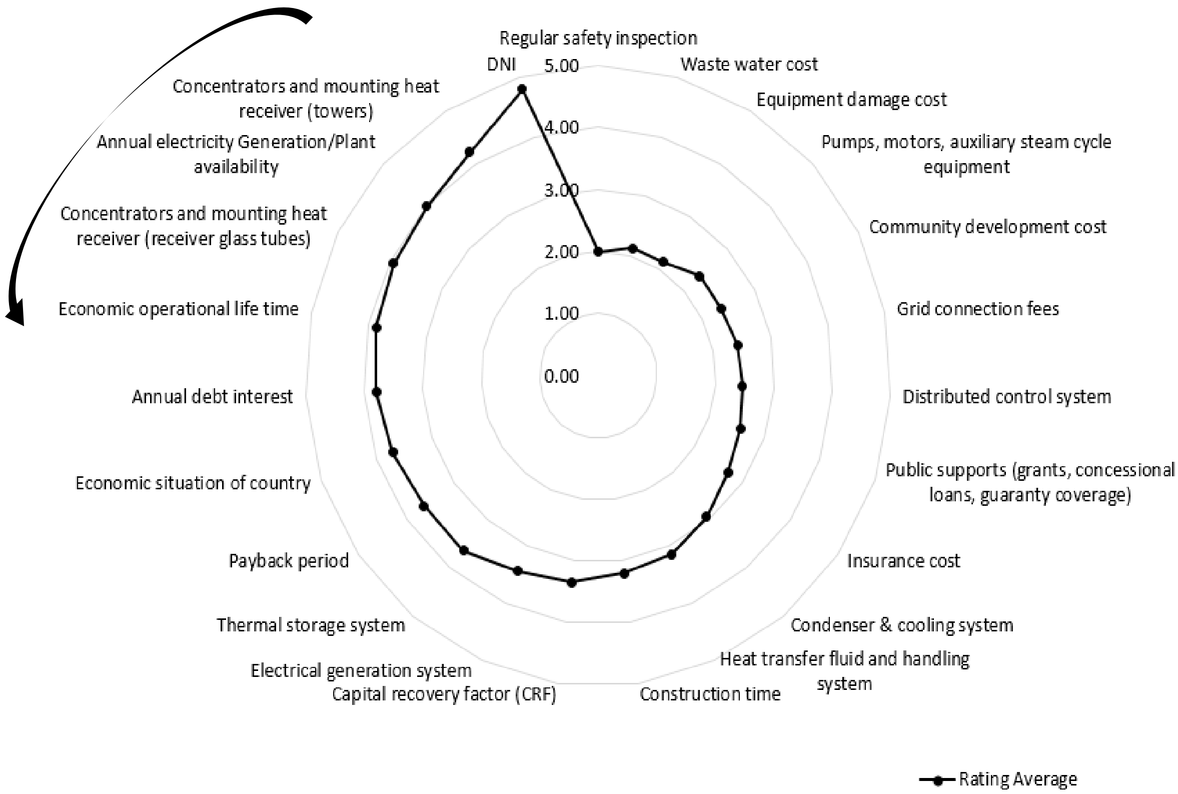


Figure 6-14: Impact of items/expenditures on overall cost of CSP

6.7 CSP Diffusion possibilities

Although they contribute to the success or failure of any technology, technical and non-technical barriers, as well as the level of RD&D improvement, are not the only drivers of diffusion (Bosetti *et al.*, 2012). While the capability and potential of CSP technology to break through in SA have been identified in this study, its success will also depend on the global acceptance of the technology and the interest of other nations to adopt it.

This section seeks to analyse the experts' opinion on the expected future global diffusion pattern of CSP technology. The experts were asked to specify how long it would take any innovative local CSP technology, which is developed in SA and has entered the local market to diffuse into the global market.

Experts according to this survey agreed that it will take a longer time for innovations in SA to diffuse into other African countries than to the rest of the world because very few African countries have shown interest in the adoption of CSP technology over the years. The deployment of new innovative technologies in these countries will be challenging even if they adopt CSP soon (see Figure 6-15).

Moreover, the experts identified that it will take between 5-10 years for most of the locally made technology to diffuse into the global market. While innovations with good and competitive qualities may have an edge, their global diffusion will also depend on the non-technical barriers presented in the study.

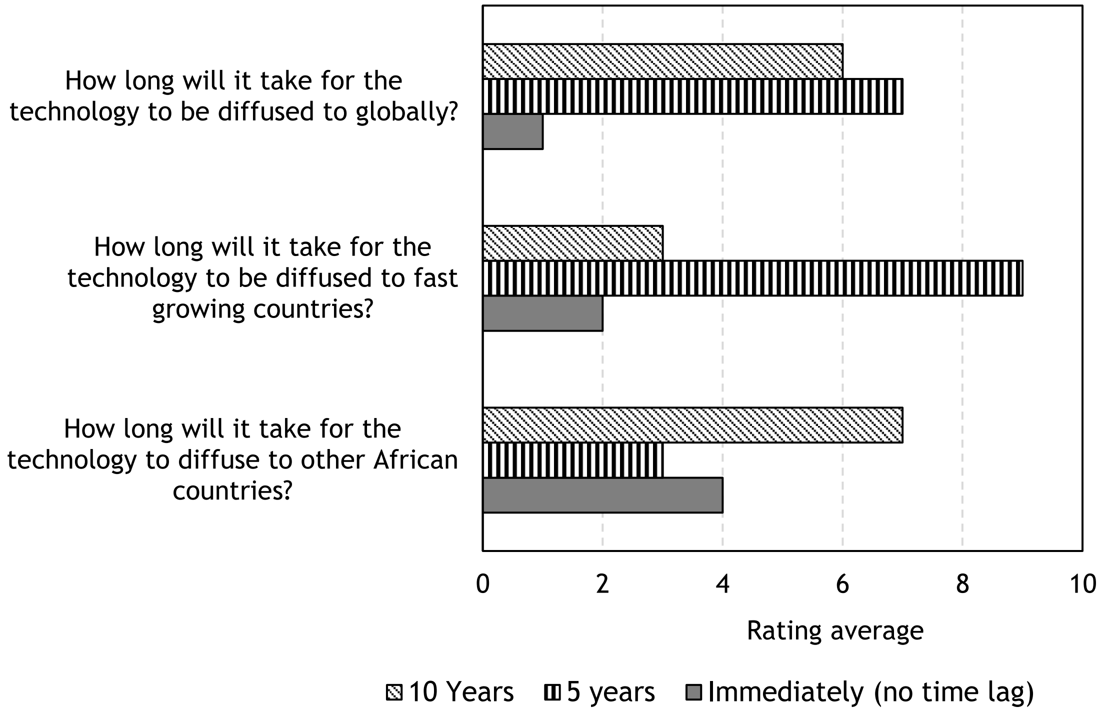


Figure 6-15: Diffusion rate of CSP innovation from SA

6.8 Conclusions and policy recommendation

In this chapter, data were collected on the effect of public RD&D expenditure, the technical and non-technical barriers to CSP technology in SA Expert elicitation protocol was carried out to understand these effects and the outlook of CSP in SA. CSP technology experts in SA commended the commitment of the DST, DoE and the government of SA to the development of RET energy sources, especially on the current RET RD&D expenditure, which makes SA one of highest contributors to a sustainable sub-Saharan Africa (ASSAF, 2014).

Eighty-six per cent of the experts believe that an increase in the RD&D budget with a good partnership among academic and research institutions, will lead to an improvement in the adoption of CSP technology in SA. Moreover, they suggested that RD&D should be done with the aim of commercialisation, and that there is need to develop deployment strategies that will aid the fast diffusion of CSP innovation from South African institutions.

Experts also identified that use of molten salt currently pose a lot of technical risks because it is new. On the other hand, the oil technology has established itself over the years, and many of the experts suggested that more research should be done in developing better and mature molten salts HTF. This chapter showed that the technical challenges facing the types of CSP technologies may be similar, but the solutions must be unique, as each technology type poses unique technical risks in their advancements.

The study has also highlighted that not only technical barriers limit the cost reduction of CSP electricity, but the non-technical barriers also have a significant impact on the cost, deployment and adoption of CSP technologies. Experts also suggested that African countries with good solar resources must partner on RD&D to encourage large scale deployments, smooth technology transfer, development of most promising components, and ease diffusion of local innovations in CSP.

While the current cost of electricity from utility scale solar PV may be on exponential reduction, CSP currently offers better capacity factors and grid support. These factors include its flexibility of operation and dispatchability features, which are essential characteristics for good penetration of RETs into the existing grid (Turchi *et al.*, 2010). In the coming years, according to this study, it is expected that RD&D will improve and help CSP technologies developing systems with even higher capacity factors, higher operating temperatures, improved thermal cycles and more efficient storage techniques.

There were no clear conclusions on the CSP RDR&D portfolio for SA. Some experts believed that the most matured types of CSP should receive a large amount of the RD&D fund with lower funds given to less matured technologies, while other experts suggested the opposite. Therefore, the results from this study imply that rather than selecting one/some of the CSP types to be the technology champion(s) in SA. The various types of CSP technologies should be allowed to compete, and the policy makers should just make sure that none of the technologies dies. This is in agreement with the suggestions of Bosetti *et al.* (2012), which suggested there is no need for selecting a technology winner when we can allow all the technology types to compete and thus encouraging speedy cost reduction.

Strategic policies, laws and funding can help any nation to fully maximize its solar resources potential to foster cost reduction and market viability of its solar innovations (Sharma, Tiwari & Sood, 2012). Braun *et al.* (2011) showed that improved RD&D funding of CSP research had led to several new patents globally. However, Afuah & Bahram (1995) stated that improved RD&D alone cannot foster adoption of any innovation. Rather, it must be supported with improved market competencies to ease its diffusion and the crossing of the valley of death (VoD).

When the impact of current RD&D expenditure in SA on cost of CSP electricity was considered, most experts agreed that the cost may slightly drop below 9 c$/kWh (ZAR 1.26 /kWh) before the year 2040 depending on the influence of the global market of CSP technology. The experts' responses show that it is very unlikely for CSP to be able to compete with other technologies if the current rate of cost reduction is maintained.

Thus, suggesting the need for an improvement in the RD&D funding. Also, the scenario of increasing the RD&D expenditure on CSP in SA by 25 % was presented to the experts and their responses predict a 20 % decrease in the current cost of CSP, which could lead to an electricity cost below 8 c$/kWh (ZAR 1.12 /kWh) in 2040.

Interesting future costs of CSP were estimated by the experts when they were presented with another scenario, which the current RD&D expenditure was increased by 50 %. About 87 % of the experts agreed that the cost of CSP will drop below 0.5c$/kWh (ZAR 1/kWh) by the year 2040. Thus, showing that the majority of experts agreed that increasing the RD&D fund of CSP would make a positive impact on CSP electricity cost reduction.

In conclusion, improving on cost competitiveness of CSP and overcoming the major technical barriers will lead to an era of massive deployment of CSP in SA, while an improvement on the identified non-technical barriers will help its local and global adoption. Willingness on the part of policy makers in terms of megawatts allocations and improved strategic tariff plans will also help in the development of CSP technology.

The next chapter therefore presents an analysis of the current and future energy economics of CSP to understand its learning effect, the cost evolution and competitiveness, and how they can all help the adoption of the CSP technology in SA.

7. The current and future energy economics of CSP in SA[7]

To fulfil the fourth objective of this research, which is to identify the current and future economics of CSP in South Africa, this chapter seeks to analyse the present state of CSP cost evaluation parameters and the capital expenditure (CAPEX) of CSP. The aim is to present the learning rate/experience rate of CSP in SA. It also seeks to analyse data retrieved from reputable sources to determine the trend and the future cost of CSP in SA. The chapter thus answers the following questions:

- What are the existing economic indicators for CSP viability in SA?
- What are the present and future costs of CSP subsystems?
- What is the CSP learning rate in terms of competitiveness in SA?
- What is the way forward?

The main barriers faced by CSP are no different from the general ones faced by most RETs. These barriers are identified from the previous chapters, these include: efficiency, finance, breaking the carbon lock-in effect and adoption and deployment.

The study presented in this chapter analyses the state of CSP in SA for the levelised cost of electricity (LCOE) and the future cost of systems. The study presents a deployment strategy for market adoption of CSP in SA. The first part of the study shows the cost of electricity in SA and presents the need for more RET deployment, while the second part shows the future cost of CSP plant development in SA based on global forecasts and roadmaps.

The data and method used in this study are based on the analysis of existing reports on CSP in SA by various reputable organisations and research centres. Some of the studies reviewed in this paper include local and international reports: SA DOE reports (DoE, 2011, 2013, 2015), StatSA report (Statsa, 2014), Eskom publications (Eskom, 2013, 2015, 2017), WWF report (WWF, 2015) EPRI report (EPRI, 2010), REN21 (REN21, 2012, 2015, 2016), International Energy Agency (IEA, 2010, 2013, 2014a; OECD/IEA, 2010), BP report (2017), Fichtner (2010)

[7] This chapter is an expansion of an already published article titled: The current and future economics Concentrating Solar Power (CSP) in South Africa in South Africa. Published in the South African Journal of Industrial Engineering. DOI: 10.7166/28-3-1835

and FS-UNEP(2016), academic publications from SAIREC, STERG, SASEC, the World Energy Outlook, and the Energy Technology Perspective (ETP) blue map.

7.1 CSP cost evaluation parameters

7.1.1 Levelised cost of electricity

Levelised cost of electricity (LCOE) is a widely accepted metric for comparing different energy sources, as its analysis is based on weighted cost average (Shum & Watanabe, 2008; Hernández-Moro & Martínez-Duart, 2012a; Silinga & Gauché, 2014). LCOE can be simply defined as, the ratio of the total cost that goes into a project over its lifetime to the energy produced over the same period (IRENA, 2012).

LCOE analysis can be good enough to equate the value of energy cost among RET, but the basic value of energy — the fluctuations in the demand and supply of electricity — is not well accounted for in the LCOE calculations (Kost *et al.*, 2012). This omission means that the LCOE does not consider the strengths of energy sources such as CSP, with the extra added value or ability to supply energy on request. The general input factors to determine the LCOE of CSP are shown in Figure 7-2.

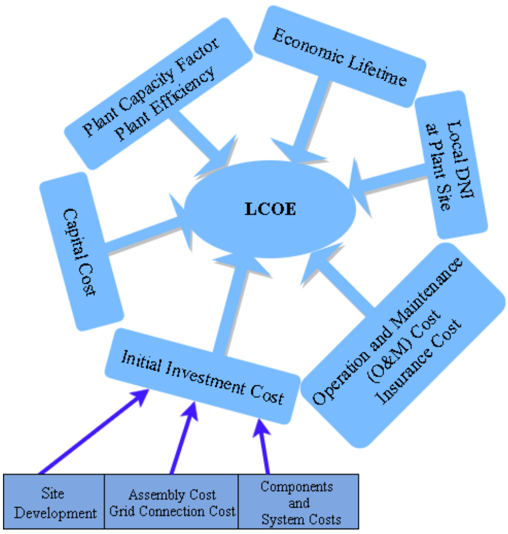


Figure 7-1: Factors affecting LCOE of CSP

The factors that affect the determination of the LCOE for RETs are different from those of conventional fossil fuel energy sources (Baharoon *et al.*, 2015; Liu *et al.*, 2016). CSP, for instance, has a high initial investment capital, a relatively low operational and maintenance cost, and little or no fuel cost. Conventional energy sources, on the other hand, have high costs for fuel, but need relatively little initial start-up capital. CSP costs are independent of the fluctuating fossil fuel price and more sensitive to investment capital and payback periods. While the cost of conventional energy is dictated by global fossil fuel prices (Hernández-Moro & Martínez-Duart, 2012a; García-Barberena *et al.*, 2014; Ouyang & Lin, 2014).

A simple LCOE formula based on the existing analysis is presented in Equation 7.1:

$$\mathrm{LCOE} = \frac{\mathrm{CRF} * \ \mathrm{CAPEX_{total}} + \mathrm{OPEX} + \mathrm{F_t}}{\mathrm{E_{e,a}}} \tag{7.1}$$

The capital recovery factor (CRF) in Equation 1 is the ratio of the present value of annuity with a discount rate (r) to the present value of the future sum of money to be repaid:

$$\mathrm{CRF} = \frac{\mathrm{k_d}(1 + \mathrm{k_d})^{\mathrm{n}}}{(1 + \mathrm{k_d})^{\mathrm{n}} - 1} + \mathrm{k_{insurance}} \tag{7.2}$$

CAPEX in Equation 7.1 is the capital expenditure; $\mathrm{k_{insurance}}$ is the annual insurance rate; OPEX is the operational expenditure; $\mathrm{F_t}$, is the fuel cost (which is zero for the CSP technology); $\mathrm{E_{e,a}}$ is the annual net electricity generation; and $\mathrm{k_d}$ is the annual debt interest rate.

7.1.2 Levelised profit of energy

The levelised profit of energy (LPOE) was used by Silinga *et al.* (2015) to determine the feasibility of CSP systems in SA. The LPOE is a function of the total income from a CSP plant, the operation and maintenance (O&M) costs, and the total capital cost, over the economic lifetime of the plant. A loan discount rate and the time value of money can be included in these calculations to level the cost. The LPOE can then be determined using Equation 7.3:

$$LPOE = \frac{\sum_{i=1}^{n} \frac{EI_t}{(1+r)^t} + \frac{I_t + OPEX + F_t}{(1+r)^t}}{\sum_{i=1}^{n} \frac{E_t}{(1+r)^t}} \tag{7.3}$$

E_t is the electricity generation in year t; F_t is the fuel cost; n is the life time of the plant; and I_t is the investment in year t. EI_t is the energy income in year t and r is the discount rate.

The LPOE can be used to determine the profitability of CSP under various loading scenarios. In their analysis, Silinga *et al.* (2015) proved that CSP will be profitable in SA if most of its supply to the grid is during peak hours. Thus, if CSP generates heat during the day, supplies a minimal amount of energy to the grid, and saves the rest for peak hours it will maximise the peak hour tariff, which is 270 per cent of the base tariff. This will lead to a more profitable CSP sector, which can drive a 'pull' that will make the sector competitive.

7.1.3 DNI, LCOE, and LPOE

As stated before, the available DNI at a CSP plant's location has a significant impact on both the LCOE and the LPOE of the plant (Kraas, Schroedter-Homscheidt & Madlener, 2013; Silinga & Gauché, 2014; Silinga *et al.*, 2015; Xu *et al.*, 2016). In its report, The International Energy Agency (IEA) (2010) showed that when a baseline of 2100 kWh/m^2/year (Spain's average DNI) is assumed, the calculated LCOE of a CSP plant declines by 4.5 per cent for every 100 kWh/m^2/year that the DNI exceeds 2100.

An analysis of DNI as a function of LCOE was extrapolated from IEA data (IEA, 2010, 2014a), to determine the future LCOE in SA as a function of the DNI. An average DNI of 2800 kWh/m^2/year was set for SA, resulting in a lower LCOE than expected, as shown in Figure 7-2. The LCOE cost of CSP in SA in 2050, according to this analysis, would be about 29 USD/MWh, compared with the current LCOE cost of 120 USD/MWh (Hashem, 2017).

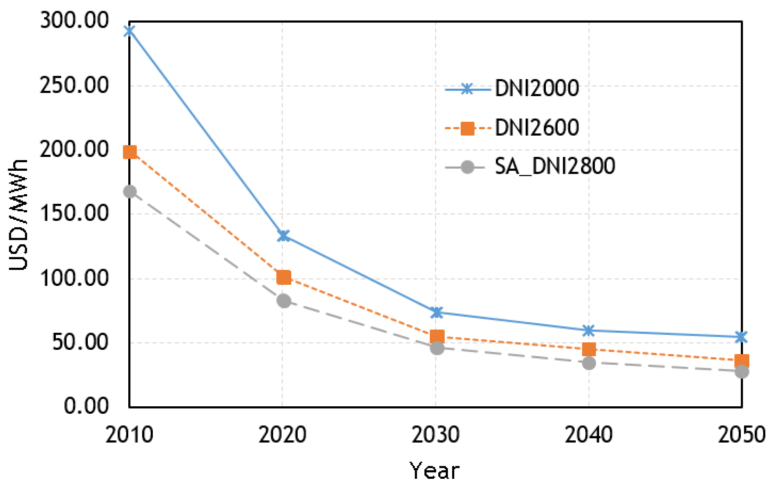


Figure 7-2: LCOE from CSP plants, in USD/MWh, under three different DNI levels in USD/MWh. Author's calculations based on projected evolution of (IEA, 2014b), (Craig, Brent and Dinter, 2017) and (Hernández-Moro & Martínez-Duart, 2012b)

7.2 Specific investment cost of CSP

The specific investment cost of CSP in this study refers to the theoretical cost of investment that should be involved in CSP development in other locations, based on DNI variance. The available DNI in a plant location can serve as an indicator of the difference in the investment cost compared with other locations (Shum & Watanabe, 2009; CSP-World, 2012; Shouman & Khattab, 2015). In Equation 7.4, the DNI in Spain and SA were compared with CSP cost to determine what the tariff of CSP electricity in SA.

The average DNI of 2800 kWh/m^2/yr in Upington in the Northern Cape Province of SA was compared with the 2090 kWh/m^2/yr DNI in Southern Spain (with the highest installed CSP capacity) (NREL GIS, 2015). CSP was widely deployed in Spain in 2010 because of the feed-in tariff that the government had introduced. The feed-in tariff of USD 34.8 cents/kWh for Spain in 2010 was then used, and the 2010 specific cost/tariff of CSP in SA was found to be USD 0.26/kWh (IEA, 2014a). This was eight per cent lower than the actual SA CSP feed-in tariff of USD 0.28/kWh proposed in the year 2009 (IEA, 2013).

$$C_{SA} = C_{Spain}\left(I_{Spain}/I_{SA}\right) \tag{7.4}$$

The difference in the tariffs show that direct comparison of DNI and cost may not be enough to determine the specific cost of CSP investment. There are several other factors that affect the cost of CSP and many of these factors are country specific (IEA, 2018). For example, in the first bid window in SA, the average bidding prices were USD 0.33/kWh, while Bookport project offered a bid price of USD 0.31/kWh in bid window 2. Figure 7-3 presents the global investment cost of CSP in 2011. The chart shows that in 2011, a parabolic plant with no storage requires 4600 USD/kW, while the same plant six hours of storage cost between 7100 to 9800 USD/kWh.

The installed costs per KW for CSP plants in South Africa was then calculated from first principle by dividing the cost of investment by the plant capacity (see Figure 7-4). Kaxu a 100 MW parabolic trough with 2.5 hours of storage cost 8600 USD/Kw while Bookport plant, a 50 MW parabolic trough with 9.3 hours of storage cost 11300 USD/kW. The cost of the other CSP plants are also shown in Figure 7-4. The analysis presented here shows that the specific cost of investing in CSP in SA is higher than the global average. This deviation, combined with a low local manufacturing capability for CSP components in 2010, may have contributed to the reduction in the learning rate of CSP in SA.

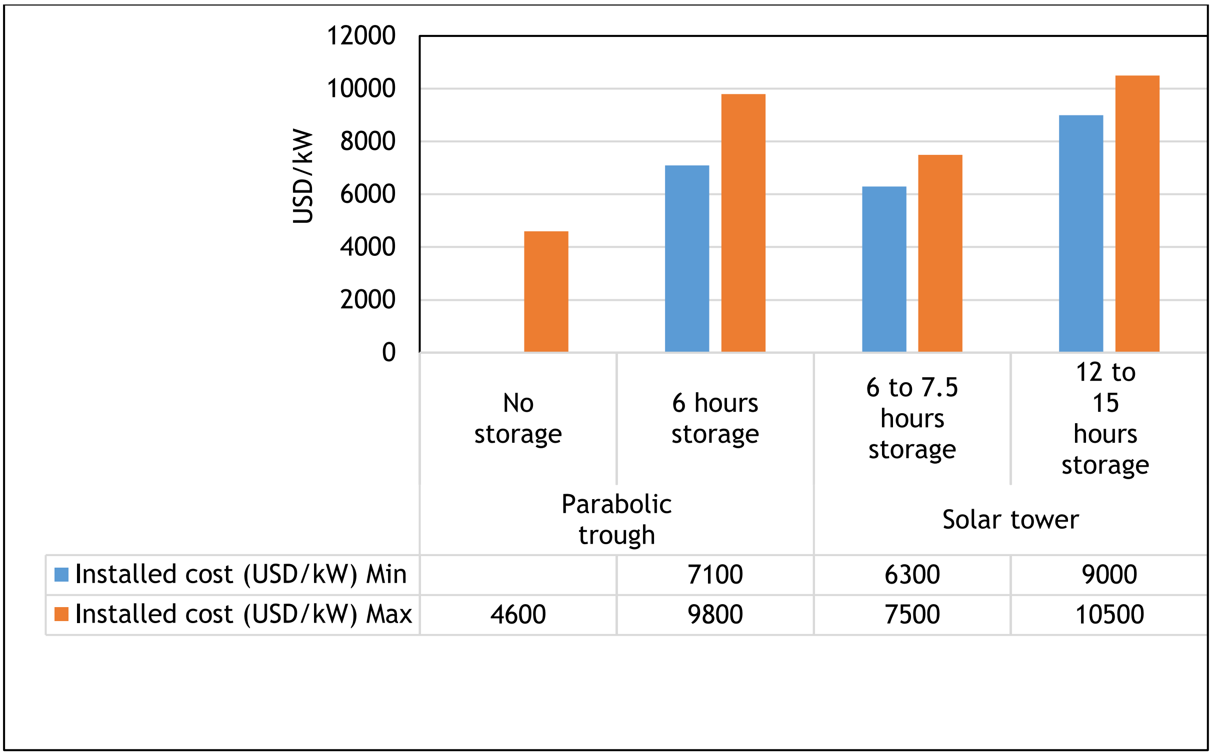


Figure 7-3: Global CSP cost in 2011

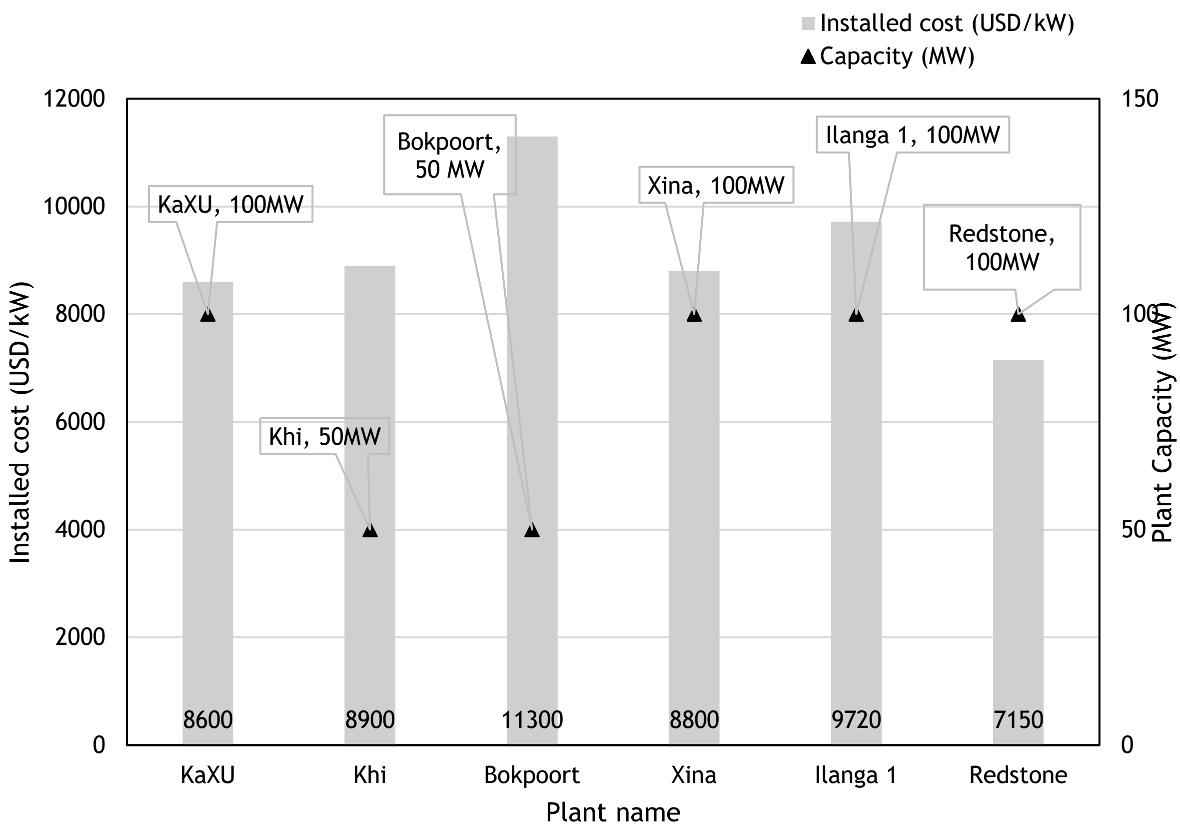


Figure 7-4: CSP cost of installation in South Africa

The expected future capital cost of CSP electricity in SA in 2050 will be 4700 USD/kW for a solar power plant with energy storage of six to eight hours and a capacity of factor of 0.6-0.8, based on all the learning analysis presented in this section.

The current capital cost of the tower technology type of CSP is between 6800 USD/kW and 12800 USD /kW, with energy storage of four to eight hours and a capacity factor of 0.4-0.8 (IRENA, 2015).

7.3 CSP cost evolution

7.3.1 Experience curve and cumulative installed capacity

The experience curve explains that whenever production doubles, the cost of a product is reduced by a certain percentage (Papineau, 2006; Weiss *et al.*, 2010). In the case of CSP, it can be referred to as the reduction that occurs in the cost of CSP when the cumulative installed CSP capacity doubles. The experience curve can be related to the global cumulative installed capacity to highlight the present cost evolution, which can then be used to predict the future cost of development (IEA, 2010).

Experience curves can also be viewed as learning curves that represent cost reduction as a function of production (Afuah & Bahram, 1995; Ibenholt, 2002; Weiss *et al.*, 2010; Platzer & Dinter, 2016). An important variable in the analysis of the learning curve is the learning rate (LR), which Hernández-Moro & Martínez-Duart, (2012b) defined as the percentage cost reduction that happens when the global cumulative installed capacity doubles. The relationship between the global cumulative installed capacity, q, and the cost of the same system, C, at a reference year, Y_0, and a future year, Y_x, is shown in Equation 7.5:

$$C(Y_x) = C(Y_0)\left(\frac{q(Y_x)}{q(Y_0)}\right)^{-b} \quad (7.5)$$

Nemet (2006) defined the b in Equation 7.5 as a function of learning rate (LR), which he expressed as:

$$b = \log(LR - 1)/\log 2 \quad (7.6)$$

Therefore, Equations 7.5 and 7.6 can be rewritten in terms of progress ratio, P, as

$$C(Y_x) = C(Y_0)\left(\frac{q(Y_x)}{q(Y_0)}\right)^{\frac{\log P}{\log 2}} \tag{7.7}$$

The reduction in the cost of CSP components has led to an overall reduction in the cost of CSP electricity. The cost has fallen globally over the years from 80 USD cents/kWh in the 1980s to around 20 to 30 USD cents/kWh in 2010, 17 to 25 USD cents/kWh in 2013, and an expected 6 USD cents/kWh in 2050 (IEA, 2010, 2014b; Hernández-Moro & Martínez-Duart, 2012b). However, this cost of electricity from CSP systems varies globally, depending on the DNI resources of the location (Black & Veatch, 2012; Boyle, 2012; Kraas, Schroedter-Homscheidt & Madlener, 2013; Shouman & Khattab, 2015).

To determine the economics and future cost of CSP, reliable global CSP roadmaps and outlooks were analysed. These included the IEA technology roadmap (OECD/IEA, 2010) and other global reports (IEA, 2010; WWF, 2015; REN21, 2016; Teske *et al.*, 2016). These studies indicated the expected global annual CSP installation to be between 5600 MW and 49000 MW by 2030 with a capital costs as low as of between 3400 and 3800 USD/kW; between 9500 MW and 75 000 MW by 2040 with an electricity cost of between 2600 and 2800 USD/kW; and between 12000 MW and 131000 MW by 2050 with an electricity cost of between 2.5 and 2.7 USD/kW.

The rate of cost reduction of CSP electricity, R, was determined using an adapted compound growth rate, shown in Equation 7.8, where y is the number of reference milestone years, and the input data were from Fichtner (2010), Black & Veatch (2012) and WWF (2015).

$$R = \left(\left(\frac{C(Y_x)}{C(Y_0)}\right)^{\left(\frac{1}{y-1}\right)}\right) - 1 \tag{7.8}$$

The SA CSP cost reduction rate based on the most realistic moderate scenario was found to be 11.4 per cent. The progress ratio, P, defined as a function of the cost reduction rate, was expressed by Shouman & Khattab (2015) as (P =1-R); thus, P, based on this analysis, was 0.886. Using the cost reduction rate and the progress ratio, with a DNI of 2800 kWh/m^2/yr, the overall experience curve of CSP in SA was determined. As a result, the average cost of electricity for CSP is expected to decrease from USD 0.12 /kWh (ZAR 1.6/kWh) to USD 0.07/kWh (ZAR 1/kWh) in 2030.

7.3.2 Limitations to future cost analysis of CSP

CSP technology has the capability to be a major player in the future energy mix of SA, owing to the available solar resources, the CSP plant configuration, and its energy dispatchability (Gauché *et al.*, 2012). It is hard, however, to estimate or predict the future cost of CSP. Although, some studies have attempted this – for example, the study of IEA (2014b). Some of the reasons for the difficulties in estimating future costs include the following:

- There are difficulties in getting actual cost information for existing plants;
- The manufacturing of each plant has different cost information structures, and these are often kept confidential;
- Factors such as solar multiple, storage capacities and solar resources, which are not general to RETs, influence the overall cost of CSP; and
- CSP electricity LCOE is difficult to analyse, as it can be country-specific.

An experience curve analysis could be based on CSP subsystems (for example, thermal energy storage, solar thermal reflector or heat receivers), or the complete system. Trieb (2005) suggests that the best way to determine the learning rate of CSP is to combine the different learning rates of the various components involved.

However, the IEA (2014b) report showed that there is a delay in the expected 10 per cent reduction for every time the CSP global cumulative capacity doubles. These delays generally affect the cost reduction rate of other components and materials (power block and balance of plants). This makes the work of the learning rate analysis complex.

7.3.3 CSP learning rate for cost competitiveness

The identified growth rate, the cost reduction rate, and the progress ratio form the basis for the analysis of the CSP learning rate. These factors act together to determine how competitive the cost of CSP would be with other conventional power generating systems in the future (Pitz-Paal *et al.*, 2007; Ummadisingu & Soni, 2011; Platzer & Dinter, 2016; Xu *et al.*, 2016).

In this paper, we use the average of all the baseline/current situation scenarios that have been published to suggest the expected CSP learning rate (IEA, 2014b; WWF, 2015; Teske *et al.*, 2016). In Figure 7-5, the expected annual CSP capacity to be installed, based on the current state of CSP and the projected cost between now and 2050, are plotted on the primary axis, while the projected global cumulative capacity is plotted on the secondary axis, all as a function of year.

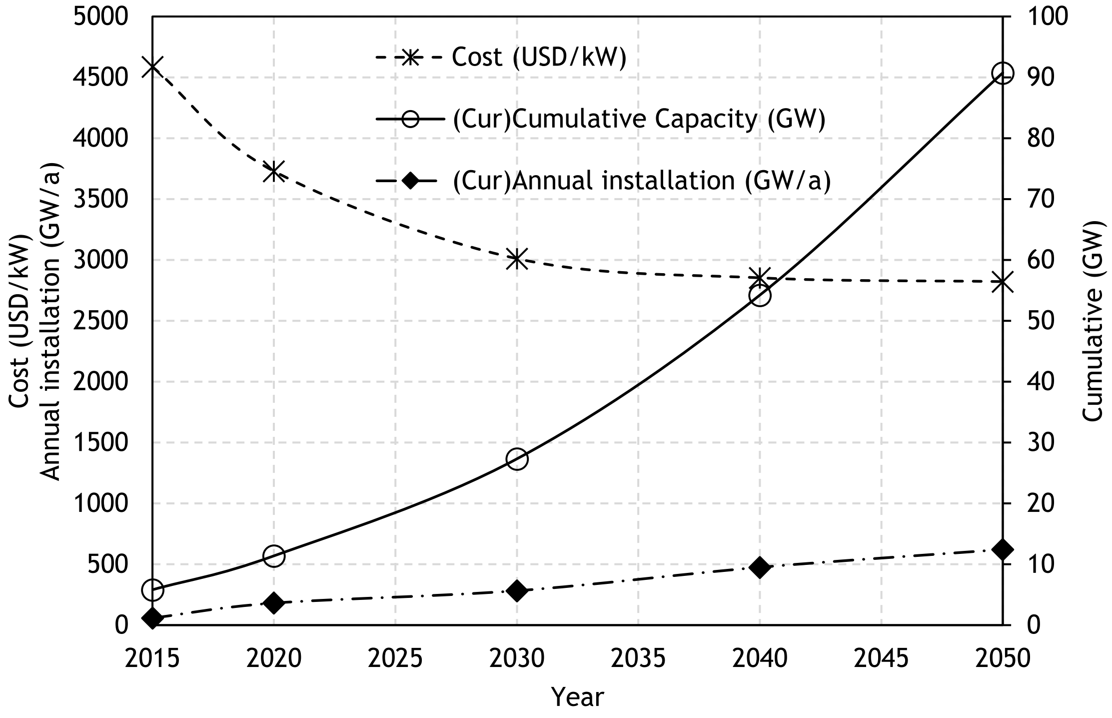


Figure 7-5: Global cost of CSP, based on best learning fit and current growth rate

From Figure 7-5 and considering the 2016 global cumulative capacity of 4.8 GW, a 20 per cent learning rate would only be achieved if the capacity is increased to 11 GW by year 2020. The global installed capacity, which doubles between 2020 and 2030, will cause a 22 per cent reduction in the cost of installation. The annual installed capacity in Figure 7-5 is expected to double between 2020 and 2030, and this will be accompanied by a 25 per cent reduction in the cost of installation. In conclusion, a 20 - 30 per cent annual global cumulative growth rate will achieve a cost reduction of around 45 - 50 per cent by the year 2050.

7.4 Future of CSP capital cost

It has been proven that CSP is capital-intensive, as the cost of investment is high (Timilsina *et al.*, 2012; Devabhaktuni *et al.*, 2013. This increases the risk and often reduces confidence about getting the funds required to deploy the technology (Charles *et al.*, 2005;

Ummadisingu & Soni, 2011; Pierce *et al.*, 2013). This section analyses the existing capital cost (or CAPEX) breakdown for a central receiver/tower plant, and a trough concentrating solar power plant with storage. The aim is to estimate the future cost of CAPEX and the accompanying experience curve in SA.

IRENA (2015) reported that the tower technology has the greatest possibilities of LCOE cost reduction in the coming years but argued that there is not enough data to substantiate this claim. Therefore, the analysis in this paper focuses only on the parabolic trough technologies in SA. The capital cost data breakdown of a CSP plant with dry cooling, six-hour storage and a solar multiple of two was retrieved from Black & Veatch (2012). The costs are shown in Table 9.

Table 9: Capital cost breakdown for a trough concentrating solar power plant with storage Adapted from IRENA (2015) and (Platzer and Dinter, 2016)

ITEM	Capital cost breakdown %
Solar field	40
Heat transfer fluid (HTF) system	9
Thermal storage	9
Power block	18
Engineering procurement, construction management services	8
Owners cost	16

The CAPEX breakdown in Table 9 was used to multiply the future cost of trough plants. The cost was based on the SA CSP CAPEX forecast, to get the future cost of various CAPEX subsystems, as shown in Figure 7-6. The CAPEX data from Fichtner (2010), WWF (2015), and, Black & Veatch (2012) for CSP in SA, were retrieved and compared with data from other sources —NREL (2016a) and OECD/IEA (2010). The data was then validated by experts to predict the future cost and possible trend of CSP in SA. The experience curve analysis in this paper describes the whole SA CSP industry, and is not merely a cost analysis based on any participating company.

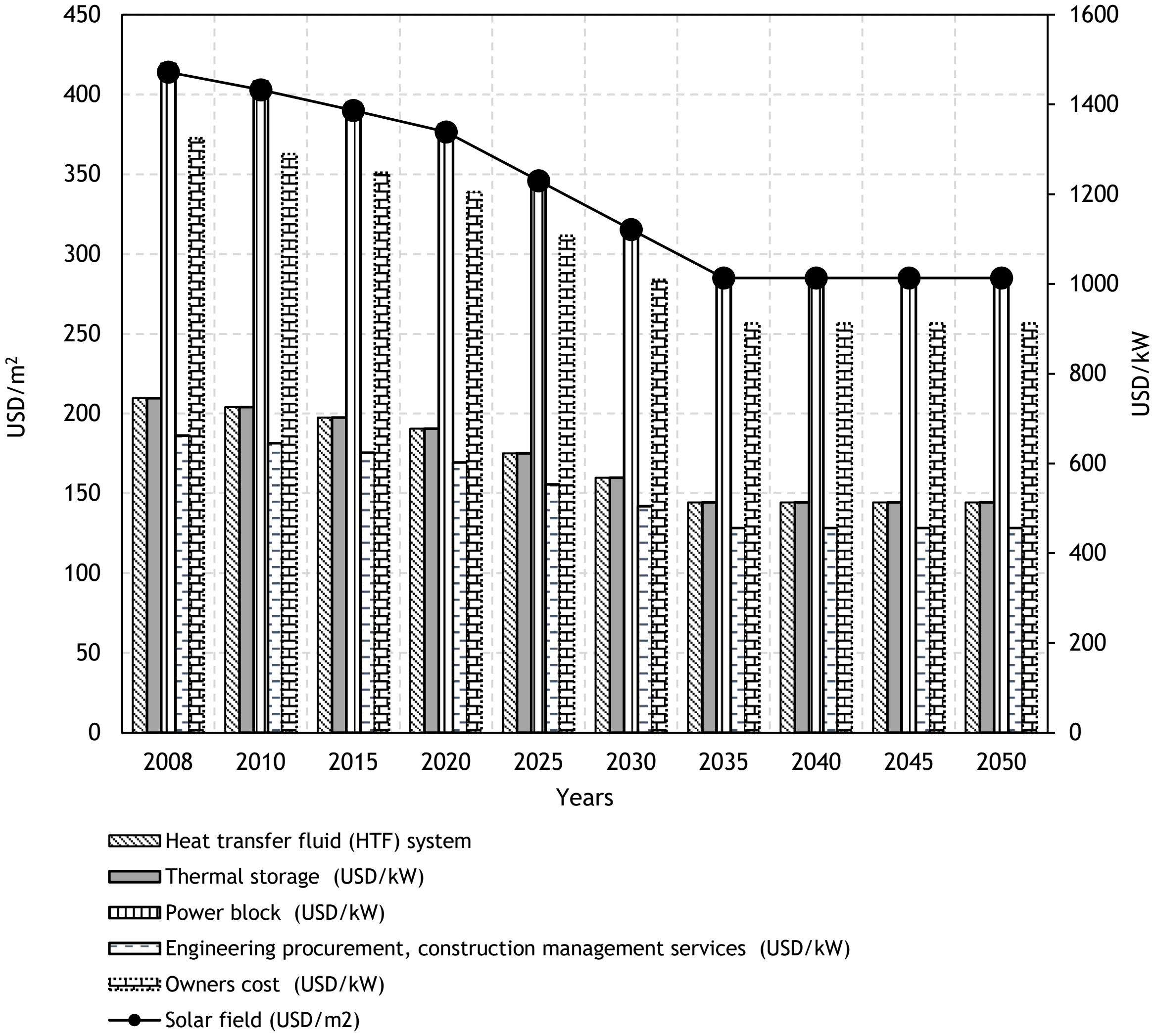


Figure 7-6: The resultant future cost of the various subsystems of trough CSP plants

According to the analysis, the various subsystems that make up the capital cost of CSP will experience about 33 per cent cost reduction between now and 2040. The cost will then stabilise and is expected to be fixed until 2050.

In SA, CSP is very promising in terms of future cost reduction. Although, with only three plants connected to the grid there is limited data to work with. The percentage share of the cost of a solar field in the CAPEX of a 100 MW parabolic CSP plant presented by Platzer & Dinter (2016), was used to determine the specific solar field cost of the existing 100 MW plants in SA, as shown in Figure 7-7. The CAPEX values were based on data retrieved from Black & Veatch (2012).

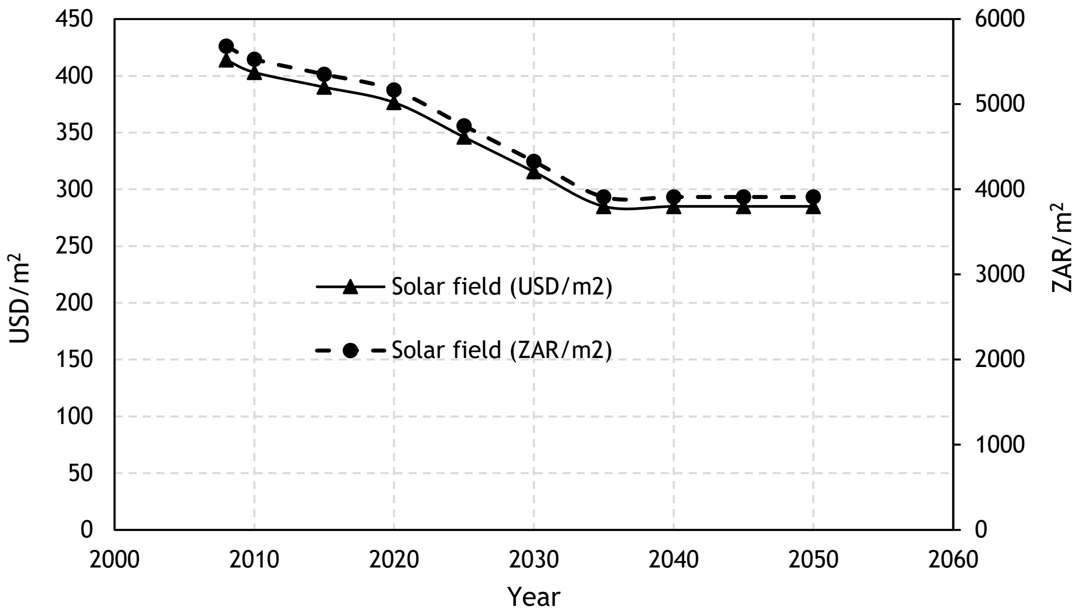


Figure 7-7: Solar field cost in SA

To get a more precise result for the current solar field cost projection of CSP in SA, a similar analysis to the one described above was performed using available data for all existing CSP trough plants in SA (Abengoa CSP SA, 2010; CSP-World, 2012; Abengoa Solar, 2014; CSP Today Markets Reports -South Africa, 2015; ACWA Power, 2016b; NREL, 2016a). The specific solar field cost was calculated by dividing the solar field cost by the aperture area. The minimum and maximum cost deviation of -35 per cent and +15 per cent, derived from Black & Veatch (2012) was used, based on an IEA (2014) forecast and SA CSP project commissioning dates. The resultant specific solar field cost for all CSP plants in SA was determined.

Only the specific solar field cost was analysed, due to the difficulty of a fractional breakdown of the components of power block and thermal storage, as well as the large disparity in the existing CAPEX fractional breakdown in the literature. This was done because the current solar field cost is easily comparable between the different types of plants, and the various types of technologies and can be validated from various data sources.

In Figure 7-8, the 50 MW plants in SA were represented by the grey and black square boxes, while the other data points represent 100 MW plants. Other subsystem cost analyses have been found to vary, based on the tenders, targets or policies of the involved stakeholders.

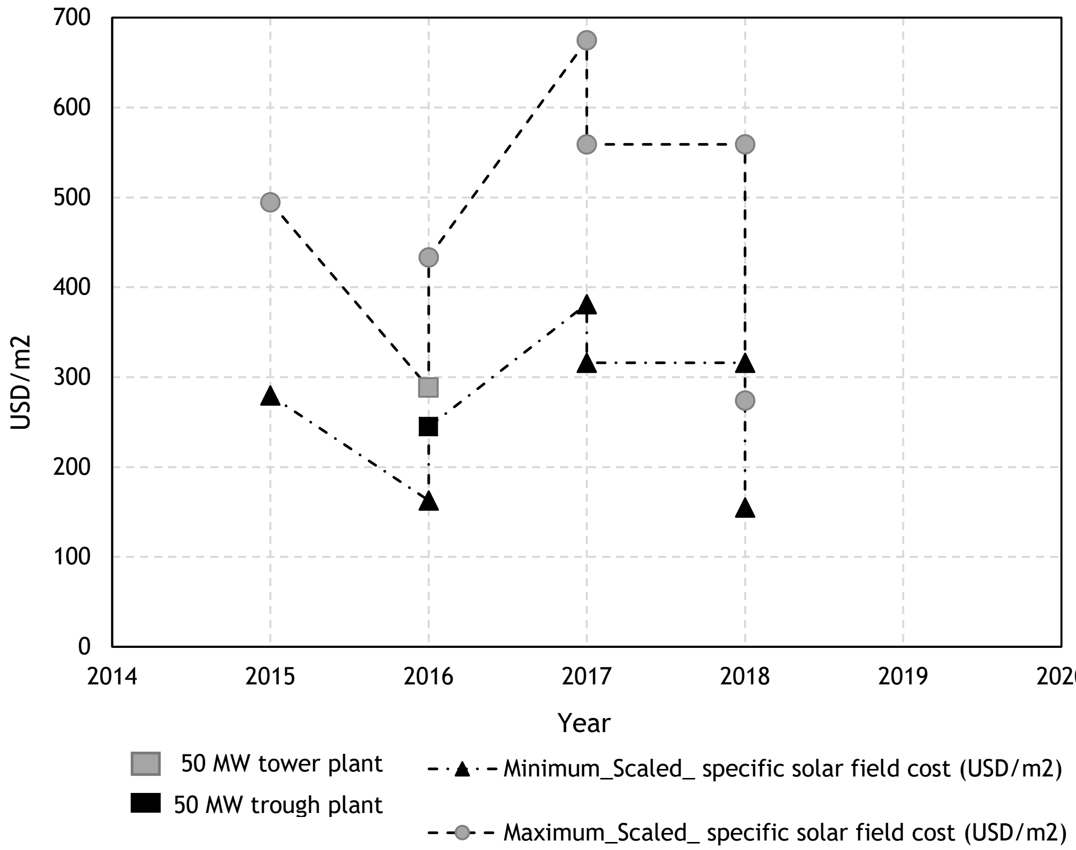


Figure 7-8: Specific solar field cost for existing plants in SA

There is no visible trend for the minimum and maximum specific solar field cost for the existing CSP plants in SA, as shown by the dotted lines in Figure 7-8. There is, however, a large spread between the costs of the solar fields for plants with the same capacity. Furthermore, the results show that there are no visible experience effects. Thus, suggesting that before a CSP company can enjoy experience effects in SA, it must have successfully developed several CSP plants locally. However, based on the maximum and minimum specific solar field cost and on expert opinion, a learning rate of nine per cent may be on-going in the solar field cost for parabolic troughs in SA.

7.5 Chapter conclusions

This chapter has highlighted the current state of CSP in SA for capacity and costs. The economic indicators of CSP, which include LCOE, LPOE, DNI and specific costs, were discussed, and the most realistic future cost of CSP in SA was presented. Limitations to the learning effect of CSP in SA were identified. Existing principles were used with limited data to develop the learning rate, progress ratio and cost reduction rate of CSP.

The study showed that there are no existing patterns in the capital costs of the existing CSP plants in SA for technology, size, solar multiple, site location or storage capacity. This makes the experience curve analysis of the CSP industry difficult. The solar field cost, which is the most significant capital cost, was analysed independently to give an idea of what the CSP experience curve might look like. The CSP learning rate in SA was calculated, the future of capital costs was then determined, and the likely experience curve for CSP in SA was presented.

To accommodate the deployment of new innovations from R&D based on recommendations from chapter 6. As projected in chapter 7, there is a need for a corresponding readiness in terms of local manufacturing capacity, labour and trade in SA, to achieve a competitive investment, operating cost and adoption of CSP. The next chapter performs an assessment of the local manufacturing capacity in SA and present the impact of CSP adoption on trade and labour.

8. Assessment of local manufacturing capabilities for CSP in SA

The potential of concentrating solar power (CSP) industry to contribute to the local economy of its host country has been proved. It has also been established that the development of CSP industry is often accompanied by temporary and permanent employment benefits (WWF, 2015; FS-UNEP, 2016; Guedez *et al.*, 2016; Craig *et al.*, 2017).

The World Bank study on CSP in developing countries (MENA and South Africa), showed that South Africa (SA) has the ability to develop several major CSP based industries (Kulichenko & Wirth, 2012). SA is a potential global leader for CSP-related markets with regards to the available solar resources and the success recorded in the sector over the last 5 years, in terms of the connected plants and those under construction (Craig *et al.*, 2017).

With the existing two-tier tariff in the REI4P, and an improvement in the political will, CSP technology could add immensely to the local RET manufacturing capability of SA. While as a result of learning experience, an appreciable reduction is ongoing in the global CSP electricity cost in the last few years (CSP Today Markets Reports -South Africa, 2015; Platzer & Dinter, 2016; REN21, 2016; Teske *et al.*, 2016). The recent cost of CSP technology cannot compete with other RET and especially not against solar PV which has been enjoying a huge cost reduction as well as the goodwill of many individuals and nations.

Capacity scale up and cost reduction often go together with new technologies, and this relationship is not different in the CSP sector. To achieve a competitive CSP electricity cost or reduced CSP investment capital, an aggressive scale up in the local manufacturing capacity is required and this should happen to the sectors that are fully developed and the ones that are in innovative stages (Craig *et al.*, 2017). Schmalensee (2015) stated that an increase in CSP manufacturing capability would only be achieved in an emerging market if the local economy benefits directly from the deployment of CSP. A realistic way to achieve this economic benefit is through the improvement of the local manufacturing capabilities. Continuous reduction in the cost of local CSP projects and CSP-related services for both short and long term will be achieved with increase local capacities to manufacture CSP components or to be involved in CSP development.

This chapter assesses the SA local manufacturing capabilities for CSP related services. The strength and the challenges are identified, and the economic and social benefits are estimated, including the employment opportunities that accompany the improvement of the technology.

The impacts and analyses done on CSP technology in this study were analysed as a single entity and the effects of increasing or decreasing other energy sources were not considered.

8.1 Lessons from other local manufacturing capability development

One major limitation which had been emphasized in almost all existing studies on RET manufacturing assessments is the thresholds which are often set by the host government for local manufacturing share in RET projects. For CSP in SA, this threshold comes with pros and cons. The overall local manufacturing capability is far above average, and it is easier for the companies to expand their capacities to develop CSP component capabilities.

The SA economy has been known to easily accommodate large-scale development of local manufacturing over a brief period. An example is the SA automotive industry which started in the early 19^{th} century, and now manufactures over 83 per cent of the total vehicles manufactured in Africa. A total of over 200,000 direct employment is accredited to the industry in SA (DTI, 2003). Also, over 60 per cent of the local content, which means that over 60 per cent of the automotive industries requirements are made directly by local companies and over 200 South African companies are leaders in the automotive component manufacturing (NAAMSA, 2016).

The success and circumstances that supported the breakthrough in the automotive sector in SA were analysed and the barriers/challenges to CSP breakthrough with regards to local manufacturing capability as suggested in previous chapters were updated as follows:

- The state of CSP in SA is unclear as no allocation had been made for building new plants beyond 2030 in the most recent IRP update.
- Eskom, the utility company has been reluctant in signing purchasing agreement from Redstone, the youngest CSP plant under development for 2 years.
- The role and integration procedures of IPP are unclear with unstable IRP updates. Consequently, no clear or reliable long-term framework exists that can convince IPP

investors to join in achieving the estimated 43 per cent energy mix from renewable sources by 2030.

- The contribution of each of the major RETs in the future energy mix is not clearly stated and the available ones have been criticised by many different agencies. Thus leading to unclarities as to the desired input from CSP, or if it has been renounced.
- Unlike the automotive sector which was highly supported by the SA government at its initial stages, CSP is more capital intensive and it will be hard for the state to finance it as it can affect her sovereign credit rating.
- Many financial institutions prefer to fund a more proven or widely accepted technology. This will limit the capabilities of local companies to raise funds for expansion or getting into CSP component manufacturing.
- The ongoing blame game and shift of responsibilities among government parastatals regarding signatories could discourage many local companies in developing capacities for CSP.
- The technology is being dismissed too soon, despite the solar resource and several ongoing basic and advanced research projects in the sector in SA.

8.2 SA Local manufacturing potential

The SA companies involved in CSP components manufacturing (steel, glass, EPC, electronic), CSP development and services delivery, were analysed based on existing studies and expert elicitation protocol (see Appendix E for details). The analysis revealed the local manufacturing potential. The resulting SWOT analysis on the CSP manufacturing value chain in SA is presented in Table 10.

Table 10: SWOT analysis of SA local manufacturing capability

Strength	**Weakness**
• There is an existing local manufacturing sector that can compete globally (Automotive industry) - possibility for development of other sectors. • Local manufacturers are experienced with designing and building large energy plants (e.g. Merdupi and Kusile). • Local industries involved in CSP components including steel, mirrors, tracker and pipes, now produce to global standards, which are used locally and some exported. • Existing basic research with significant output (e.g. Helio 100) which can support local industries component development. • Heavy presence of standard construction companies. • There are several global companies already involved in the CSP sector.	• The local basic R&D is still behind as compared to advanced research within international companies. • Limited local industrial R&D as compared to other competing countries. • Local productivity lower compared to other CSP favoured countries. • Most raw materials for most CSP components are more expensive when sourced from the local market. • Scarcity of required CSP skills and limited capability training programmes. • High cost of transportation of imported components (distance to ports). • Unstable political will.
Opportunities	**Threats**
• One of the best locations for CSP in the world with regards to solar resources (DNI). • High local content requirements from the SA government. • Possibility for hybridisation with existing conventional power plants or conversion of old power stations. • The technology is still new, and many opportunities for pioneers and innovations. • Export opportunities to neighbouring SADEC countries with good solar resources and other sub-Saharan African countries. • Local companies are open to international co-operation and technology transfer. • There is a lot of room for local companies to participate in the CSP industries with a huge economic benefit. • Coal is still the major source of energy in SA, which suggest a huge future for appropriate RETs of which CSP is a major player.	• Limited equity from foreign financial institutions. • Difficulty in securing financial support because financial institutions prefer to support proven, tested and more acceptable technologies such as Solar PV. • Tender/REI4P bids qualification are too restrictive to the interested local companies. • Low MW allocation to CSP in the previous REI4P bids and possibility of no allocation to CSP beyond 2030. • Other manufacturing companies in countries with low DNI resources produce CSP component majorly for export and thus creating tough market competition. • The future of CSP in SA in uncertain. • The continuous reduction in the cost of investment and electricity from other RETs. The continuous reduction in the battery cost for solar PV is a major threat. • Political stability and government's over-ambitious demand for local manufacturing. • Lack of experience in CSP component manufacturing.

For there to be a visible development in the local manufacturing capabilities for CSP in SA, the major companies/global leaders in the CSP industries that already own the existing plants in SA have a huge role to play, by continuing to form partnerships with the local companies. This will encourage technology transfer and localisation. The current state of the local companies was analysed as well and the capability of the local industries in SA to actively participate in CSP component manufacturing. Development is between 60- 70 %. However, there are some aspects that the capability is still missing, and this can be developed with time.

8.3 Scenarios for South African local manufacturing for CSP

Three scenarios were considered to analyse the benefit of developing local manufacturing capability for CSP in SA's economy. The major assumption in this section is that the local manufacturing capacity is proportional to the CSP capacity of the nation, and thus new local capacity development will be because of the need for local components in new CSP development.

Scenario 1: Business as usual

In this scenario, the current 600 MW CSP capacity is retained, the uncertainties around the future of the technology persist and the existing local CSP companies involved in glass and steel manufacturing continue at the same capacity and majority of other CSP components are imported.

Scenario 2: Unit development

With only 600 MW of CSP in SA since 2010, no new CSP plant signed since 2015. Due to the inconsistence MW allocations in the IRP for future new plants, this scenario assumes that there will be some unit CSP signing in SA over the years due to global progress rate and the new change in government. Thus amounting to a total capacity of 1 GW installed in SA in 2030 and accompanied by tougher laws for local inclusion, thereby resulting in demand for CSP components and thus leading to a gradual increase in the manufacturing of these components locally. The local companies involved in CSP becomes stronger and form moderate knowledge-sharing partnerships and technology transfer.

Scenario 3: Ambitious

This scenario was based on the promises made by the SA minister of energy at SAIREC 2015 where SA was projected to be interested in signing off several RET contracts and strengthening the REI4P, to encourage mass development of these technologies, with a target of exporting an appreciable amount of the electricity produced to the neighbouring SADEC countries and other sub-Saharan African countries (SAIREC, 2015). The CSP market volume in SA was assumed to become 2 GW and the locally manufactured export components reaching 1 GW by 2030.

The participation of local industries is seen to increase with many local companies getting involved in the manufacturing of high tech CSP components with high precision as well as the production of glass and steel of very high quality for the global market. By 2030, the majority of local companies involved are now global contenders and supplying components to both the local market and manufacturing for exports. There is a high progress ratio, high learning rate and reduced cost of raw materials for CSP, which will invariably force down the investment cost of CSP.

8.4 Future of local manufacturing of CSP components in SA

Existing studies have shown that new CSP projects will contribute immensely to the SA economy and could spring up another era of massive industrialisation which could easily flow to the other sub-Saharan African countries. World Bank projections on similar studies for the Middle East and North Africa (MENA) showed CSP projects will lead to foreign direct investment (FDI) because of a rise in the citizen's purchasing power (Kulichenko & Wirth, 2012). Conversation with the experts during the elicitation process carried out in this study also shows that supporting CSP projects will boost the acceptance image of the government by the citizens. Thus, projects will lead to the creation of direct and indirect jobs, as identified earlier in this study.

8.5 Economic impact of a strong CSP components local manufacturing capability

This section aims to evaluate the economic benefits of the scenarios presented in Section 8.3 (the business as usual, unit development and ambitious scenarios) for SA. To determine the direct and indirect economic impacts of developing the local manufacturing capability for CSP in SA, the Jobs and Economic Development Impact (JEDI) model for CSP by NREL was used (NREL, 2016b). The model allows users to analyse the development of CSP projects and its accompanied economic impacts using project specific data. The analysis was done on 100 MW CSP plant (each for central receiver system and parabolic trough)[8].

The cost input data are from data retrieved from reports (Black & Veatch, 2012; WWF, 2015). The solar resources input were from WWF data and updated with NREL data use (NREL GIS, 2015), solar field and other project descriptive data were taken from NREL (2016a). The model calculates in 2009 USD rate and the result was converted to the February 2018 Rand value.

The economic impact of each of the scenarios on the SA's GDP is presented in Table 11 and the direct and indirect impact are also considered in this study. The direct economic impacts in the Table 11 is defined as the effects of improved local capabilities in direct design, fabrication, operations and continuous maintenance of CSP plants in SA, while the induced economic impacts are the resulting effects on supply chain because of increase in the demand, thus increased multiplier effects.

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[8] JEDI was only developed for Parabolic trough and the author had to modify the model to solve the central receiver system)

Table 11: Estimated economic impacts over two CSP project life cycle in SA

CSP technology type/Scenario	Business as usual	Unit development	Ambitious
Total impacts during construction period (Earnings ZAR/million)	4773.49	5465.52	7489.79
Total impacts during operation year Earnings/Annual (ZAR million)	99.219	107.52	229.22
Total impacts during construction period (Earnings ZAR/million)	3968.66	4544.01	6183.43
Total impacts during operation year Annual Earnings (ZAR million)	109.96	117.88	117.88

The direct and indirect employment generated from the development of local capabilities for CSP are also presented. The model used in this analysis does not consider the SA government's local content requirements in REI4P or other local labour laws including BBE and BBBEE[9]. These laws demand that a company must have a certain percentage of specific race or a percentage of any procurement to be done by any foreign investor be achieved locally, even when the capacities rarely existed. A regulated robust and open market will give an opportunity to foreign investors to join in the development of the local RET market in SA. Thereby eventually building local capacity for CSP and other aspects of the economy.

8.6 Labour and trade impact

The operation and maintenance part of CSP systems will ensure continuous jobs throughout the life cycle of the plants (Kulichenko & Wirth, 2012). It can also be argued that with the

[9] BBE - Black Economic Empowerment; B-BBEE- Broad-Based Black Economic Empowerment

low labour cost in SA, more people can be employed for these services over longer periods with the same budget than the number that would be employed in other developed CSP competitive countries. Although the continuous increase in the automation in CSP plant maintenance could reduce the estimates in this study, there will always be a need for human capital.

The assumption made in the analysis of trade impact is that there is local demand for CSP components in the SADEC region and the rest of the world. This is only feasible in the ambitious scenario and CSP components such as solar field equipment (mirrors, heliostats) that are already manufactured in SA and exported to the global market. Depending on the progress rate of CSP in SA and the current ongoing reduction in cost of CSP components, exportation of these materials may begin in SA by 2020. This is expected to be accompanied by an increase in job creation and direct positive impact on the SA economy. If an accelerated CSP component development would be supported, sub-Saharan Africa could earn over US $ 3.6 billion from exporting locally manufactured CSP component by the year 2030 (Fichtner, 2010, 2014; Kulichenko & Wirth, 2012).

The resultant jobs and impact of a 100 MW CSP plants in SA during construction (see Figure 8-1) and during the operational life of the plant (see Figure 8-2), were calculated in a JEDI model. This model was based on data from a CSP plant[10] in SA, the analysis was performed for the three scenarios for the jobs created by the various sectors and the results are presented below.

[10] CSP owners that supplied data for this analysis prefer to remain anonymous

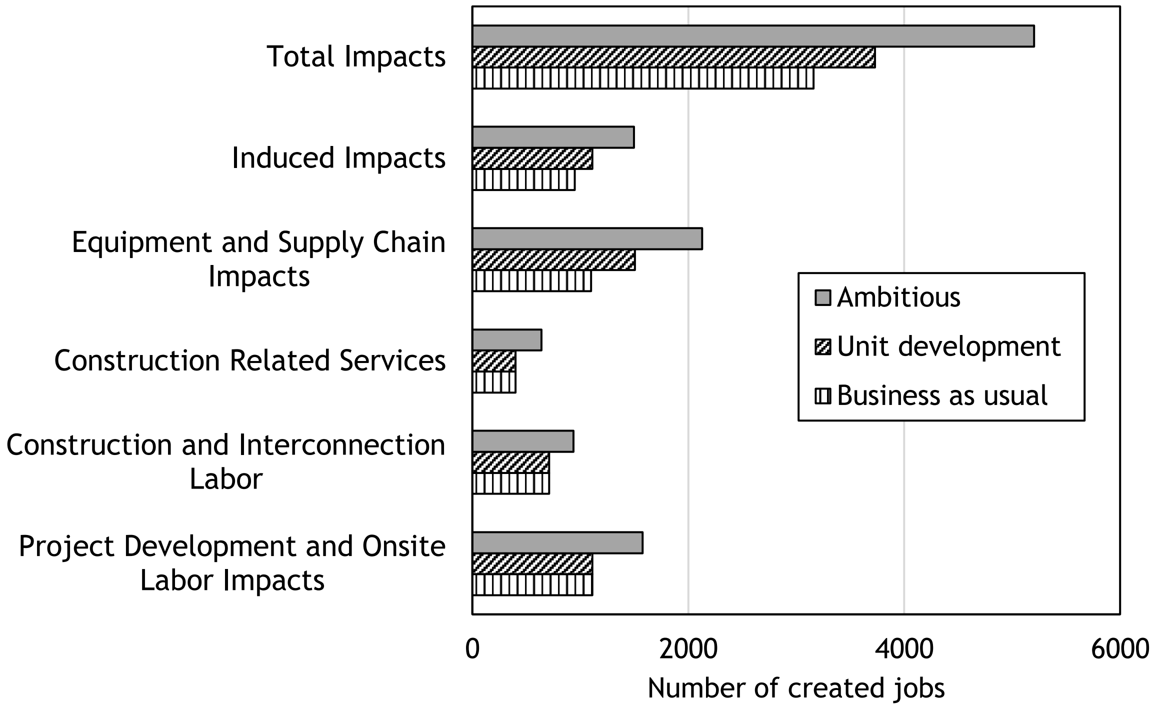

Figure 8-1: Jobs created during the construction period

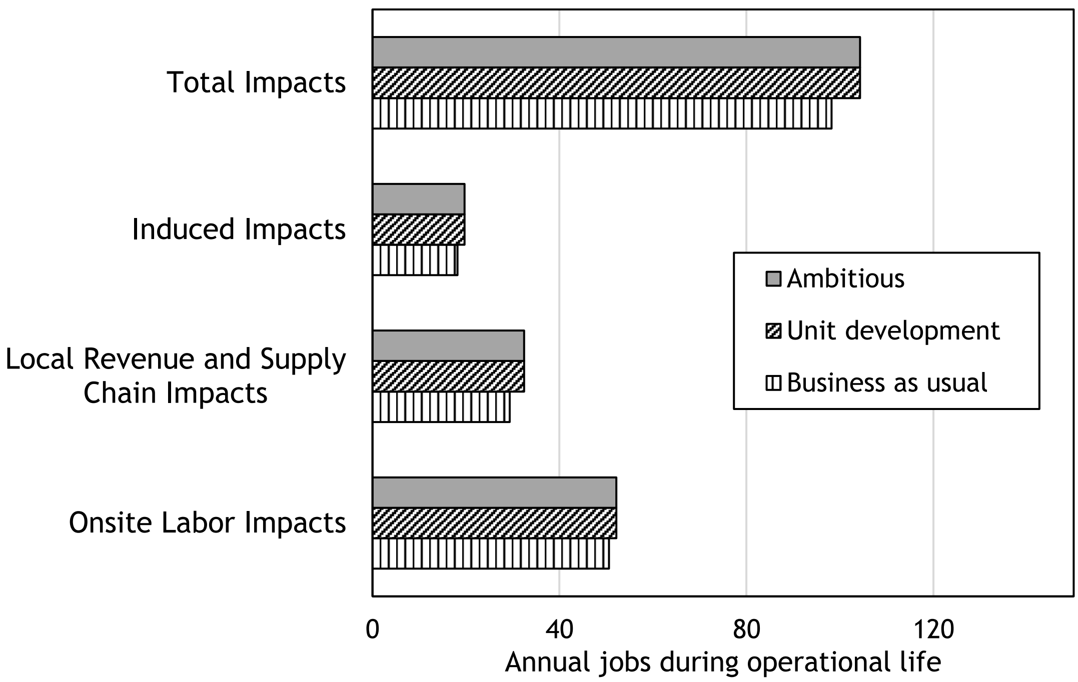

Figure 8-2: Jobs during the operational life of a 100 MW CSP plant in SA

9. CSP technology roadmap

The identified potentials of CSP in South Africa (SA) in terms of capacity, cost and adoption and the on-going technological advancement elsewhere, proves the need for SA to identify options that will allow the energy mix of the future to align to these global advances. The final objective of this research which was to develop an adoption framework for CSP in South Africa. An approach to achieve this is through the development of a technology specific roadmap for CSP based on the results from the previous chapters and the existing roadmaps.

9.1 Background

A roadmapping approach was first formally developed by Motorola in the 1970s (Willyard & McClees, 1987). A two-in-one technology roadmap was presented: emerging and product technologies. Willyard & McClees (1987) stated that the roadmap was developed to aid strategic planning of Motorola's integrated products and technologies. Since this introduction, roadmaps have been used as a flexible strategic planning tool by various organisations and in various sectors.

Various authors have different definitions for roadmaps, and Cetindamar *et al.* (2010) defined a roadmap as "*an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field*". This definition infers that a roadmap uses consolidated knowledge and identified drivers of change of a subject, to present a broad view of the future of that subject. This future is then presented as a summary in terms of a compact framework of the various elements that must work together to achieve the aim of the organisation. According to Cetindamar *et al.* (2010) a roadmap presents an opportunity to the stakeholders of a subject to present their perspectives on the interaction between the major drivers of the subject and thus provide an option for easy communication and dissemination of the final document among policy makers.

Carvalho *et al.* (2013) identified the two major components of roadmapping as the roadmap processes, which is the application and the roadmap itself, which is the output document. The first applications of roadmapping processes was by large corporations in various sectors including, electronics, defence, health and aerospace. However, the pliability of the approach made it easy to also be applied in smaller sectors (Cetindamar *et al.*, 2010). Thus, users have adopted it to address technological management issues in strategic manners grouped together by Cetindamar *et al.* (2010) as identification, exploitation, and learning. To develop an effective roadmap, the roadmap process should generally answer three questions: Where are we? Where are we going? How do we get there? (See Figure. 9.1).

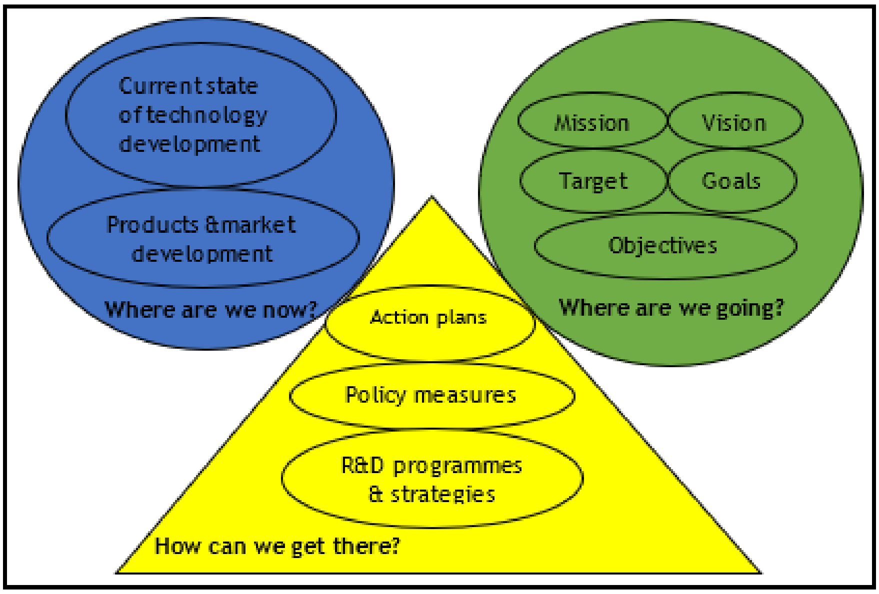

Figure 9-1: Descriptions of the fundamental questions of an effective roadmap (Adapted from (Carvalho *et al.*, 2013; Musango & Brent, 2015)

Garcia & Bray (1997) explained these three questions as three phases of the roadmapping process namely: preliminary activity, development of the technology roadmap and follow up activity. Each of these activities has a complete process of "ideation, divergence, convergence and synthesis", as identified by Phaal & Muller (2009) (illustrated in Figure 9-2).

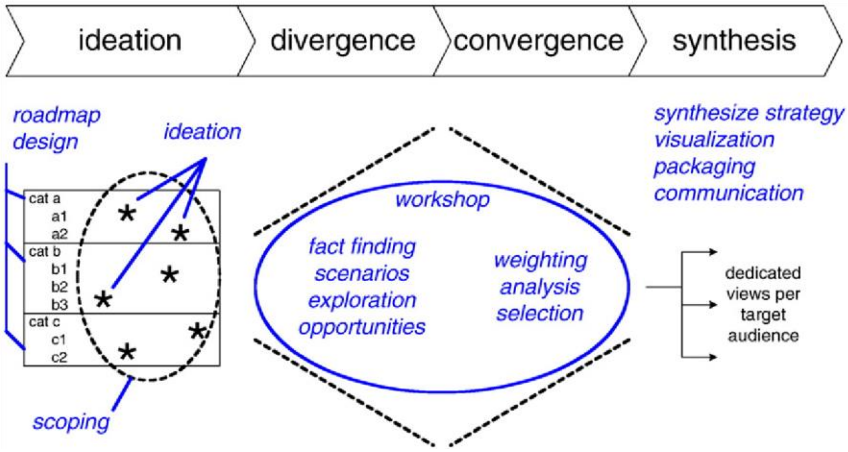

Figure 9-2: Phases of roadmapping processes (Phaal & Muller, 2009)

Phaal & Muller (2009) highlighted that roadmaps are applicable at any level of a system, to any subject, from units to complex systems and can also be used for a specific idea or an entire sector or field. Roadmaps are therefore structured or designed in a manner to suit the specific focus and application. The roadmapping processes are often claimed to be more important than roadmap itself (Phaal & Muller, 2009).

There is no one-method-fit all strategy or tool for developing roadmaps and thus the objectives of a roadmap often determine the course of actions and approach to develop it (Amer & Daim, 2010). Amer & Daim (2010) presented a comprehensive review of the use of roadmaps in the renewable energy technology (RET) sector. They found that at the year 2010, roadmapping had been used in the RET sector to create common visions, determine log-term targets, identify alternative technologies and hybridisation options. Moreover, roadmaps present aids and guidelines for policy makers and develop frameworks for partnerships that will foster a massive deployment of RETs. Amer & Daim (2010) concluded that despite the vast roadmapping application in RETs, it was not clear how many of suggestions in the roadmaps were translated into actions.

Furthermore, Jeffrey *et al.* (2013) presented an evaluation of roadmaps in RET sector, and they identified that there are now ways to measure the success of the roadmaps in this sector. Mostost of the measures are unique to RET, as the process for developing roadmaps for this sector is different from other conventional sectors. This difference is due to the multiple organisations and stakeholders that are involved. For instance, the International Energy Agency (IEA) has been able to develop global energy outlooks for RETs (IEA, 2010) and global CSP specific roadmaps (IEA, 2014b).

Country-specific roadmaps have also been developed for other major RETs, for example Khan&Pervaiz (2013) and Hutchby (2014) developed solar PV roadmaps. Amer & Daim (2011) and Gómez *et al*. (2011) developed wind energy roadmaps. Conversely, while there are some global CSP outlooks, there are no country specific CSP roadmaps. The existing country specific CSP technology roadmaps in literature have only considered various aspects of the technology or have been developed alongside PV with most of the attention given to the latter.

Amer & Daim (2010) identified that the first steps involved in roadmap processes are the identification of the stakeholders and arranging a workshop with them. The IEA (2014a) guide to the development of a technology roadmap identified two processes involved in roadmapping as a) expert judgement and consensus activities and b.) data and analyses activities (see Figure 9-3). The entire timeframe for a roadmapping process is often between 6 to 18 months.

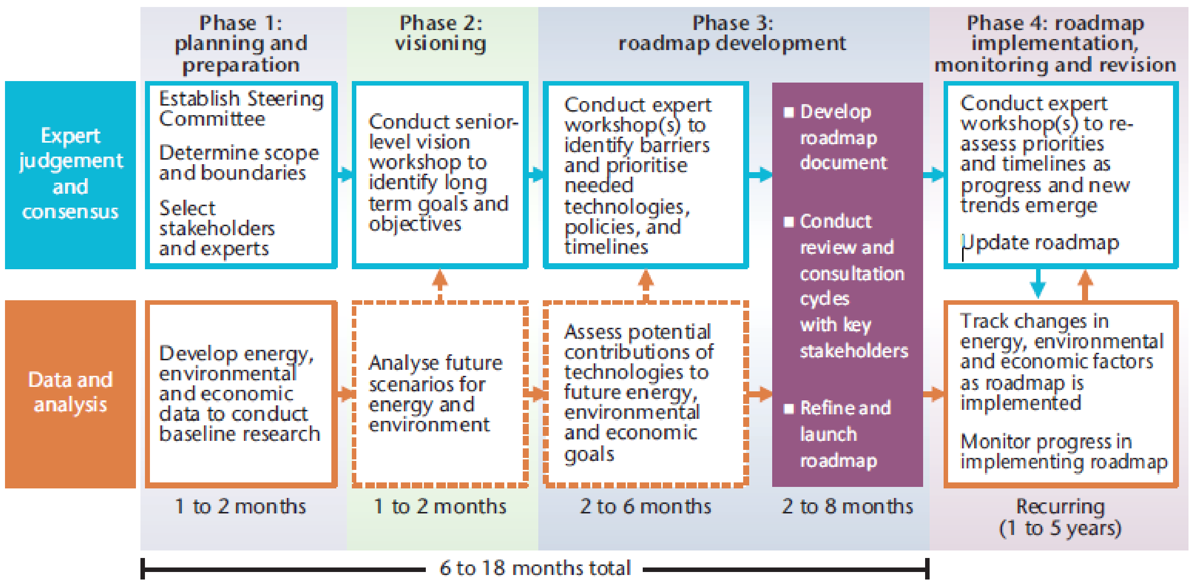

Figure 9-3: IEA outline of a technology roadmapping process [11]

[11] The dotted lines indicate activities that are optional, based on analysis capabilities and resources

9.2 Approach

The aim of this chapter is to perform a roadmapping process to present reliable data and analysis on the future of CSP in SA in terms of technology and services. To fulfil this aim, the chapter fulfils the following objectives:

- Develop a baseline scenario for CSP technology in SA in terms of opportunities, drivers, and policies;
- retrieve and update data from the South African solar energy technology roadmap (SETRM)[12];
- establish CSP deployment milestones and performance target;
- determine the action items/pathway to achieve the targets.

Brent (2015) stated that a roadmap is need-driven and thus does not assume the future, but it rather presents the potential as well as steps and action to attain the desired future. Therefore, to develop a CSP R&D roadmap, the opportunities, market potentials and the competition with other RETs is the first approach.

Methodology

In this section, the methodology used to develop the CSP roadmap for SA is described. The conceptual framework forms a basis for the adoption and deployment of CSP technology. The framework is based on the existing methodologies in literature (see Figure 9-4) and the major studies that form the foundation for the frameworks developed are shown in Table 12.

[12] SETRM is an unpublished/uncompleted roadmap developed for Solar PV and CSP in SA by a consortium of DOE, CSIR, SU and University of Pretoria.

Table 12: Key references for framework development

Framework aspect/Phases	Key literatures
Technology roadmap architecture	IEA guide (IEA, 2014a), (Garcia & Bray, 1997), (Phaal & Muller, 2009) and (Phaal, 2004).
Methodologies for data retrieval and scenario analysis	(Musango & Brent, 2015), (Saritas & Aylen, 2010) and (De Smedt *et al*. 2013).
Innovation theory and analysis	(Cetindamar *et al*., 2010), (Musango & Brent, 2015) and (Rinne, 2004), (Craig *et al*., , 2017).
Gap and migration analysis	(Craig et al., 2017), (Gerdsri *et al*., 2009), (Huang *et al*., 2014), SETRM .

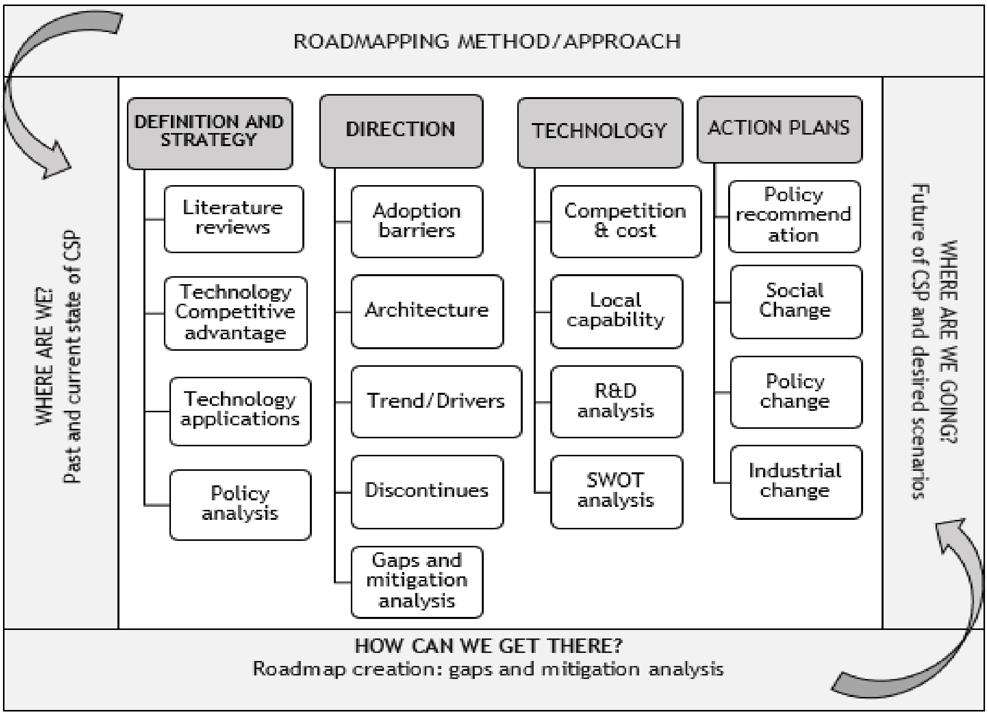

Figure 9-4: New CSP roadmap framework

Where are we?

This is the analysis of the history and the current state of CSP technology in SA. The analysis performed at this stage is similar to the history and current stage in the roadmap framework developed by Musango and Brent (2015). However, this stage performs an analysis of the following:

- Market drivers of CSP in SA;
- the existing energy policy and CSP regulatory framework;
- the organisational and technological requirements of CSP plants; and
- public opinions on solar electricity generation.

The best methods to perform the activities stated above include the review of existing literature; and analysis of the trends and indicators for CSP deployment (Saritas & Aylen, 2010; Musango & Brent, 2015). The details of this activity had been extensively presented in Chapter 2 and 3 of this thesis report.

Gaps and CSP adoption migration paths

To achieve the target and goal, there is a need to identify the gaps and the migration path to follow. This activity answers the question, how do we get there? The migration paths to achieve the target or goals include policy changes, technological changes, industry and social change (see Figure 9-4). The needed information on the possibility of achieving the set targets is gathered here. In this study, the methodology followed are: i.) innovation analysis (identification of the trends and indicators) see Chapter 3 of this thesis; and ii.) SWOT analysis.

Scenarios and desired target of CSP in SA

This activity answers the question, where are we going? The design of the desired scenarios and target for CSP were performed here. The scenarios adopted were based on the existing policy documents, plans or reputable reports on CSP in SA.

Case study analysis and method

The framework developed in this chapter was not to carry out all the entire roadmapping process, but to identify the best method to perform the data analysis activity of roadmapping process for CSP technology adoption, which represents our case study.

9.3 CSP Roadmap

9.3.1 Current state of CSP: Progress since 2010

The majority of the electricity generation in SA is from coal. While the government has shown interest in RET, only 600 MW of CSP commercial plant has been installed since 2010, and less than 300 MW is grid connected. Recent developments in the IRP updates also contribute to the uncertainties around the future of CSP in SA.

SA REI4P discussed in Chapter 3, was developed by DOE and Eskom to help the deployment of RETs in SA. The two-tier tariff option which was introduced during bid window 3, was done to specifically favour CSP. While the REI4P has been successful in helping RET deployment, many artificial limitations still exist that limit the effectiveness of this policy. The DOE often stated their interest in supplying electricity to sub-Saharan Africa, starting with the Southern African Development Community (SADEC) countries in the coming years.

While a relatively huge amount of MW allocation has been given to solar energy, very little has been awarded to CSP.

There has been a significant reduction in the CSP electricity cost since the introduction of the two-tier tariff plan in the REI4P, from the initial ZAR 2.85/kWh during bid window 1 to ZAR 1.46 kW/h in bid window 3.5 (see Table 13). For a summary of the existing CSP plants in SA, see Appendix B

SA leads in terms of CSP installed capacities in sub-Saharan Africa. However, there are other limitations that prevent it from being the leader in RET in Africa and in the world. With the current carbon emissions from SADEC countries being the largest in Africa (BP, 2017), there is a need for a shift to a low carbon energy generation and economic development in the region. The deployment of CSP plants in SA and SADEC region can help achieve this target and can lead a re-industrialisation as well as make SADEC region a market champion in CSP component research, manufacturing, and supply (IEA, 2014b). Conversely, this can only be achieved by a conscious commitment from all the governments of the countries in the region.

The global growth rate of CSP deployment as illustrated in Figure 9-5 was also reflected on the CSP sector of SA where there was a rapid development in 2010 to 2015. However, there has been no new CSP plant development in SA since then, while the global growth rate has been between 40 - 45 % till today.

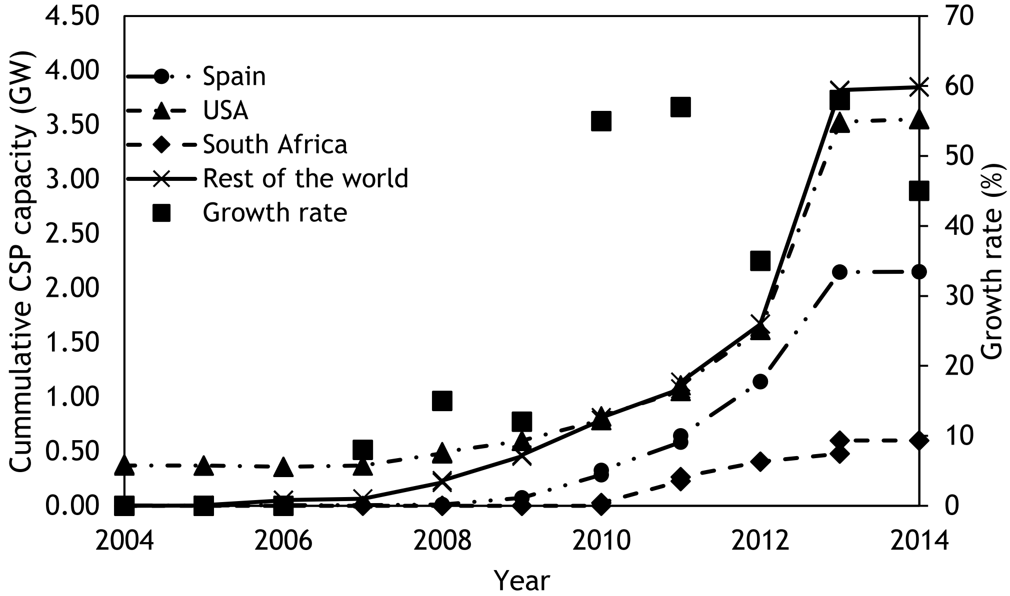

Figure 9-5: Author comparison of SA CSP deployment with global CSP deployment based on ETP

Table 13: CSP Progress in SA since 2010

	End of 2010	End of 2017
Total installed capacity	0	300 MW
Annual installed capacity connected to grid	0	100 MW
Proposed electricity cost	ZAR 2.85/kWh	ZAR 1.46/kWh
Estimated STE generated during the year	N/A	1.1 GWh

9.3.2 Migrating towards CSP competitiveness

Investment Cost

IEA reported that the investment cost of CSP is still high globally, ranging between USD 4 000/kW to 9000/kW, and this range is often determined by the capacity factor, the available DNI on site, the solar multiple and the desired storage capacity.

In SA, the cost of KaXu Solar One, which was started in November 2012 and connected to the grid on March 2, 2015 was approximately 860 USD million. While Xina solar one, a plant with the same capacity which started in December 2014 and connected to the grid on August 16, 2017 cost approximately 880 USD million. It can be inferred that here has been significant improvement in terms of annual electricity production and storage capacity, however, this came at a cost, thereby showing little learning effect. From the comparison presented in Table 14, the investment cost of CSP in SA seemed to be going higher instead of reducing.

While the results from Chapter 7 of this study and IEA (2014b) predicted a 10 - 14 % cost reduction, this is yet to be seen in the investment cost of CSP in SA. The ongoing uncertainties around CSP in SA had reduced the market opportunities for CSP and had thus led to an increase in the cost of CSP materials and components. The dominance of a single technology in the global CSP market had also limited the option of competitiveness. Other new plants are built uniquely thereby having a considerable risk and/or high development cost.

Table 14: Comparison of KaXu and Xina. Author analysis as adapted from NREL (2016a)

	KaXu Solar One	**Xina solar one**
Break Ground:	November 2012	December 2014
Start Production:	March 2, 2015	August 16, 2017
Cost (approx.):	860 USD million	880 USD million
POWER BLOCK		
Turbine Capacity (Gross):	100.0 MW	100.0 MW
Turbine Capacity (Net):	100.0 MW	100.0 MW
Turbine Manufacturer:	Siemens	Siemens
Output Type:	Steam Rankine	Steam Rankine
Power Cycle Pressure:	100.0 bar	
Cooling Method:	Dry cooling	Dry cooling
THERMAL STORAGE		
Storage Type:	2-tank indirect	2-tank indirect
Storage Capacity:	2.5 hours	5.5 hours
Thermal Storage Description:	Molten salts	Molten salts
SOLAR FIELD		
Solar-Field Aperture Area:	817,500 m^2	872,500 m^2
No of Solar Collector Assemblies (SCAs):	1,200	

Operations and maintenance (O&M)

CSP plants operate on the principle of conventional steam generation cycle and the only difference is the source of heat, which is the sun. The power block aspect of CSP plants are operated all day and night and often require monitoring. IEA (2014) reported that most local safety regulations require that a number of operators should monitor the system round the clock. The solar field of CSP has been highly automated to track the sun and withstand wind and other incidents. Despite this, it still requires monitoring, inspection, and regular maintenance.

While a minimum number of 30 operators and 10 maintenance staff are needed to operate and maintain a 50 MW CSP plant, a 300 MW plant requires the same number of operating staff with a few more maintenance staff because of the solar field size (IEA, 2014b).The results from Chapter 7 of this study and Craig et al. Brent & Dinter (2017) shows that the higher the size of a CSP plant, the lower the O&M cost. I In locations with good solar resources like SA, the cost of O&M could be halved with larger plants (IEA, 2014b).

9.3.3 CSP barriers and implications in SA

The existing barriers to CSP deployments are the same globally (see Figure 9-6) and the few country specific ones are as a result uniqueness in terms of the economic strength, local manufacturing capacity, government commitment and policy uncertainties. The implications of the identified barriers in the overall development of CSP plants are presented in Table 15.

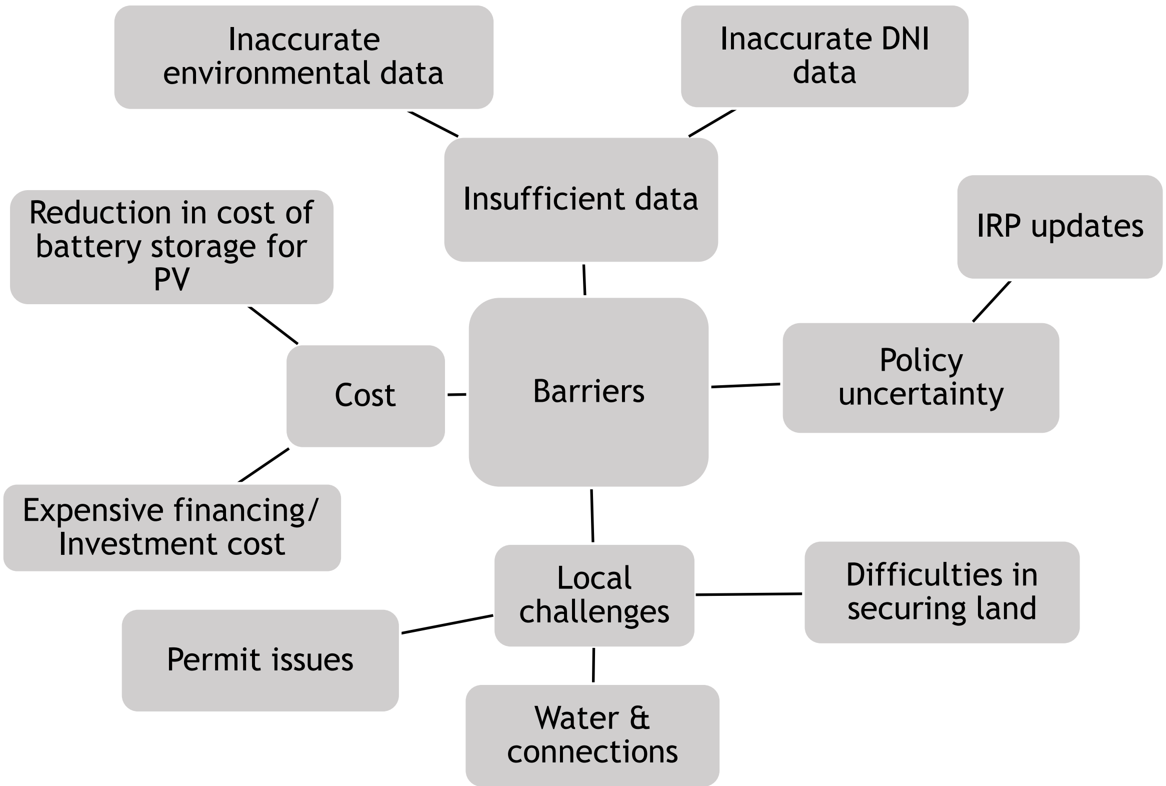

Figure 9-6: CSP deployment barriers in SA

Table 15: Implications of CSP barriers, adapted from (IEA, 2014b)

Barriers	Implications
Permit issues	• Difficulty in reaching financial closure. • Conflict with biodiversity and water use. • Safety challenges.
Inaccurate DNI data **Inaccurate weather data**	• System design errors. • Severe interference from ground-level atmospheric turbidity, soiling, wind, dirt, and storms.
Expensive financing **High investment cost**	• Difficulty in reaching financial close or securing debt. •
Decrease in cost of battery storage for PV	• Reduction in the value of CSP storage. • LCOE challenges. • Loss of interest in CSP by policy makers.

9.3.4 Medium-term outlook

Since the closure of bid window 3.5, there has been no new CSP plant in SA, despite the continuous increase in the global CSP development rate. There is a need for the new energy minister to sign off the outstanding Redstone plant contract (which has affected the development of the CSP plant) and the public opinion about SA's interest in RETs. To fulfil its initial target of energy exportation, new CSP plants need to be developed to export electricity to neighbouring SADEC countries.

Vision for deployment of CSP system[13]

The R&D community considers the following aspects in terms of taking CSP systems forward in the South African National System of Innovation NSI:

- Plant types, in terms of scale and use;
- heliostats and concentrators;
- receivers;
- storage, heat transfer and working fluids; and
- cooling technology and water.

The main technology developments for the plant types, over the next five years, are summarized as follows:

Parabolic troughs, and Linear Fresnel:

Direct Steam Generation (DSG), molten salt trace heating, and a better lifetime of evacuated tubes are the global focus areas for this plant type. However, given the existing experience and capacity of the South African R&D community, considerable focus here will be on DSG, and specifically for Linear Fresnel systems that will see an increase in market share. It is expected that the market share of parabolic troughs will dwindle in the coming decades.

[13] The data retrieved from SETRM was updated and the result of the analysis informed most of the suggestion presented here. Details of the process followed in the SETRM is illustrated in Appendix D.

Central receiver, or power tower:

The focus here will be improved performance across the plant, and especially lower cost heliostat systems, high temperature metals and receivers and storage.

In term of the latter, a key opportunity for CSP systems lies in their dispatchability characteristic due to the potential of thermal storage. In other words, CSP systems offer the potential to address peak demands (see Figure 9-7) or even to supply baseload power in future (Silinga *et al.*, 2015). Silinga *et al.* (2015) showed the high profitability of an optimised CSP electricity supply technique, in which CSP systems supply electricity during peak hours rather than during standard demand period to maximise the two-tier tariff highest option. Gauché *et al.* (2012) have demonstrated this benefit of CSP systems by modelling the supply potential from a large number of CSP plants, similar to the Gemasolar plant that is operational in Spain (see Table 16).

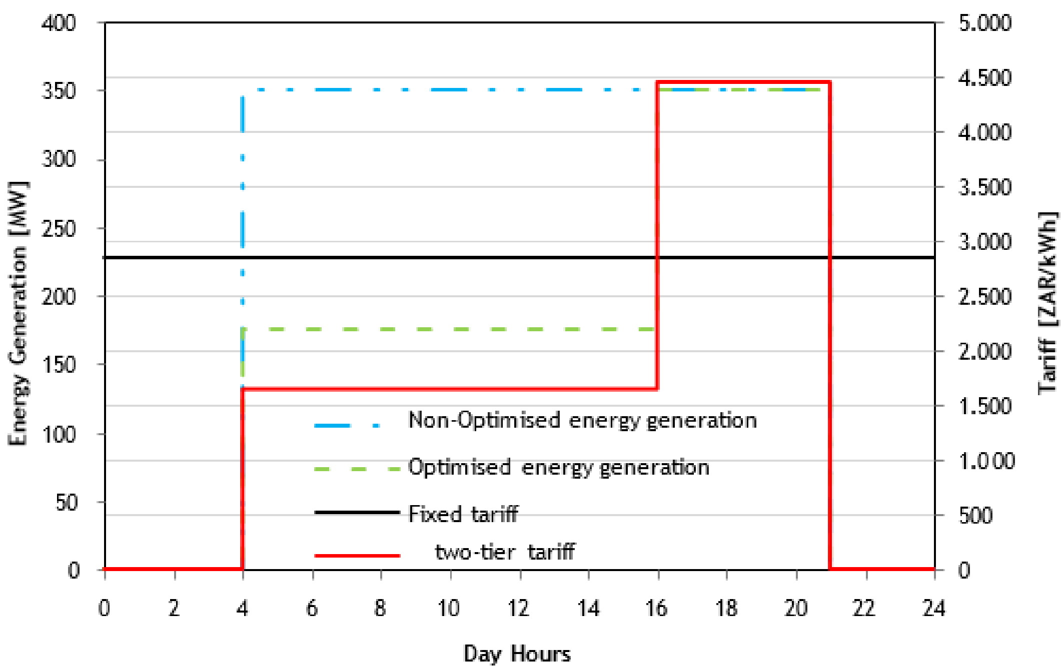

Figure 9-7: Optimised and non-optimised CSP system load profile and tariff plans

Table 16: Key Gemasolar parameters (Gauché *et al.*, 2012)

Item	Value
Country, Region	Spain, Seville Andalucía
Location	37°33′ 44.95″ North, 5°19′ 49.39″ West
Land area	195 Ha
Solar resource	2,172 kWh/m^2/yr
Electricity Generation	110 GWh/yr (planned)
Cost	230,000,000 Euro
O&M jobs	45
Heliostat aperture area	304,750 m^2
Number of heliostats	2,650
Heliostat size	120 m^2
Tower height	140 m
Heat transfer fluid	Molten salt
Receiver outlet / inlet temperature	565 °C / 290 °C
Turbine capacity (gross)	19.9 MWe
Cooling	Wet
Storage	2 tank, 15 hours

The model shows that a CSP fleet (of 823 plants of 20 MW_e peak capacity) generally manages to reach a production ceiling of just over 16 GW for several hours a day but plunges overnight as storage at some sites becomes increasingly depleted (see Figures 9.8 and 9.9). For that particular year, bad weather occurred across the country on one day (January the 9th, 2010), where the Upington site was badly hit and output across the fleet dropped significantly (but did not stop entirely).

The models with smaller power block capacities, but similar sized storage capacities, demonstrate increasing potential for dispatchability. To capitalise on this opportunity of CSP, the South African NSI should thus focus on central receiver systems in terms of the following working fluids and storage options:

- Brayton exhaust for 500 to 600 °C storage, which can be achieved through direct air to packed beds of South African rock or synthetic materials that have been produced through other R&D efforts; and
- CO_2 cycles indirectly storing heat in salts or other solutions, liquid metal receivers with phase change material (PCM) metals, or ceramic storage. In this regard, local R&D efforts can be capitalised on.

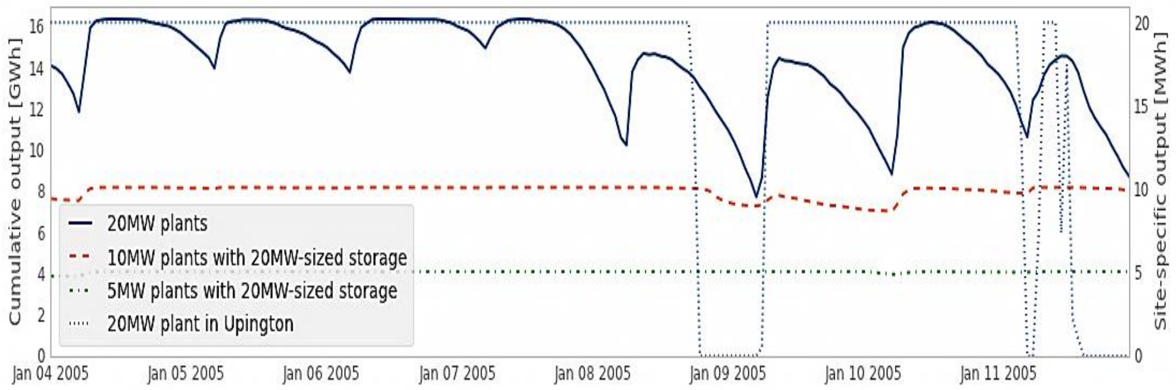

Figure 9-8: Model results in summer (only the three models with baseline storage capacity and Upington)

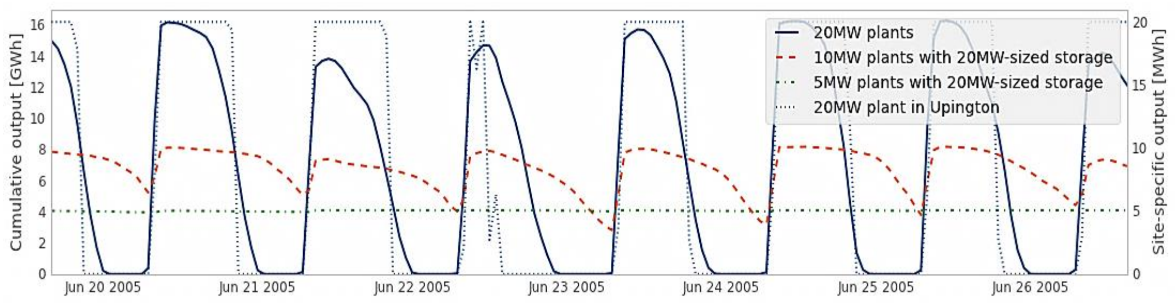

Figure 9-9: Model results in winter (only the three models with baseline storage capacity and Upington)

Another opportunity is that the materials used to construct CSP plants are (mostly) readily available and many of the components can be manufactured locally. The South African Renewables initiative (SARi) has estimated that more than 60 % of CSP systems could be manufactured locally with little government support (see Figure 9-10).

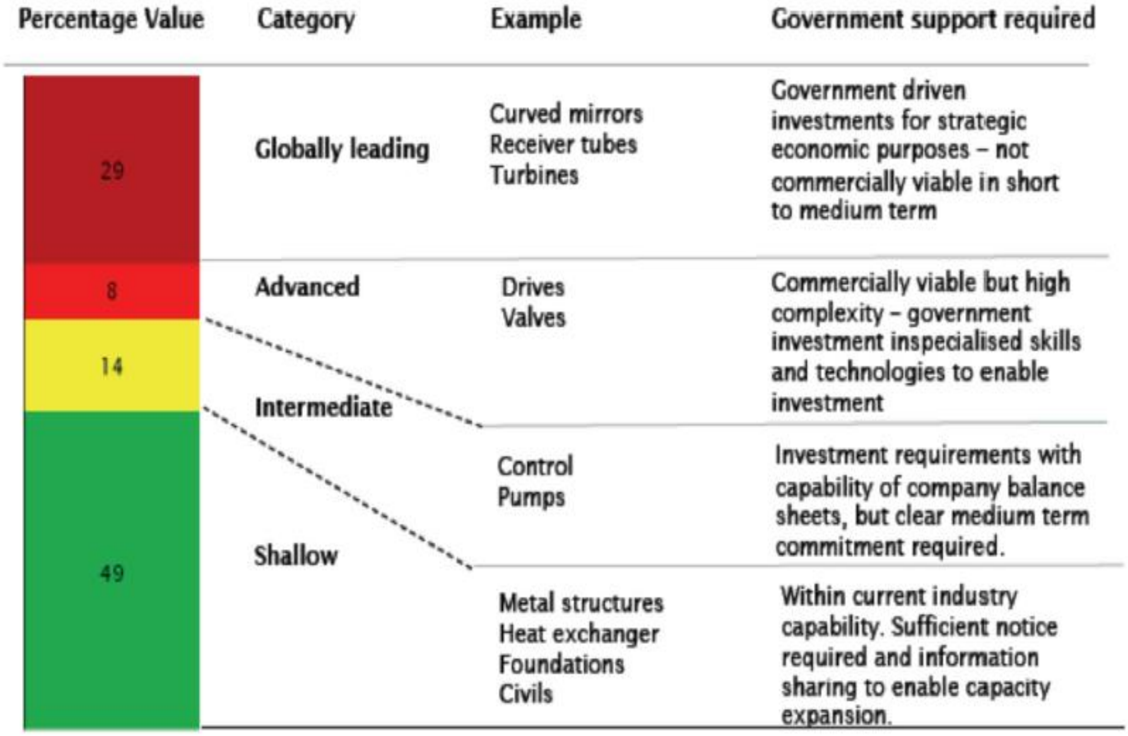

Figure 9-10: Localisation potential for a parabolic trough system with storage (Source: South African Renewables initiative (SARi), 2011)

A SWOT analysis[14] of such value chains in South Africa has subsequently been conducted (see Table 17).

[14] SWOT framework analyses the strength, weakness, opportunity and threats of an organisation (SEE Appendix F)

Table 17: SA CSP industry SWOT analysis

Strengths	**Weaknesses**
• Continuous increase in electricity demand. • Low cost of labour. • High local manufacturing capability (established local construction companies). • Reputable R&D institutions and activities. • Well established EPC companies. • CSP value proposition (dispatchability and storage). • Strong related industrial background with transferrable expertise/skills/component (e.g. mining and petro-chemical industries).	• Deficient transport and energy infrastructure. • High raw materials cost. • Shortage of skills and limited training schemes. • High transportation cost of imported materials from port to site. • Low CSP R&D funding in institutions. • Lack of local R&D in CSP companies as compared to international companies.
Opportunities	**Threats**
• High DNI resources. • REI4P two-tier tariffs. • High export potential to sub-Saharan countries. • Coal is currently the major source of power. • High local content requirements and targets by the government. • CSP hybridisation potential with new coal and gas plants. • Availability of land in the Northern Cape region. • Significant increase of local content with the gradual increase in the participation of local companies in CSP project.	• Difficulties in obtaining finances as financial institutions see CSP as relatively new technology and prefer to fund other tested and more accepted technologies (e.g. PV). • Low CSP R&D funding. • Uncertainty around allocation to CSP in REI4P. • Continuous decline in PV electricity cost. • Water scarcity in SA. • Competition with suppliers from other countries with lower labour cost (e.g. China, India) • Restrictive labour laws. • IRP instability. • Uncertainty in government support for CSP.

The local value chain in SA was hoped to cause a massive CSP deployment and a significant reduction in the electricity cost. Although there was a significant reduction in cost, it is still relatively high as compared to other RETs while the initial cost of investment in CSP still remain high as shown earlier in Section 7.3.2 of this report.

With no effect of the existing CSP value chain on the cost of investment, there is a need for component changes (innovation, design standards and redesign) and changes in input prices. This can be achieved through R&D activities, such as optimised heat and cheaper heat storage techniques and innovative collector/heliostat designs. Thereby concentrating on partnerships with industry to drive down the cost of the solar field.

With respect to the power block, SA contains the world expertise in dry-cooling. With the large-scale rollout, this will be a key competence to minimize the water consumption of CSP systems. The optimisation of dry-cooling thus needs to be supported. Ancillary, R&D activities in innovative mirror cleaning and solar tower calibration using robotic systems should be increased and applied on site.

9.4 Chapter conclusions

A technology roadmap for CSP deployment in SA was developed in this chapter. This was done by reviewing the existing literature on technology roadmapping, its usage and effectiveness in the RET sector and updating the unfinished SETRM roadmap. A CSP technology roadmap framework was developed. The framework uses the existing principle of the roadmapping process to create a comprehensive list of barriers, activities and their interaction and it explains how they can be overcome in SA.

The developed framework was put into practical use by performing a case study analysis: CSP technology in SA. The potentials and the opportunities of CSP with milestones were identified and the major causes of limitation barriers to its adoption and cost reduction were highlighted. The activities performed prove the capability of CSP to be a future leader in the CSP industry. The chapter showed that the progress of CSP has not been as anticipated and it thus provided a pathway to the future. The proposed major actions and drivers as presented in this chapter will aid the effectiveness of the identified policy instruments.

The framework developed here can also serve as an assisting document for stakeholders involved in policy decisions, finance institutions, academic and research institutions and companies interested in CSP. The framework developed was applied to CSP technology in SA. An expert elicitation was carried out to further identify the manufacturing capability of SA in terms of CSP component designs and services. This was used to create an updated SWOT analysis.

The limitations encountered in this chapter involve the reliance on stakeholder meetings and workshops that were done in 2012. However, the data was found relevant as the result showed that participants were optimistic about CSP at that time, because the challenges of government reluctance had not yet surfaced.

The roadmap developed in this chapter shows the collective efforts that are required for better CSP adoption and deployment in SA in the coming years. However, it does not provide the detail plans for implementation. The suggestions presented in this chapter must be elaborated and agreed upon jointly by a team of selected stakeholders in the SA CSP sector.

Although the roadmap developed here was adjustable as far as possible to accommodate all the CSP technology types in terms of market dynamics and deployment horizons, each of the technologies faces its specific technological challenges., Therefore further actions can be carried out based on the recommendations from this roadmap to further help the deployment of those technologies.

Because expert opinions and technology specificity is of high importance to the effectiveness of a roadmap, the following chapters presents expert elicitation on the critical issues affecting the adoption and deployment of CSP.

A detail CSP adoption roadmap is presented in Appendix I of this study.

10. Conclusions and recommendations

The outcomes, key findings, summary and contributions of this study are presented in this final chapter. The study presents a detailed assessment of concentrating solar power (CSP) technology in South Africa, by making a case for the adoption and application of the technology using various approaches. The aim for the methods used was to address the knowledge gap in the innovation and adoption analysis of CSP in terms of cost, progress ratio, learning effect, technical, non-technical, social, trade and economic impact.

A critical research into these factors is expected to play an important role in CSP value proposition, future allocations in the energy mix and to serve as a policy instrument for decision makers. Research is essential as CSP technology is new, and each plant in SA had been built uniquely and there are very limited data.

10.1 Research summary

There is a chasm, commonly referred to as valley of death (VoD) that exists in the technology adoption life cycle of each new innovation or product. This VoD represents the constraint that limits the advancement of new technologies from early adopters to early majority groups. There are various existing technology adoption models or approaches that have been used in literature to overcome this limitation to help new products or innovation cross this VoD.

The majority of these approaches have helped to study and understand various technology and market trends, including computer, electric cars, bioinformatics, pharmaceutical drugs, television, camera, consumer goods and PV. However, the existing the technology adoption studies which relate to CSP have only been done in comparison with Solar PV. Therefore, CSP has not been treated uniquely in any technology adoption study despite the numerous potentials of the technology.

Technology adoption is core to the cycle of invention, innovation and diffusion. It is a determining factor for the survival of technical changes or new products. The existing approaches for technology adoption analysis of products or innovation in literature were found not to be applicable to CSP because the technology can only be very effective on a large scale and cannot be treated as consumer/unit-based technology. A unique approach was developed, which involved the use of technology management principles to perform an adoption analysis of CSP in SA.

To fulfil its aim which was to perform a technology adoption assessment that will provide a framework and strategy that can be used to accelerate the adoption of CSP technology in SA, the research fulfilled five main objectives which are discussed in the sections below.

Objective 1: To perform a detailed CSP innovation analysis

To fulfil its first objective, a detailed innovation analysis of CSP in SA was carried out and presented in Chapter 3. The chapter showed the existing operations of CSP, established the impacts of CSP innovations on local research and development (R&D) and identified the possible improvement methods based on the current state of innovations. Consequently, the state of RETs in SA was analysed and the current state of the technology in the energy mix was presented. An analysis of the CSP average bidding tariff and electricity cost were also discussed and the adapted innovation processes for CSP in SA were identified.

To further understand the innovation value chain of CSP in SA, a detailed analysis of the existing technology transfer model of the technology in SA was performed and the impacts and challenges of CSP based on those adopted innovation strategies were presented.

Innovation analysis is incomplete without accessing spin-off companies and existing research facilities and infrastructures. Therefore, Section 3.8 of this study analysed the dynamic roles and interaction of organisations, universities, and government as relating to CSP innovation and funding. Finally, the various challenges faced by the identified stakeholders in the value chain were presented in terms of technical and socio-economic challenges.

Objective 2: Critically review of technology adoption approaches and CSP technologies

The identified challenges based on the adopted innovation approach as identified in answering objective 1 suggested the need to critically review the technology adoption methods and how they can be or have been used for CSP globally. This was achieved in the second objective of this study.

An ample volume of literature was found to address studies relating to innovations, transfer, diffusion and adoption of new technology. The various existing technology adoption models were grouped in Section 4.1 based on their modalities of operation or dimensions of study. The various models and frameworks for adoption was found to have been used to study various technology and market trends, including computer, electric cars, bioinformatics, pharmaceutical drugs, television, camera, consumer goods, PV and other incidents and occurrences such as HIV/AIDS. However, no adoption technique or framework was found for CSP technology in literature. Nonetheless, a similar process line was found in all the examined studies and this was grouped into 5 stages (awareness, interest, evaluation, trial and adoption). This corresponds to the TAL curve of Moore (1991), which was presented in the introduction chapter of this study. The findings from the review informed the decision to critically examine the existing adoption approach and how it has been used for a similar technology, in this case, Solar PV.

In section 4.2, critical analyses of two case studies were done, and it was based on how the identified approaches were deployed for solar PV technology adoption in two different countries (quantitative method in Germany and qualitative method in South Korea). The strength and limitations of the methods were identified, and the results show that the existing technology model cannot be used for CSP based on the uniqueness of the technology which had been presented extensively in Chapter 2.

Further analysis shows that technology management principles can be used to perform adoption studies and to develop a technology adoption framework for a unique technology such as CSP which currently thrives on a large scale and cannot be treated to be adopted as an individual or consumer-based product.

These findings informed the direction that the rest of the study took. The need arose to apply the desired technology management principles, to analyse critical factors that affect CSP as well as identify the interaction and dependencies of the various actors involved in the value chain of the technology's adoption. To achieve this, a third objective was formulated, namely to identify the impact of the critical factors affecting CSP adoption in South Africa.

Objective 3: Identify critical factors affecting CSP adoption in South Africa as well as their impact

The system analysis of CSP technology was carried out and presented in chapter 5 of this study. A system dynamics approach was used to identify the most critical factors to the adoption the CSP technology in SA. The process followed was based on five systems thinking and modelling phases which are: problem structuring, causal loop modelling, dynamic modelling, scenario planning and modelling, implementation and organizational learning. A causal loop was established, and a dynamic model was developed in Vensim PLE pro. The unit for technology adoption of CSP was based on cost, LCOE, environmental footprint, operational flexibility and energy dispatchability.

A baseline scenario was presented based on the current state of CSP in SA which had been established in chapters 2 - 4. Three other scenarios were then analysed based on predictions from reputable studies and expert opinions. The results from the system analysis show that local R&D development is very important to the local diffusion and adoption of CSP in SA. The results also show that a compromise can be made in terms of CSP plant location and solar resources. CSP plants can be placed in places with lower DNI and better grid facilities and that improved R&D will enhance the local capacity and ultimate adoption of the technology.

These findings suggest the need to further analyse the state of R&D in CSP in SA. Because there are limited data and few plants, an expert elicitation into the R&D budget was carried out in chapter 6. The aim of the elicitation was to know the current state of the R&D public budget and its impact on CSP cost, improvement and adoption. A survey was carried out and top experts in the CSP sector from the industries, government institutions and the academia were the respondents.

The experts were presented with the current R&D budget and various other scenarios for future funding and its effect on CSP cost of electricity and adoption. Zar 1.0/kWh was set as the threshold electricity price for adoption. In one scenario, 70 % of the experts believe that, if the current R&D funding remain the same over the next 5 years, CSP cost of electricity will not go below the threshold. In another scenario, over 61 % believe that the cost of electricity in CSP will go down as low as Zar 0.7/kWh in the year 2030, should the current public expenditure be increased by 50%.

Industrial R&D data were not considered in this analysis as none of the existing industrial stakeholders was willing to share their data on R&D budget for CSP. The activities reported in chapter 6 further analysed the technical and non-technical factors that affect CSP technology in SA. The diffusion possibilities for the technology when developed in SA were also presented.

Objective 4: Identify the current and future economics of CSP in South Africa

To understand the cost dynamics which is regarded as the ultimate determinant of any innovation, the fourth objective of the study was to use the existing principles, mathematical analysis and limited data to determine the overall current and future economics of CSP technology in SA. This was fully reported in chapter 7.

The present state of CSP cost evaluation parameters and the capital expenditure (CAPEX) of CSP were analysed. The results of the analysis were used to determine the learning rate/experience rate of CSP in SA. Data retrieved from reputable sources were also analysed and used to determine the trend and the future cost of CSP in SA. Here, the economic indicators of CSP were identified as the levelised cost of electricity (LCOE), the levelised profit of energy (LPOE), the specific investment cost, the learning rate and the progress ratio.

The solar field cost, which is the most significant capital cost, was analysed independently to give an idea of what the CSP experience curve might look like. The CSP learning rate in SA was calculated, the future of capital costs determined, and the likely experience curve for CSP in SA was presented. The analysis showed that there are no existing patterns in the capital costs of the existing CSP plants in SA for technology, size, solar multiple, site location or storage capacity. This makes the experience curve analysis of the CSP industry difficult. However, existing principles were used with the limited data to develop the learning rate, progress ratio, and cost reduction rate of CSP.

Objective 5: Develop an adoption framework for CSP in South Africa.

For CSP technology and CSP services to reach the desired destination in terms of the projected cost and adoption as suggested in this study, an important supporting framework is the local manufacturing sector, because the capability of this sector determines the effect that CSP adoption will have on the nation's trade and economy. Chapter 8 of this study thus assessed the local manufacturing sector of SA to understand its current and future capability to usher CSP into an era of mass innovation and adoption.

Furthermore, to fully understand how SA's economy reacts to large-scale sectoral development over a brief period, an analysis of other successful sectors and how they developed was done. The automobile sector case study was examined. The successes and circumstances that supported the sector's breakthrough were critically analysed and the lessons from it were used to estimate the barriers and challenges that the local manufacturing sector may face in embracing mass CSP product developments.

A survey was carried out and the results from the responses were used to further determine the specific strengths, weaknesses, opportunities and threats (SWOT) of the local manufacturing sectors and the results were compared to existing studies and global reports in other places. Different scenarios were presented in the survey to predict the impact of developing a local manufacturing capability for CSP on the SA economy and the results were presented. The labour and trade impact of the sector were identified and the economic and social benefits of improving them for CSP related services were estimated, including the employment opportunities that accompany the improvement of the technology.

The identified potentials and impacts of adopting CSP technology on a large scale was extensively presented in this study and the final step in building an adoption framework was through the development of a technology-specific roadmap. Chapter 9 of this study consequently used the principles of a roadmapping process to develop a technology-specific roadmap framework for CSP in SA. SETRM, an unpublished/uncompleted roadmap developed for Solar PV and CSP in SA by a consortium of DOE, CSIR, SU and the University of Pretoria, was analysed and updated and CSP data from it were retrieved it. The results from the analyses were used to determine the procedure for CSP to migrate to a competitive RET in SA. The roadmap also presented a medium-term outlook of CSP system in SA.

10.2 Research contributions

This study contributes to the limited literature on the impact of RD&D expenditure on cost and characteristics of CSP technology and can be useful in preparing proposals, tenders, reports and policies as relating to RETs, solar energy, CSP as well as RD&D.

- The results from this report can serve as a guide and policy instrument to stake holders in decision making towards CSP funding.
- A simpler method was developed to overcome the difficulties around the estimation of CSP progress ratio, learning rate analysis.
- The CSP economics analysis results can be used in future CSP plant development by EPC companies, investment banks and project finance experts.
- The results from the jobs and employments analysis can be used to reduce the resistance of labour associations to RET/IPP adoption.
- A specific roadmap for CSP in SA was developed and the migration path to CSP adoption was presented.
- The diffusion impact and strategies to cross the valley of death VoD in the technology adoption lifecycle TAL has been presented.

10.3 Discussion and recommendations

With vast uncultivated land and DNI resources that are second only to Chile, CSP can become a major stakeholder in the energy mix of SA in the future. However, a collaborative approach is needed for CSP technologies to break through in efficiency and cost, because more CSP plants need to be rolled out to allow for the learning effect. This only comes by doing and because CSP components and facilities often need to be on a large scale before they can be highly efficient. In SA and other parts of the world, there are few CSP plants, which are often built only a few units at a time. All the existing CSP facilities are near-unique, as they were developed on site due to their fragility, size and other complexities involved in moving CSP components. This near-uniqueness and the small number of unit constructions slow down the lowering of cost, which would otherwise have resulted from the learning effect and the exploitation of economies of scale.

Both a demand-pull and a technology-push approach should be deployed to make the cost of CSP competitive. Demand-pull will be effective when the locally available CSP technologies are subsidised, and the economies of scale and the learning effects draw the cost down. A better alternative is the technology-push approach, in which there is a significant increase in the funding and motivation for basic and advanced research and development of CSP and its components. The technology-push will lead to the development of new technology, with reduced cost and higher efficiency that can penetrate the market without subsidies or with reduced support.

The learning rate for CSP systems and components is highly uncertain, given the early stage of CSP technology deployment. Estimates of eight to ten per cent based on other technologies are considered conservatively realistic. Strategic market introduction, in terms of smart cost calculations for the peak, medium, and base load power supply, will be a positive step in the quest towards massive CSP deployment. Calculating the cost of technological subsystems, as performed in this study, will aid the optimisation of fund distribution and cost.

This study has shown that for CSP adoption to be accelerated in SA, there is a need for improved research, development and demonstration plants. This will increase the potential applications of CSP and hence make it easier to be developed for user-oriented usage and isolated systems. This will also increase the potential market for CSP rapidly and thus its deployments. New methods of application would then be developed with reduction in cost of raw materials. The improvement of R&D will also develop platforms by which CSP can be hybridized with other RETs and this has been proved in this study to cause a drastic increase in the rate of CSP adoption. Also, the participation of local industries should be encouraged by the SA government by raising the number of megawatts apportioned to CSP in the REI4P as this will increase competition and ultimately reduce the tariff cost.

Finally, it is important for the DoE to encourage localisation of the CSP technology, as this will boost the ability to maximise profit in the CSP innovation cycle. This will also allow local companies to access the technology development ideas, technology know-how, and transfer, and then to develop new processes and perform independent R&D.

10.4 Future research

There is a need to analyse the dedicated industrial R&D funding to CSP in SA and the willingness of the foreign companies to develop the local sector.

There is need to assess the cost dynamics of other subsystems in CSP that were not looked at, provided the companies become more contented and willing to share their cost data.

There is need to update the projected future and the outlook suggested in this study in the next 5 years to incorporate the unforeseen circumstances and to the adjust the factors base.

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Appendix A: A sample of an expert's response to the survey in Chapter 6

#1

COMPLETE

Collector: Email Invitation (Email)
Started: Tuesday, May 02, 2017 4:52:56 PM
Last Modified: Tuesday, May 02, 2017 5:04:18 PM
Time Spent: 00:11:22
Email: xxxxxxxxx
IP Address: xxx.xxx.xxx.xx

PAGE 1: CSP Technology Evaluation: Technology push approach towards CSP adoption in SA by O.O. Craig

Q1: Please indicate how you would evaluate your level of expertise with respect to each of the following concentrated solar power (CSP) technologies

Concentrated Solar Power	Among the top experts
Parabolic troughs	Among the top experts
Solar power towers	Expert Knowledge
Linear Fresnel reflectors	Expert Knowledge
Dish/Stirling system	Good knowledge
CSP policies in South Africa	Among the top experts

Q2: CSP technology evaluation

Parabolic trough (oil)	Technology is matured and no advances needed
Parabolic trough (molten salt)	Technology is matured and no advances needed
Solar power towers (steam)	Technology is matured and no advances needed
Solar power towers (molten salt)	Technology works but room for development, advances needed
Linear Fresnel reflectors (steam)	Current state is excellent and slight advances needed
Linear Fresnel reflectors (molten salt)	Technology is new and may not be successful without significant advancements
Dish/Stirling system	Technology works but room for development, advances needed

mirror deposition, and material development for heat transfer fluids. Engineering and applied RD&D include specific process improvements: air cooling and wet/dry hybrid cooling systems, increasing the efficiency and durability of specific technology components (receivers, concentrators, reflectors, and the balance of solar field), optimizing manufacturing techniques, reducing O&M costs by simplifying systems and learning from experience, and power block optimisation. Demonstration: The building of pilot projects for production of electricity with CSP technologies. A demonstration test facility to prove the technology works and could be scaled up.

Parabolic trough (molten salt)	Basic RD&D
Linear Fresnel reflectors (steam)	Engineering and applied RD&D
Linear Fresnel reflectors (molten salt)	Engineering and applied RD&D
Dish/Stirling system	Engineering and applied RD&D

Q4: Evaluation of RD&D budget allocation Consider the current South Africa's annual budget and assuming that it corresponds to 100 chips, please allocate these chips among the selected research areas by writing the number of chips in each cell.(PLEASE MAKE SURE THEY ADD UP TO 100)U chips (0 column) = there is no need for RD&D spending in this area for the given technology (e.g. technology is already mature, and further advances are not foreseeable)> U chips (other columns as appropriate)= with RD&D spending in this area the technology is more likely to be commercially successful in 2040.

Parabolic troughs	45
Solar power towers	20
Linear Fresnel reflectors	35
Dish/Stirling system	U chip

Q5: Please rate the impact of the following items/expenses on the overall cost of CSP plant and electricity.

Solar concentrators and mounting heat receiver (receiver	5 = Extremely-high impact glass tubes)
Solar concentrators and mounting heat receiver (towers)	5 = Extremely-high impact
Heat transfer fluid and handling system	4 = High impact
Electrical generation system (including generator, steam turbine and ancillary equipment)	2 = Low impact
Condenser and cooling system	2 = Low impact
Thermal storage system	3 = Moderate impact
Distributed control system	2 = Low impact
Pumps, motors and auxiliary steam cycle equipment	2 = Low impact
Insurance cost	4 = High impact
Annual debt interest	4 = High impact
Grid connection fees	2 = Low impact

Regular safety inspection	1 = Negligible impact
Waste water cost	1 = Negligible impact
Equipment damage cost	1 = Negligible impact
Community development cost	2 = Low impact
Public supports (grants, concessional loans, guaranty coverage)	3 = Moderate impact
Economic situation of country	2 = Low impact
Capital recovery factor (CRF)	1 = Negligible impact
Payback period	3 = Moderate impact
Construction time (the period from development to the first day of first electricity sale)	3 = Moderate impact
DNI	5 = Extremely-high impact
Annual electricity Generation/Plant availability	5 = Extremely-high impact
Economic operational life time	3 = Moderate impact

Q6: Please estimate your expected cost of electricity produced with CSP technologies in 2040 under the following public RD&D investment scenario

≤ 8.6 c$/kWh (Zar 1.2/kWh)	Scenario 1: suppose that research in the field of CSP receives the current yearly amount of R&D
≤ 7.2 c$/kWh (Zar 1.0/kWh)	Scenario 2: Suppose that the current yearly amount of R&D expenditure in CSP increasesby 25%
5.0 c$/kWh (Zar 0.7c/kWh)	Scenario 3: Suppose that the current yearly amount of R&D expenditure in CSP increases by 50%

Q7: Please rank the following indicators, from 1 to 5 in order of their influence to the reduction of CSP electricity cost, where the factor with the least influence is 1, and the factor with the highest influence is ranked 5.

Balance of plant costs and other issues	3
Thermal energy storage	5
Heat transfer fluids	4
The solar field: Mirrors, receivers and support structures	1
Increasing plant size	2

Q8: Which of the following countries do you think is
more likely to be the first to reach a commercially Others
(please specify) successful breakthrough in CSP technologies?

South Africa, Chile

Q9: Assess the importance of each of the following non-technical factors limiting the further adoption of CSP technologies

Long range transmission	Low impact
Water usage	Moderate impact
Land availability	Negligible impact
Other energy sources (e.g. Nuclear deal)	Extremely-high impact

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Q10: What percentage of the total SA power generation will be from CSP by 2040

Conservative estimation	5 %
Pessimistic estimation	<1 %
Advance/optimistic estimation	10 %

Q11: SA CSP technology diffusion: Once a local CSP technology is developed in SA and it reaches the market, how long will it take to diffuse?

How long will it take for the technology to diffuse to other African countries?	Immediately (no time lag)
How long will it take for the technology to be diffused to fast growing countries?	5 years
How long will it take for the technology to be diffused to globally?	5 years

Appendix B: Installed CSP technologies in South Africa

Table 18: Details of CSP plants in South Africa

Window no	Name	Technology	Location	Capacity	Storage capacity (hrs)	Owners	Solar field size (km^2)	Cost (USD million)	PPA/Tariff period or rate	Total jobs	No of household covered	Carbon emission prevented/yr	Start year
1	KaXU	trough	Pofadder	100 MW	2.5	Abengoa, IDC, KaXU community trust	0.8	860	20 yrs.	1000	80,000	300,000	2015
	Khi	tower	Upington	50 MW	2	Abengoa, IDC, Khi community trust	0.6	445	20 yrs.	600	45,000	183,000	2016
2	Bokpoort	trough	Groblershoop	50 MW	9.3	ACWA Power, Solafrica Bokpoort CSP Power Plant (Pty) Ltd	0.6	565	20 yrs.	1300	200,000	n/a	2016
3	Xina	trough	Pofadder	100 MW	5	Abengoa, IDC, PIC, KaXU community trust	0.6	880	20 yrs.	1,300	90,000	398,000	2017
	Ilanga 1	trough	Upington	100 MW	4.5	Emvelo, Cobra	n/a	972	20 yrs.	n/a	n/a	n/a	n/a
3.5	Kathu solar park	trough	Kathu	100 MW		Kathu Solar Park Consortium	n/a	n/a	20 yrs.	1200	80,000	300,000	n/a
	Redstone	tower	Postmasburg	100 MW	12	ACWA, Solar reserve	n/a	715	$124/MWh	4000	68,000	200,000	n/a
4.0	-	-		-		Bids accepted							

Appendix C: System dynamics parameters

Table 19: Modelling parameters

Variable name	Baseline parameters	Improved R&D Scenario	Low DNI + Improved R&D Scenario	Water consumption scenario
Initial LCOE	0.2	Baseline	Baseline	Baseline
Availability of DNI	1	Baseline	**0.3**	Baseline
Fraction of import levies	1	Baseline	Baseline	Baseline
Size of land	0.8	Baseline	Baseline	Baseline
Cost of raw materials	0.7	Baseline	Baseline	Baseline
Distance from Port to factory site	1	Baseline	Baseline	Baseline
Population of host community	0.6	Baseline	Baseline	Baseline
Fraction of fuel cost	0.2	Baseline	Baseline	**0.1**
Fraction of current impact on environment	0.3	Baseline	Baseline	**0.1**
Rate of building demonstration plants	0.1	**0.7**	**0.8**	Baseline
Rate of reducing water consumption	0.5	Baseline	Baseline	**0.1**
Rate of hybridisation of CSP with RET	0.3	**0.5**	Baseline	Baseline
Rate of development of control system and smart grid	0.4	Baseline	Baseline	Baseline
Rate of development of new system through R&D	0.6	Baseline	Baseline	Baseline
Rate of government support	0.5	Baseline	Baseline	Baseline
Current flexibility fraction	0.3	Baseline	Baseline	Baseline

The four scenarios were run with the same time horizon of 20 years (the year 2010- 2030) using a time step of 0.0625 and RK4 integration method. The unit of time was set as “year” in Vensim PLE software.

Appendix D: SETRM

The process of developing the Solar Energy RDI Roadmap for the need and market potential for solar energy RDI in South Africa have been assessed, considering competing options in the NSI in which the R & D will take place.

Figure 60 below shows how this study developed a national Solar Energy RDI Roadmap through a multi-stakeholder process.

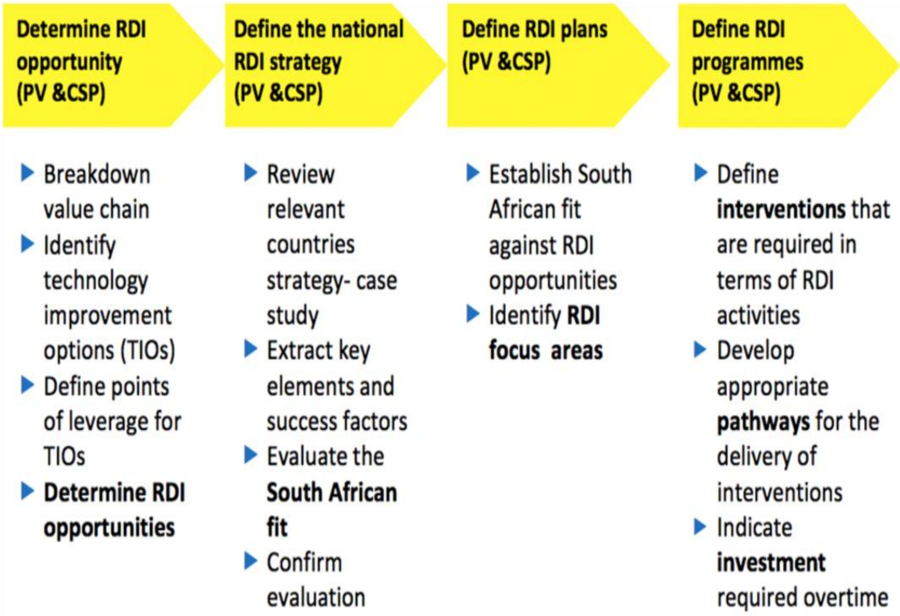

Figure D-1: Process of developing the RDI Roadmap

Appendix E: Expert elicitation of the local manufacturing capability for CSP in SA

A survey was carried out to assess the capability of the SA local manufacturing sector to manufacture CSP components and to provide CSP related services.

Elicitation layout

The study presents an elicitation of the opinions of manufacturing experts and CSP industrialists in SA. It considered the existing manufacturing capabilities in SA and examined their potential to either manufacture CSP components or to provide state of the art CSP related services.

Expert Elicitation Procedure

The respondents to this survey were recorded anonymously and the participating experts were drawn from the manufacturing sector, the SA CSP industries, consulting firms, EPCs and the academia. The survey was conducted from March through July 2017. The survey was sent out through emails and the responses with inconsistencies were clarified through one on one chats or via telephone calls. 50 emails and 11 web links were sent out but only 12 experts responded. All 12 responses were analysed to ensure a wide range of opinions within the SA manufacturing community and to reflect the diversity of the experts' views.

Elicitation focus

This study focussed only on South Africa and the local capability for CSP components. It however did not consider the government target/ expectations for the local manufacturing potentials.

Experts were then selected to participate in the survey to identify the potentials of local manufacturing sector to foster a boom in the deployment of CSP in SA. The questionnaire was divided into 2 sections:

- The first section analyses the financial strength and the research and development potential of the various CSP related component manufacturing sectors in SA.
- The second section analyses the existing potential within SA to manufacture some specific CSP components.

In the questionnaire, experts were asked to rank the potentials for each sector between 1 and 5, where 1 means very low potential and 5 means very high potential.

The results are presented in the table below and the details of the weighted average for each sector are presented in the figures in the appendices.

Table E-1: Financial strength and R&D potential of SA manufacturing sector

CSP related component sector	Financial strength	R&D potential
Steel manufacturing	High	High
Automotive component manufacturers-	High	Very high
Glass manufacturing sector -	Medium	Medium
Electrical equipment	Medium	High
Engineering Procurement and Construction (EPC) firms	High	Medium
Professional services (engineering consulting and project management)	High	Medium
Cement and concrete manufacturing	High	High

The financial strength and R&D potential of the various sectors involved in the local manufacturing in CSP components in SA according to the results from this survey is above average. The result shown in the above table shows that the local manufacturing capability for CSP components in SA is far above average and can be ranked between 65 – 70 % based on the results from this survey.

Some selected CSP specific component manufacturing were also analysed in this survey. The same process as above was used and the result from the current study was compared to the result of a similar analysis carried out by the WORLD BANK (2011), to understand the progress or retrogression of the potential to manufacture specific CSP components in SA. Experts were asked to rank the potential within SA to manufacture the selected CSP-specific components or systems. In the survey, 1 represents very low potential and 5 represent a very high potential to manufacture the various components locally in SA.

Table E-2: Survey result- Local manufacturing potential for CSP

CSP specific system/component	Potential for manufacturing within SA
Structural steel	High
Concrete and steel piping	Very high
CSP shaped glass	Medium
Heliostats	High
Pressure vessels and storage tanks	High
Medium Voltage, Low Voltage Electric motors, DC motors, Valves and actuators (engineering consulting and project management)	High
Steam turbines	Very low
Heat Exchangers	High
Aluminium conductor for overhead lines	High
Molten salts	Low
Oil-based HTF	Low
Water treatment plants	High
Chemicals for water treatment	High
Heaters	High
Heating, ventilation and air conditioning equipment (HVAC)	Very high
Fencing material and firefighting equipment	Very high
Tracking systems	High
Weather measurement equipment	High
Telecommunications and telecontrol equipment	High

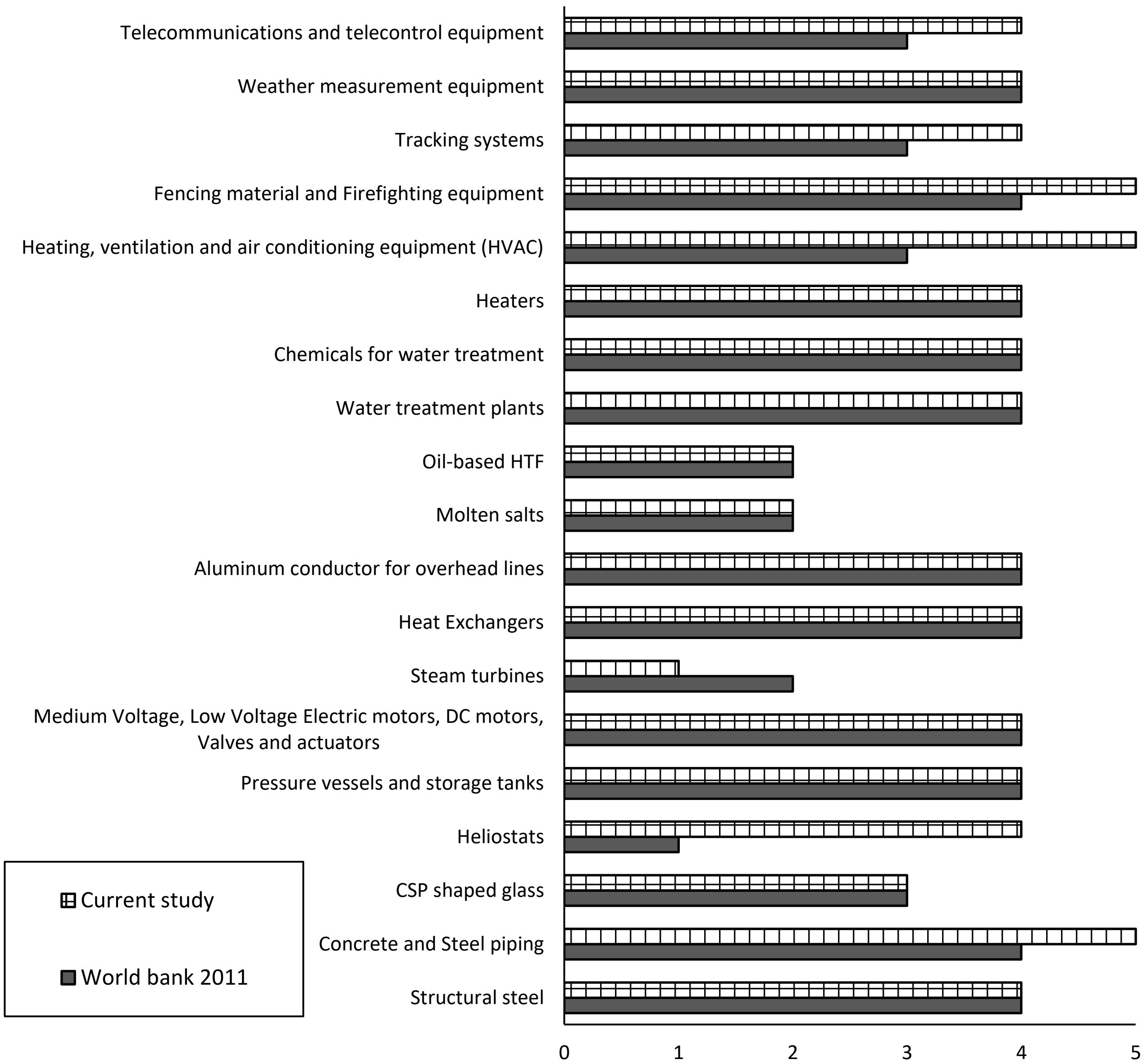

Figure E-1:Comparison of results between the current study and the World Bank report

The potential to manufacture non-CSP specific components such as fencing and firefighting equipment, HVAC, concrete and steel piping, tracking systems, telecommunications and telecontrol equipment have increased significantly from their states during the previous researches to high or very high state of local manufacturing potential in the current research. However, it was interesting to find out that most CSP specific components had little or no improvement in potential to be manufactured locally. The potential to manufacture Oil based HTF, molten salts and CSP shaped glass has experienced no major development in their capability over the years. The potential to manufacture Heliostats locally was however ranked high by the majority of respondents to the survey. The reason could be the success of a 100-kW demonstration plant, Helio 100, which has been developed by local engineers at the Solar Thermal Energy Research Group (STERG), at Stellenbosch

University. In the project, heliostats were developed from local materials and the site was showcased to the world during the Solar Paces conference which was held in Cape Town in 2016. Based on the results from this study, the following further conclusions can be drawn regarding the assessment of the local manufacturing capability for CSP components in SA:

The news of a decline or reduction in the public's confidence in ESKOM call for concern. The fact that many of the experts believe that Eskom is declining calls for urgent action. The CSP components and services value chain is a young and thriving market and each aspect is open to growth which will benefit the local capabilities and institutions in engineering, EPC, raw materials and R&D and will also boost investors' confidence level for CSP.

Some of the needed services or components for CSP production can be manufactured locally by companies that are less experienced with CSP. Companies who have been active in electrical, electronics, robotics and chemical con conveniently develop the capability to supply their needed services for CSP. The technology specific manufacturing potential is low (examples include, oil based HTF manufacturing, molten salt manufacturing and parabolic mirrors production) and as a result needs a higher technological knowhow which can only be developed through partnerships, technology transfers or learning by doing. Developing these potentials will lead to a huge export capability as they constitute the back bone of major CSP projects globally. Some companies/capabilities thrive well, as they are not CSP specific and their capabilities can be used to respond to other industrial demand, while some service providers such as heliostat manufacturers or receiver suppliers solely rely on the CSP market economics to survive.

There is an above average local capability in SA to manufacture CSP equipment, the few specific components that has low manufacturing potential can be improved through formation of partnerships and subsidiaries. An example is Rio glass that has been able to develop a local subsidiary that manufactures mirrors for CSP plants.

Appendix F: SWOT Analysis

According to Nikolaou *et al.* (2011), SWOT framework was initially developed for analysing critical issues around business and market development, and the usage has been extended to environmental and energy management (Chen, Kim & Yamaguchi, 2014). SWOT framework analyses the strengths, weaknesses, opportunities and threats of an organisation, a plan, a strategy or even public policy (Cetindamar *et al.*, 2010). Checking the strengths (most often are resources that help increase capacities and improve performance) and weaknesses of an organisation (which are factors that negatively influence the competitive capability of a company), are often referred to as the internal assessment. The analysis of the opportunities and threats of an organisation, which includes changes that could improve or inhibit the competitiveness as defined by (Paliwal, 2006) are referred to as external assessment. Using SWOT framework makes one realise several opportunities that surrounds a subject or policy. The analysis, when it is well performed, can suggest factors that can be improved on the subject/policy. It also lays the foundation for developing strategies for improvement or successfully overcoming competitions.

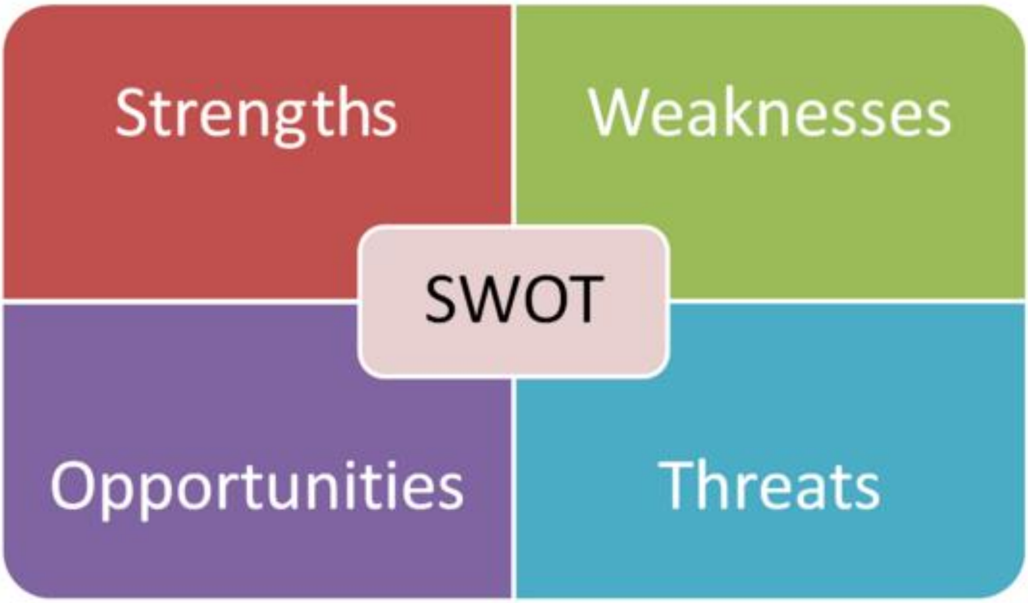

Figure E-2: SWOT Framework

Appendix G: Estimated economic output interpretation (NREL, 2016)

Impacts During Construction

1. Project Development and On-site Labour Impacts During Construction:

This category includes money spent on labour (wages and salaries and associated impacts) for people working to develop the project such as environmental technicians and lawyers, and people who construct the project such as road builders and concrete pourers. These impacts encompass jobs that are performed on-site at a given power plant, fuel production facility, or other project, as well as basic project development services and construction management. This category is divided into the following two subcategories that do not include any parts or materials:

- **Construction and Interconnection Labour:** These jobs are calculated based on cost and local share information entered in these fields in the JEDI model: Foundation, Erection, Electrical, Management/Supervision, and HV Sub/Interconnection Labour fields.
  Examples: crane operators, road contractors, construction managers, electricians, tower erectors, excavation workers, backhoe operators, foundation workers, installation workers
- **Construction related services:** These jobs are calculated based on cost and local share information entered in the Engineering and Legal Services fields in the JEDI model.
  Examples: civil and electrical engineers, attorneys, permitting specialists

2. Local Revenue and Supply Chain Impacts During Construction:

This category includes the materials and equipment necessary for the power plant or fuel production facility (e.g., turbines, modules, and boilers.) as well as the smaller components that make up the balance of system (e.g., wiring, inverters, mountings, and transformers). Impacts in this category are derived from spending on project development and on-site labor (hard hat purchases), equipment costs (turbines, blades, towers, transportation), manufacturing of components required to produce these components, materials (construction, transformer, electrical, HV line extension, HV sub-interconnection materials), and the supply chain of inputs required to produce these materials. This category also includes expenses such as land easements, site certificate/permitting, and miscellaneous labour.

Examples (for a CSP power plant): turbine manufacturers, turbine suppliers, gear manufacturers, blade suppliers, glass fibre manufacturers, tower manufacturers, tower suppliers, gravel workers, banks, cement producers, accountants, heavy equipment rental companies, bookkeepers, etc.

3. **Induced Impacts from Construction:**

These impacts refer to jobs and economic impacts that result from spending by workers involved in the first two categories (Project Development and On-site Labour Impacts as well as Local Revenue and Supply Chain Impacts).

Impacts During Operations

1. **On-site Labour Impacts During Operations:**

These impacts relate only to workers at power plants, fuel production facilities, or other projects; their administrative staff, and managers. Jobs calculation based on cost and local share information provided in the JEDI model cells called: Field Salaries, Administrative, and Management.

Examples: clerical and bookkeeping support, site managers, field technicians, O&M workers, etc.

2. **Local Revenue and Supply Chain Impacts During Operations:**

These impacts are derived from expenditures related to on-site labour, materials and services needed to operate the power plant, fuel production facility, or other project (vehicles, site maintenance/miscellaneous services, fees, permits, licenses, utilities, insurance, fuel, consumables/tools and miscellaneous supplies, replacement parts/equipment, spare parts inventory), the supply chain of inputs required to produce these goods and services, and project revenues that flow to the local economy in the form of land lease revenue, property tax revenue, and revenue to equity investors.

Examples (for a CSP power plant): turbine, and tower component suppliers for replacements, motor vehicle retailers, hardware and tool retailers, tool manufacturers, maintenance providers, metal fabricators, welders, material suppliers, agents at insurance companies, attendants at gas stations (for the vehicles used to operate and maintain the power plants), local government employees, local utilities, bookkeeping and accountants, banks, lawyers, etc.

3. Induced Impacts from Operations:

Refers to activities that result from income (earnings) spent by workers involved in the first two categories (on-site labour and local revenue and supply chain impacts.

4. Total Impacts

The total impact of the construction and operation of the power plant, as defined by JEDI, is the sum of the above three categories for construction and for operations. State-specific multipliers and personal spending patterns are used to derive the results.

(See https://www.nrel.gov/analysis/jedi/results.html)

Appendix H: Expected future cost

Drivers for cost reduction in STE		
	2018	2030
Solar field [ZAR/m2]	3000 - 5500	2000 - 3200
Thermal Storage [ZAR/kWhth]	450 - 700	380 - 450
PowerBlock [ZAR/kWe]	15200 - 16000	14700 - 15500
System Efficiency (%)	15 - 17	18 - 20

		2010-2020	**2020-2030**	**2030-2040**	**2040-2050**
Cumulative	Calculated learning rate	600	654	712	780
Installed Capacity (MW)	R&D improved funding - SD	600	675	760	850
	R&D improved budget	600	600	1100	2200
	(< 1 ZAR/kWh PPA in 2020)				

Jobs (minimum)	(operational jobs during CSP lifetime)	60000		71000	78000
Annual CO2 Saving (minimum)	(million tonnes)	1.86	2.02	2.31	2.418

Appendix I: CSP adoption recommendation based on the results from the various aspects of the study

The Tables in this section present the policy recommendations for a roadmap based on the results from the various activities carried out in this study. The sections are divided into the necessary steps needed for CSP to become a competitive and a major shareholder in the future energy mix of South Africa.

The text in bold represent the actions that require immediate attention.

1.

2018	2030	2040	2050
FINANCE AND RD &D			
Provide an average of 2.5- 4.5 million Rands annually **for CSP RD&D in South Africa** **> 25% of the 2016 RD&D fund for CSP**		Continue to monitor and adapt CSP financing strategies as experience increases	
Encourage more advance research type of RD&D	Promote the Incorporation of locally developed technology in commercial CSP plant		
Improve relationship between industries and R&D Institutes			

2.

<table>
<tr><th>2018</th><th>2030</th><th>2040</th><th>2050</th></tr>
<tr><td colspan="4">UTILITIES AND GRID OPERATORS</td></tr>
<tr><td rowspan="2">Negotiate tariffs for exports of CSP electricity</td><td>Build more HVDC lines from Northern Cape to connect other provinces</td><td></td><td></td></tr>
<tr><td colspan="2">Build more HVDC lines between South Africa and SADEC countries for energy export</td><td></td></tr>
<tr><td>Sign power purchase agreements with independent CSP producers.</td><td>(Encourage project proposals from CSP IPPs)</td><td colspan="2" rowspan="2">Take advantage of CSP flexibility to manage more variable renewable electricity</td></tr>
<tr><td colspan="2">Encourage the return of CSP to IRP</td></tr>
<tr><td colspan="2"></td><td colspan="2">Reward storage and backup capacities of CSP plants</td></tr>
<tr><td></td><td colspan="2">Participate in CSP project development</td><td></td></tr>
</table>

3.

2018	2030	2040	2050
Department of Energy **Department of Science and Technology**			
Regulatory frameworks in place for CSP demonstration and further research	Comprehensive regulatory frameworks in place for commercial deployment	Continue to review and refine legal and regulatory frameworks as CSP experience increases	

4

2018	2030	2040	2050
GOVERNMENTS			
• **Keep the two-tier tariff for CSP electricity and extend it to the heat energy aspect of CSP** • **Lift restrictions on generation from CSP in IRP updates (including limits to plant size and hybridisation ratios)**		Adjust tariff to evolving market conditions	Eliminate incentives / special tariff for power from CSP
Support the established solar resource mapping companies (spin-off companies) to enter SADEC markets. **For on-ground and satellite measurements**			
Establish incentives for solar fuels			
Facilitate grid access for CSP projects			
Increase support to RD&D, establish incentives for innovation. **Encourage industrial based RD&D**			
Encourage local manufacturing			

5.

2018	2030	2040	2050
PUBLIC ENGAGEMENT			
Provide greater governmental resources	Develop and apply best practice public engagement techniques to CSP demonstration projects	Refine public engagement strategies in all regions as CSP experience increases	
Engage the public on the benefits of Renewable Energy technologies including CSP	Increase the labour and social impacts of CSP plants		
Emphasize the possibility of skill transfer and the importance of existing know how			