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Science in Sustainable Energy Engineering**

Title:

**Geophysical and industrial requirements of large scale rollout of concentrating
solar power (CSP) in South Africa**



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DISCLAIMER

Except where otherwise stated and acknowledged, I certify
that this dissertation is my sole and unaided work.

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21 August 2009
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ABSTRACT

This study investigates the requirements and implications if South Africa were to evolve its electricity supply structure to a large emphasis on Concentrated Solar Power (CSP). It does this by assessing the local geographical conditions and what are the land, water and radiation requirements of CSP followed by an investigation into the transmission grid requirements. Recommendations are drawn up of possible grid expansion options followed by a comparison of current national expansion plans. Energy storage was pinpointed as being a key to the large scale uptake of CSP where intermittent, solar energy's capacity factor can be significantly up scaled to suit the national load profile. Storage options were evaluated, assessed and compared after which recommendations were made for immediate and future installations. The other key issue for the national uptake of CSP is sustainable development and the need to cultivate and grow a local design, manufacturing, construction and operations industry centred around CSP. This dissertation looks at the potential employment creation of CSP, along with materials estimates, manufacturing requirements and the skills needed to facilitate the industry.

Data was collected through a number of avenues, including from the literature of multiple peer reviewed journals and articles, through various semiformal interviews with key professionals and consultations with various academic and scientific peers. The dissertation concludes that the infrastructure requirements for large scale CSP has been shown to not be a barrier in the development of this energy path. Solar radiation of the Northern Cape is one of the highest in the world and land is undeveloped and unutilized in the majority of this hotspot. Water requirements are of concern, however the technology of dry cooling allows up to 90% less water than conventional cooling but at an additional 5% increase in energy cost. Grid capacity, however requires an upgrade as the capacity numbers estimated in this dissertation

will outstrip the grid capacity in less than 2 years following the required CSP deployment. High voltage Direct Current has proved itself as an efficient, economical and more environmentally sound option, for the transport large capacities of electricity to the main load centres. Thermal storage appears to offer the best advantages of which molten salt is the most mature and favourable for immediate installations. Future storage options are more difficult to assess as the technologies are under continuous development. Around seven technologies were recommended for further observation and evaluation as there does not appear to be a silver bullet yet but the progression and research is advancing rapidly.

Creating a local CSP industry, which can handle the large capacities that the science requires, was investigated under local South African conditions. With a national unemployment rate of 23% and climbing, employment estimates for CSP are very promising and offer over three times the amount of jobs as coal, and over ten times the amount of nuclear energy. If the CSP capacity, stated in the Eskom 2008 annual report, of 30 Giga Watts by 2050 is taken, an estimated 177 000 direct jobs could be created and a total of 708 000 direct and indirect jobs. A simple breakdown, of a standard plant, was undertaken to assess the materials and manufacturability of the various components inside South Africa's borders. The raw material estimates did not yield any projected short falls, however the ability of the country to manufacture the storage material, molten salt, was unfounded and therefore seen as an import material. Critical prototype components design is recommended from experienced, international CSP community following which adaptations and optimizations should be made once experience and understanding have been learned. Skills requirements spanned all levels from multiple sectors, unlike some mainstream fossil technologies, and with the automotive sector showing particular promise for redirection towards a CSP future, thereby minimising job losses and sustaining a major workhorse in South Africa GDP.

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ACRONYMS ABBREVIATIONS AND UNITS OF MEASURE

ASGISA	– Accelerated and Shared Growth Initiative of South Africa
CDM	– Clean Development Mechanism
CO ₂	– Carbon dioxide
CO ₂ e	– Carbon dioxide equivalent
CRSES	– Centre for Renewable and Sustainable Energy Studies
CSP	– Concentrated Solar Power
DC	– Direct Current
DEAT	– Department of Environment and Tourism
DLR	– German Aerospace Institute (<i>Deutsches Zentrum für Luft- und Raumfahrt e.V.</i>)
DME	– Department of Minerals and Energy
DNI	– Direct Normal Irradiation
DSMP	– Demand Side Management Programme
DWAF	– Department of Water Affairs and Forestry
EC	– Eastern Cape
EER	– Emerging energy Research
EJ	– Exajoule (1 EJ = 10 ¹⁸ J)
EU	– European Union
FIT	– Feed-In Tariff
FS	– Free State
GACGC	– German Advisory Council on Global Change
GDP	– Gross Domestic Produce
GHG	– Green House Gas
GIS	– Geographic Information Systems
GMI	– Global Market Initiative
GW	– Gigawatts (1 GW = 1,000 MW)
GWC	– Growth Without Constraint
HVAC	– High Voltage Alternating Current
HVDC	– High Voltage Direct Current
IEA	– International Energy Agency
IPP	– Independent Power Producer

IPCC	– Intergovernmental Panel on Climate Change
kV	– Kilo Volt (1000 volts)
kWh	– Kilowatt-hours (1 kWh = 3.6×10^6 J)
LTMS	– Long Term Mitigation Scenario
Mt	– Metric ton
MTPPP	– Medium Term Power Purchase Programme
MW	– Megawatts
MWh	– Megawatt-hours
NC	– Northern Cape
OCGT	– Open-cycle Gas Turbine
PBMR	– Pebble-bed modular reactor
PPA	– Power Purchase Agreement
PSA	– Plataforma Solar de Almería
PV	– Photovoltaics
REFIT	– Renewable Energy Feed in Tariff
SAPP	– South African Power Pool
SEGS	– Solar Energy Generation System
ST	– Solar Thermal
STEG	– Solar Thermal Electric Generation
TJ	– terajoule (1 TJ = 10^{12} J)
UNFCCC	– United Nations Framework Convention on Climate Change
US	– United States
US¢	– United States Dollar cent (US\$ 1 = US¢ 100)
US\$	– United States Dollar (US\$ 1 = ZAR 7.7)
WC	– Western Cape
ZAR	– South African Rand

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1 INTRODUCTION

Global warming and climate change affects the entire world as a whole, but the effects on Sub-Saharan Africa will be severely damaging, according to Intergovernmental Panel on Climate Change's (IPCC) working group two's fourth assessment report (IPCC, 2007). Economies of Sub-Saharan Africa are partially reliant on environmental tourism and subsistence farming, this means the poor unavoidably shoulder the brunt of climate change. Carbon dioxide is the major anthropogenic Green House Gas (GHG) contributing to global warming and climate change. Electricity in South Africa is primarily produced by the national supplier, Eskom. Some 50% of Africa's total electricity, 96% South Africa's, production comes from Eskom of which 90% is primarily produced by coal fired power stations (DME, 2009). Eskom and Sasol, a major Petro-Chemical South African company, produce roughly 45% of the country's greenhouse gases (SouthAfrica.info, 2008). However, South Africa does not qualify and have quantified commitments to reduce emissions under the Kyoto protocol, due to its "Developing" country status.

Renewable electricity generation can reduce the carbon dependency of a country's energy system (or grid electricity) dramatically. In Africa, renewable energy resources are abundant, meaning the continent can produce ample carbon friendly, sustainable energy not only for its own use but a good surplus for export opportunities (Earthlife Africa, 2009). Of the renewable energies, solar energy is said to have the greatest potential where Africa has around 95% of the world's best winter sunshine area (Earthlife Africa, 2009). South Africa has one of the highest solar radiation figures in the world, with the town of Upington receiving an annual DNI of 2955 kWh/m², and it would appear that solar based energy is South Africa's best renewable alternative (DME, 2003).

Solar energy is the by far the most abundant energy resource on earth (see Figure 1.1) (IEA, 2008). The amount of solar energy that radiates the earth's surface in an hour is roughly the same as the total energy consumed by all human activities in a year (IEA, 2008). The draw back of solar energy however, is its low energy density and intermittency, which make it complex and costly to convert and utilize on a large scale. Due to these reasons, solar energy currently provides less than 1% of the world's total commercial energy requirements.

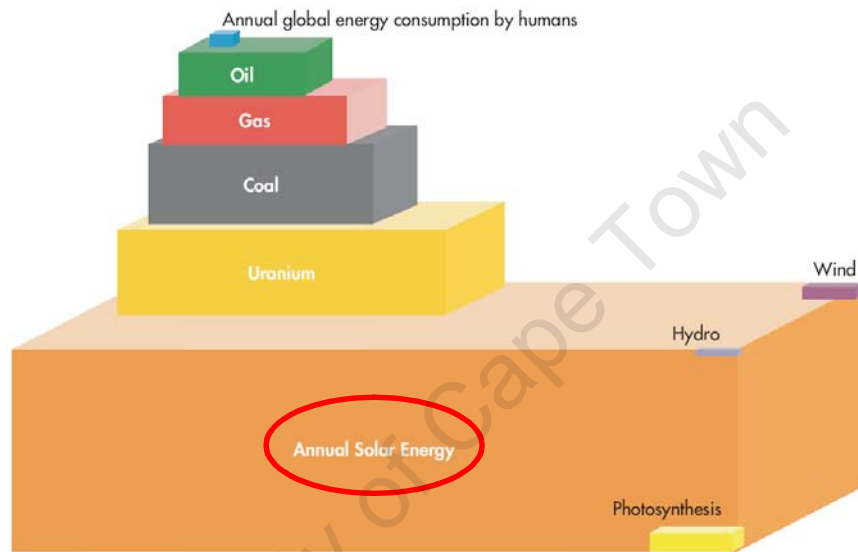


Figure 1.1: Graphic representation of the quantities associated with the total annual human energy consumption compared to the traditional energy resources. Source: (IEA, 2008)

Currently, solar energy can be harvested in several ways. It can be used passively as a heat source, to heat water and air in households and buildings, and as a light source in building design, both in residential and industrial processes. Additionally it can be converted to electricity, which has the benefits of being easy to transport and converted to other useful energy forms (IEA, 2008). There are two common methods of converting solar radiation into electricity, firstly by photovoltaics (PV) where photons of light knock electrons of highly purified silicon crystals or thin film materials, into a higher state of energy, thereby generating electricity. Secondly through concentration of solar thermal radiation or concentrated solar power (CSP), which drives a heat engine, thereby producing electricity. Additionally solar energy can be used to convert substances into fuels, notably hydrogen and metal oxides.

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

The utilization of solar energy is expected to grow up to a thousand times the size of current capacities by the year 2050 according to two scenarios (ACT and BLUE maps) investigated by the IEA. The ACT Map uses technologies that already exist, or are in an advanced state of development, to bring global CO₂ emission back to current levels by 2050 and the BLUE Map scenarios uses more uncertain or revolutionary technologies to reduce CO₂ emissions by 50% from current levels by 2050 (See figure 1.2 below) (IEA, 2008).

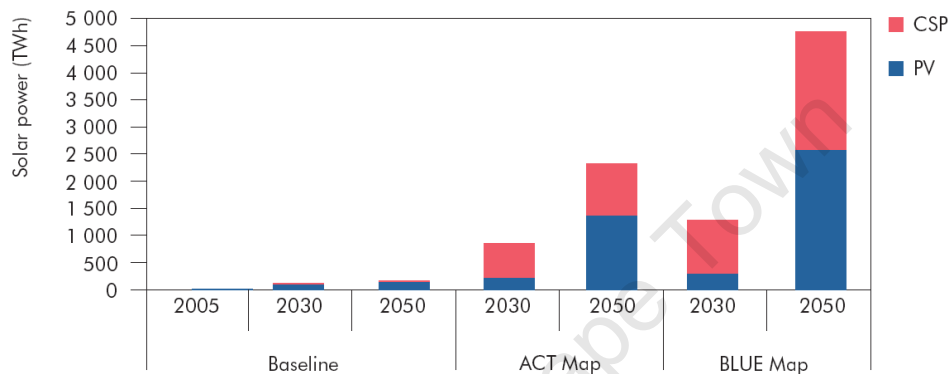


Figure 1.2: Graphic representation of the quantities predicated by two modelling scenarios of the predicted solar capacities of PV and CSP. Source: (IEA, 2008)

Concentrated solar thermal power plant technologies could have a significant role in the share of clean and renewable energy in the future. Solar thermal power plants are already a well proven and demonstrated technology and since 1985, nine parabolic trough type solar thermal power plants in California have fed more than 10 TWh's of solar based electricity, over the last 20 years, into the Southern California grid (Muller-Steinhagen, 2008). Currently, over 500 Megawatts (MW) of CSP are being built worldwide and a further 11 000MW are in the project development stage (Muller-Steinhagen, 2008). When CSP plants utilize thermal energy storage, CSP plants can provide dispatch able electricity, greatly increasing the value of the energy and plant. CSP plants are already among the most cost effective renewable power technologies and with further technological improvements and mass production of the components, they will become competitive with fossil fuel plants within the next decade (Muller-Steinhagen, 2008). Additionally CSP plants can combine electricity production with water desalination.

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

South Africa has been marked out as having one of the cheapest electricity tariffs in the world (Eberhard, 2005). This is due to the capital cost of the older power generation plants been mostly paid off and the slow uptake of new investments power generation sector (Eskom, 2008a). The country has been endowed with a large natural coal reserve, some 48 500 million tons, which makes it the 5th largest in the world and thus the electricity generation sector took the traditional and economical route of coal fired power plants (BP, 2007). Since the end of 2007, the country has been facing a crippling electricity supply capacity and a diminishing reserve margin (Edkins). The national electricity supplier, Eskom, released two scenarios in which they plan to supply the increasing demand which includes increasing the renewables component to at least 1 600MW by 2025 (Eskom, 2008). Both these scenarios were drawn up to mitigate climate change and reduce the country's carbon dioxide emissions. The first scenario significantly increases the share of nuclear power and envisages some 8.5GW of solar energy by 2050.

Table 1.1: Eskom planned mitigation case scenarios A and B. Source: (Eskom, 2008)

Technology	Reference Case	Scenario A	Scenario B
Efficiency	Load growth 4.4% per year to 2026; 2.5% (no efficiency) to 2050	Reduces expected growth in annual demand by estimated 0.23%	Reduces expected growth in annual demand by estimated 0.23%
Renewables	900MW wind by 2026, 2GW by 2050	4.5GW wind plus 8.5GW solar by 2050	4.5GW wind plus 30GW solar by 2050
Nuclear	No new nuclear	40GW by 2050 (20GW by 2026)	30GW by 2050 (20GW by 2026)
Hydro imports	No new imports	17GW by 2050	17GW by 2050
Clean Coal	Supercritical (36%)	41% (2025); 45% (2030); 47% (2035)	41% (2025); 45% (2030); 47% (2035)
Capture & Storage	None	All new coal plant from 2035	All new coal plant from 2035

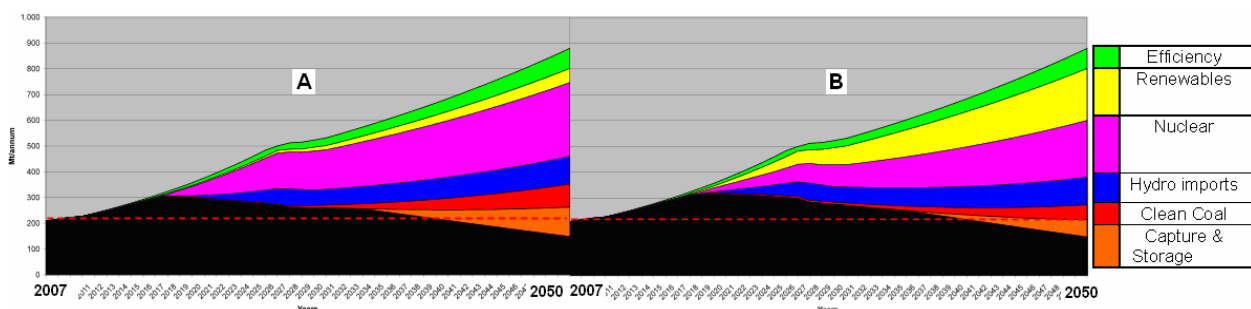


Figure 1.3: Graphic representation Carbon Dioxide mitigation wedges for scenarios A and B. Source: (Eskom, 2008)

The second reference case chose a greater dependence on renewables, in particular 30GW capacity are expected to come from solar by 2050. This has lead to some of the reference bench marks for solar capacity used throughout this dissertation. In addition to this, Harald Winkler of the Energy Research Centre of the University of Cape Town, recommended that research should investigate the institutional arrangements, human capacity development, risk sharing, distributed generation systems and storage options (Eskom, 2008). He also advised that solar thermal electricity deserves particular attention, notably concentrating solar power (CSP) where a capacity factor of greater than 60% is achievable and is of much greater value to the load profile of South Africa (Winkler, 2009).

The technology of CSP has been commercially proven on a small scale in many countries and has proven to be cheaper than solar photovoltaics for electricity production. Additionally it has the possibility of containing an energy storage system thus being available as a base or peak load electricity producer. It is one of South Africa's most promising renewable energy options to reduce the country's carbon intensive electricity supply but more study is needed on the understanding of large scale roll out. This dissertation will aim to understand this technology and bring to light the various implications of committing to a mass manufacturing, deployment and operations of this technology.

Past and current solar thermal research, from the major institutions of National Renewable Energy Laboratories (NREL) from America, DLR from Germany and Plataforma Solar de Almería (PSA) of Spain, has been focused on the more small scale, prototype- type plants with institutions and professionals more keen on proving that the technology works. This dissertation will thus explore the requirements of committing to constructing a range of 1GW, 10GW and 30GW's of Solar Thermal electricity supply by 2050. It aims to assist policy makers, power utilities,

governmental officials and anyone who is directly involved with the structuring and planning of South Africa's solar thermal future. The dissertation will systematically break down what would be needed if South Africa were to commit to a very large scale solar thermal power scheme. This breakdown will yield a wide variety of topics and sections which will be too large in scope for a partial dissertation thus two key areas will be analysed, investigated and discussed.

The two key area's which are researched in this dissertation are: (i) The geophysical and infrastructure requirements for large scale CSP and (ii) the employment potential and requirements for creating a local industry. These two topics were decided on after careful discussions with recommended professionals in key areas. In building up to answer these two key questions, the methodology used is stated and explained where two main tools are used, in-depth interviews and a thorough literature review. The methodology is followed by a background section which delves into the environmental issues and the purpose of this dissertation. The background section then looks into the various solar thermal technologies and which will be most effective in South Africa's climate. The various plant designs are researched and compared with respect to their properties and suitability for the South African climate and load profile. Properties of importance would be cost, efficiency, energy storage capability and ability for local manufacture. Finally the background section investigates the country's demand and electricity load profile, along with the planned capacity expansion and South Africa's role in the climate change negotiations.

The first section begins by looking at the specific geographical requirements for CSP in South Africa including the physical size and land requirements for the plants such as topography and vegetation. Detailed maps of South Africa's land and solar radiation readings are presented from which suitable areas are highlighted as CSP requires very high flux, direct solar radiation for best yield. Certain CSP technologies

require large volumes of water for cooling and condensing the working fluid while and others are said to have dry cooling as an option. In the case for water cooling, requirements are calculated following which, suitable rivers and dams will be flagged with appropriate flow rates to achieve the least damage to down stream ecosystems.

The second section of the infrastructure question looks at the national grid structure, its current and future planned capacity and how this relates to the CSP generation capacities coming from the solar radiation hotspots, designated before. For this large amount of energy to be distributed, a large, costly infrastructure needs to be designed and constructed from a very remote part of South Africa to locations where the demand can draw from. This section analyses the capacities and costs and offers recommendations to the future planning if required.

The final section associated with the infrastructure question has to do the technical issue of energy storage, which allows this intermittent renewable energy source the ability to supply the South African load curve. The criterion for assessing the technologies is stated and explained from which the main properties are extracted and recorded. The various energy storage options are assessed, tabulated and compared as to which is the most convenient for the South African Case from which conclusions are drawn.

The second key question of this dissertation relating to the requirements for creating a local industry is assessed. It begins by researching the predicted employment potential of large scale CSP facilities around the world. Following this, a break down of the standard plant into its various parts and materials is assessed as to the capacity of the South African manufacturing industry. For the construction of the plants, various materials, parts and manufacturing techniques are required. Local production takes preference however certain specialized parts may need to be

imported. This section breaks down the mechanics of a plant and estimates the amount of raw materials required such as glass, steel, copper etc, the possible construction of specialized parts such as heliostats and turbines, and what percentages of this can be performed locally. These results are then extrapolated into the larger scale where it is made evident whether South Africa can support, upscale or even construct a new industry to supply the construction of plants. A diverse labour force is needed for the planning, design, construction, operations and maintenance of these large plants. The labour requirements of this infrastructure is assessed with particular emphasis on job creation. The types of jobs and skill level are analysed. The planning and design will need to be carried out by highly skilled engineering and management firms and some of the designs may be more economical and carry less risk if bought from international sources who have experience in solar thermal plants. The majority of job creation would come from construction both of parts and plants, operations and maintenance where these areas will be thoroughly assessed on numbers and skills required.

In concluding this dissertation discussions and interpretations will be made which will reinvestigate the key findings of the various questions posed. Following this, conclusions will be drawn from which recommendations will be made as to the planning required for a large CSP infrastructure along with the possible barriers projected for South Africa.

2 RESEARCH QUESTION

The overriding research question addressed in this thesis is:

What are the physical and industrial requirements, if South Africa were to evolve its electricity supply to a large emphasis on Concentrated Solar Thermal Power?

After interviews with specialized professionals, Mark Pickering of Palmer Development Group, Grove Steyn of the Managing Infrastructure Reform and Regulation (MIRR) of UCT, Max Edkins of the Energy Research Centre UCT, and consultations with my supervisor Harald Winkler of the Energy Research Centre UCT, it was decided that a further breakdown of this question was needed and an analysis of two main questions would be greatly beneficial to the understanding of what this energy path entails. The economics of such a path has traditionally been the main constraint to this technology, however this area has been thoroughly investigated by Edkins (2008). Edkins thesis and many other studies were used to establish the next key questions and most beneficial to the South African case that needed to be addressed:

- I. **What are the geophysical and electrical infrastructure requirements for large scale, intermittent renewable energy, and its timely diffusion into the South African grid?**
- II. **What are the logistical and skills requirements for creating a local design, manufacturing, operations and maintenance industry?**

Too accurately and conclusively assess these questions, the research covered four specific areas:

PART A: CONTEXT TO IMPLEMENTATION OF CSP

Firstly, this dissertation portrays the background to the study and lays the foundation of information to which it can base the analysis of the two core questions. This section has been divided into four main parts:

1. *Solar Energy and climate change:* This dissertation briefly summarises and breaks down the core facts and issues on climate change from a global perspective from recently published studies and discusses the need for and resources of renewables and in particular concentrated solar thermal power. Additionally it highlights the other key benefits of choosing a CSP path, such as: solar being a renewable resource not limited to finite reserve, CSP falling under the title of sustainable development, less dependence on coal which, being finite, will run out eventually, and CSP's positive job creation potential
2. *Analysis of concentrating solar thermal technologies:* It then briefly reviews the current CSP technologies and weighs them against each other with regards to the South African situation.
3. *South Africa's electricity supply and demand structure and global and local sustainable development:* Finally it evaluates the South African electricity supply and load demand structure, briefly explaining the recent electricity crisis and how CSP could solve some of the issues. Lastly, South Africa's role in international climate change negotiations is addressed along with its contribution to sustainable development.

PART B: METHODOLOGY

Secondly, the dissertation states the methodology structure used to answer the core questions stated above. The methodology uses two techniques for the collection of data, namely an expansive literature review and a series of in-depth interviews and personal communications with specialists and key informants in the respective fields. Following this, basic mathematical and analytical modelling is used to filter the various options, of each section, to arrive at the best probable solutions to the key questions.

PART C: *INFRASTRUCTURE REQUIREMENTS FOR CSP*

Thirdly, this dissertation assesses the first core question of the study, namely the infrastructure requirements for large scale CSP. This section is broken up into three main parts of which the energy storage section is split into two further sections:

1. *Geographical analysis of radiation, land, water and power grid:* The dissertation investigates the geographical conditions of South Africa with respect to the requirements of CSP and illustrates the physical, potential sizes of plants of varying capacity.
2. *Transmission and distribution:* The dissertation then analyses and investigates the transmission and distribution infrastructure requirements for the varying CSP capacities. Analysis will be done on the existing grid structure and capacity of power lines and substations. Results will then be determined as to what additional infrastructure is required and estimates on costs will be calculated.
3. *Energy Storage:* The importance of energy storage is discussed where it can either spread the time of delivery of power, or concentrate it.
 - 3.1 *Technology options and comparison of properties:* The dissertation assesses the various technology options and tabulates the properties comparing the important attributes.
 - 3.2.1 *Present and future technology projections:* Finally it analyses and compares the maturity of the various storage technology options and models them against each other for a time scale of immediate applications to long term applications.

PART D: *REQUIREMENTS FOR CREATING A LOCAL CSP INDUSTRY*

Finally, this dissertation assesses the second core question of my study, namely the requirements for creating a local industry. This section is broken up into six parts:

1. *Employment potential of CSP:* The dissertation investigates and compiles multiple studies on predicted employment potential of CSP and makes estimates on the direct and indirect job creation potential of the various CSP capacities.
2. *Breakdown of the plant and its constituent components:* The dissertation identifies and compiles all recent studies on the solar thermal plants and break up the most popular design into its various components. The components will then be broken up into ones that can be locally manufactured and specialist parts that will have to be imported. This will be confirmed and supplemented by interviews with specialist.
3. *Raw material estimates:* The dissertation assesses and formulates estimates of raw materials needed from the breakdown of the plant and compares these to basic estimates given by published papers. These are then be compared with local resources and manufacturing capabilities.
4. *Manufacturing requirements:* By consulting experts in the resources and manufacturing fields, this dissertation analyses what factories are locally available for the manufacture of certain parts and what capacities of production they offer. From here it identifies what additional factories will be required and they're optimum location in terms of transport and resources.
5. *Skills and labour requirements:* The breakdown in manufacture of parts, factories and quantities will assist it in determining the skill and labour requirements. These results will be tabulated and confirmed after interviews with experts in industry and human resource management.

3 METHODOLOGY

The research methodology that has been chosen has two main techniques for collection information, namely a very detailed and expansive literature review and a series of in-depth interviews with specialists and key informants in the associated fields (Figure 3.1). This direction was selected to give both global and national level views, global, in the climate change and renewable energy perspective, and national in relation to South Africa's electricity generation, both infrastructural and industry based. This methodology has both a qualitative and quantitative effect, whereby one source of information or data is certified by the other, and vice versa. This leads to a more complete analysis of the research question.

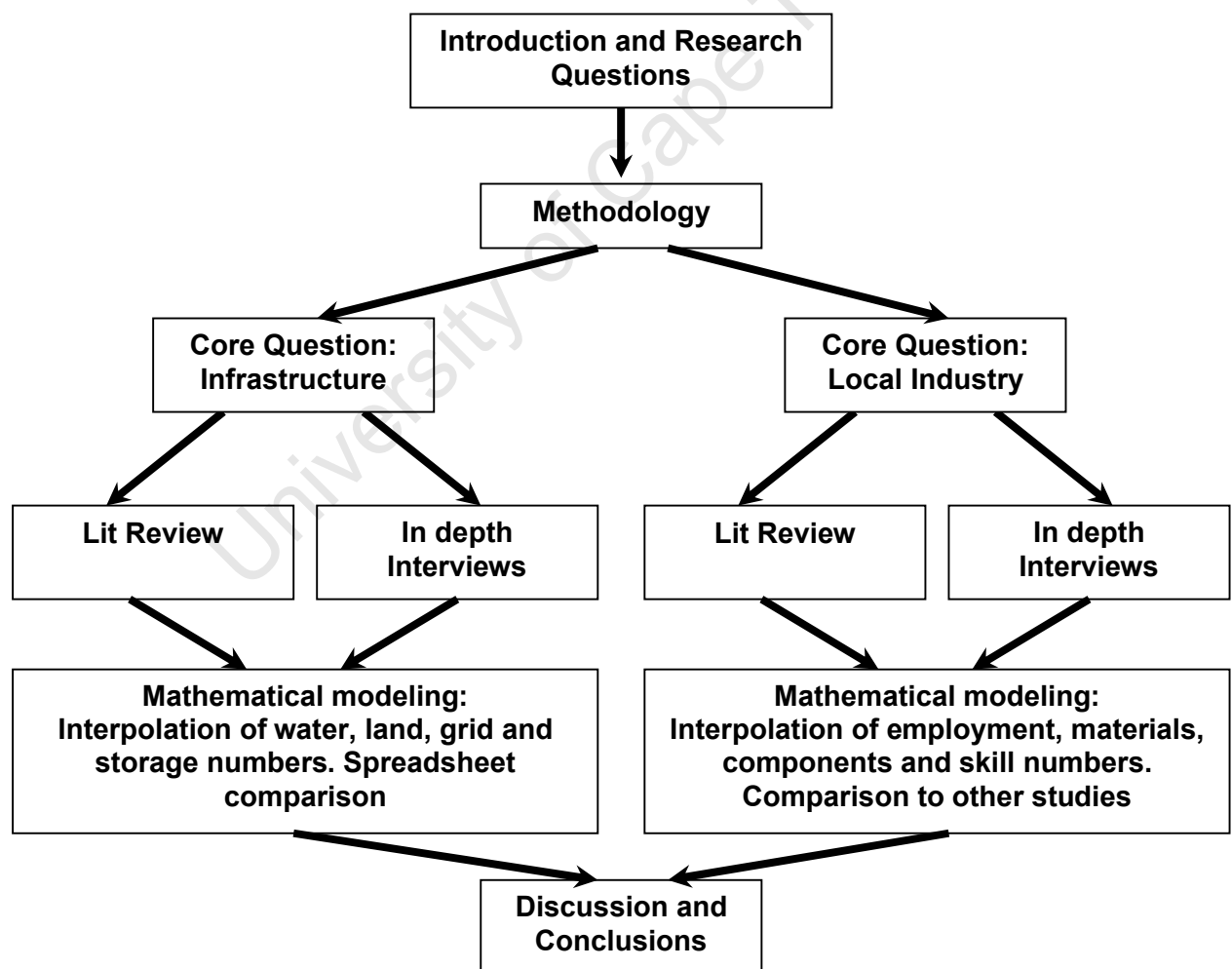


Figure 3.1: Research model of the study – The mathematical and optimization modeling was accomplished with inputs from the two methodological approaches, the literature review and in depth interviews with key informants

3.1 LITERATURE REVIEW

A broad range of literature was accessed for the arguments and findings from chapter four through to chapter six, on the discussion on the requirements for large scale deployment of CSP in South Africa (Refer to list of references in chapter nine). All referencing has been based on the UCT approved, Harvard Reference style guide. Most of the literature on concentrated solar thermal power is based on reports from the small scale pilot plants in the US and EU, of the institutions of NREL, DLR and PSA, along with published papers on the various technologies, and theories and policies related to concentrated solar thermal power. For the latest developments in the industry, new plants and technologies, online publications and press releases were cited.

The Science Direct online database was extensively used for peer reviewed, published papers. These papers ranged from in-depth technical design of CSP core components and planning to broad scoping, policy based projections of future world energy scenarios. The German Aerospace Centre (DLR), proved invaluable for their massive selection of widely accessible public CSP reports. All data and information drawn from these published papers, in chapters four through six, has been cited and referenced back to the original source in the reference chapter 9.

For the South African state of electricity generation, the majority of reliable information comes from Eskom, the national energy supplier, whose reports have been used along with published reports of the National Energy Regulator of South Africa (NERSA). These sources have been combined with other, independent, research reports and peer reviewed published papers. Press releases have been used for the most up to date information and are listed in the references.

3.2 IN-DEPTH INTERVIEWS

In- depth interviews were used as the second method of data collection along with the planning and scoping of the thesis. Interviews with energy experts were conducted in the initial stages of the report to assist in defining the core questions and research areas. Further interviews were conducted during the course of research and write up either in face to face meetings, telephonically or via email if proved convenient. All information gathered from these specialized personal has been referenced and cited.

3.3 MATHEMATICAL MODELING

Simple modeling has been used to assess various options, thereby highlighting the most compatible or efficient alternative. Modeling has predominantly been compiled in Microsoft Excel where the tabulated format, easily allows graphic illustrations of the comparative results. These graphic results have been included in the chapters four, five and six to allow viewing of the selection process.

4 CONTEXT FOR IMPLEMENTING CSP

4.1 Solar Energy and Global Climate Change

It is widely agreed that the world needs to transition towards a sustainable energy system to prevent a climate change disaster (IEA, 2008). This needs to be achieved by reducing fossil fuels from country's primary energy supply. Low carbon energy technologies, already in use today, can be expanded and scaled up to address a significant part of the need for primary energy supply (Climate Group, 2008). These sources of low carbon energy generation include wind, biomass, nuclear, geothermal and solar. The German Advisory Council on Global Change expects (GACGC) solar energy to make up the main future energy supply globally (see figure 4.1).

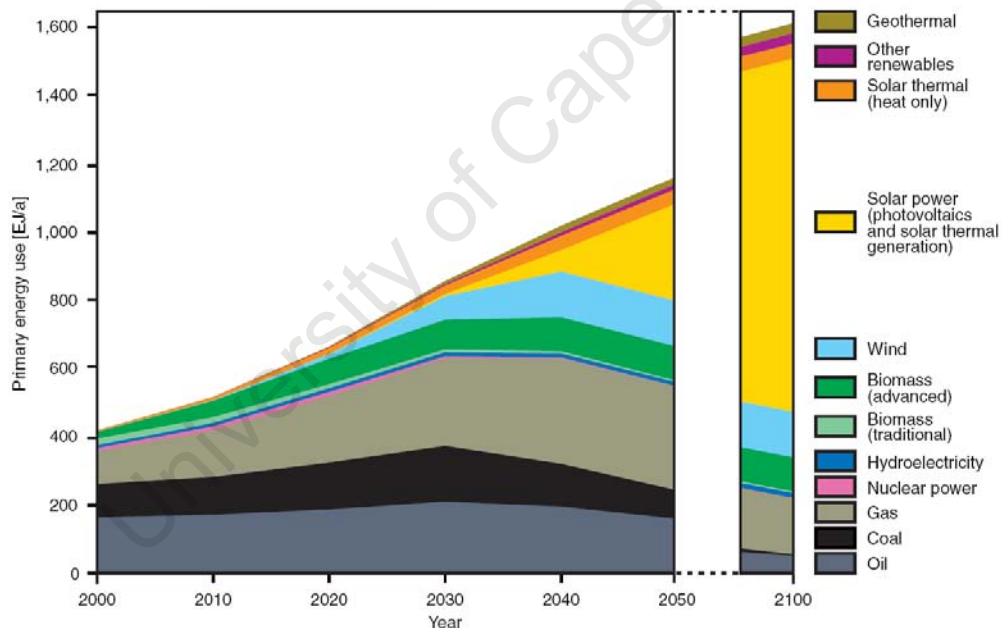


Figure 4.1: Transforming the Global Energy Mix: The Exemplary Path until 2050 and 2100.

Source: (German Advisory Council on Global Change, 2003)

A technology which has been implemented commercially and progressing, in cost reduction and scale, for converting solar energy, is Concentrated Solar Power (CSP). Various additional names are used such as Solar Thermal (ST), Concentrated Solar Thermal Power (CSTP) and Solar Thermal Electricity Generation (STEG) but all encompass the core generation technologies which will be discussed further in the section 4.2.

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The amount of solar radiation that falls on the earth everyday is approximately 7,500 times the total annual primary energy consumption of the world (world = 450 EJ per year) (World Energy Council, 2007). An approximation made by Philibert (2005), was that if global energy needs rise to levels as projected by 2030, a solar conversion system, of 10% efficiency, covering 0.6% of emerged lands would be sufficient to supply the entire globe's demand (Figure 4.2). The figure below shows an illustrative approximation of this statement where the larger red square, measuring 338km by 338km, would provide as much electricity the world is now using if populated by solar thermal plants (Desertec-uk, 2009). This is likewise for the EU square which would supply the entire European Union, measuring 139km by 139km and the MENA square for the Middle East and North Africa equating to 60km by 60km, approximately the same of Africa's electricity demand as a whole.

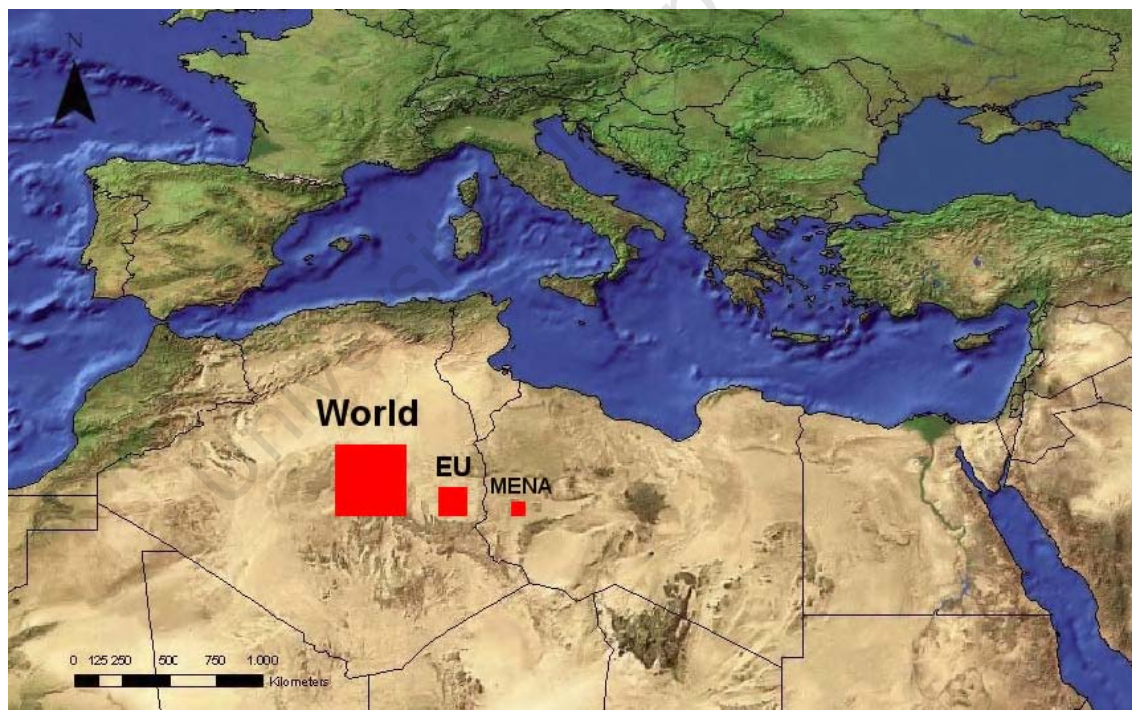


Figure 4.2: Approximated area of the Northern African deserts required for CSP to deliver the electricity needs of the world, the EU, and the Middle East and North Africa MENA. Source: (Desertec-uk, 2009)

The electricity generation market has reacted to the renewed interest in sustainable energy development and has been reaching record levels of new investments on a year on year basis. 2007 reached a record level of US\$ 148.4 billion in new

investments, a 60% increase over 2006 (UNEP, 2008). Total investment in sustainable energy, including acquisition activity, was US\$ 204.9 billion in 2007 and in 2008, investment growth continued amid the turmoil of the global financial markets (UNEP, 2008). Solar energy technologies are the fastest growing sector in renewable energy, 70% growth rate in 2008 compared to 29% in wind (REN21, 2009), and in 2007 they achieved a total investment of US\$ 28.6 billion and have averaged an annual growth of 254% between 2004 and 2007 (UNEP, 2008). In utility sized renewable generation, CSP had the second fastest growth after wind and should expect US\$ 20 billion investment between 2007 and 2012 (EER, 2007).

The IEA states that with a 50% reduction in carbon dioxide emissions by 2050, under their BLUE scenario, would require approximately 46% renewable power generation, primarily sourced from wind, solar and biomass (IEA, 2008). This level of penetration however, requires policies such as carbon taxing and incentives to drive the evolution of technologies into reduction of costs and improvements in efficiency.

Climate change is one of the major threats to the planet and to its inhabitants. According to simulated climate models, South Africa has been said to be particularly vulnerable to the effects of climate change (IPCC, 2007). Additionally, South Africa emits very large amounts of the greenhouse gases and is one of the highest emitters per capita in the world. Under the Growth With-out Constraint scenario of the Long Term Mitigation Scenario's (LTMS) for South Africa, energy-related emissions of greenhouse gasses are predicted to grow substantially at an average of 2.9% per year (SBT, 2007). This LTMS report indicated that of a total 118GW of renewable energy capacity by 2050, the key technology for South Africa is to be CSP broken down into 61GW of Trough, 42GW of Central Receiver and 15GW of wind (SBT, 2007).

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

In addition to mitigating GHG emissions, CSP has other important environmental and social benefits when compared to conventional fossil sources. These include reducing particulate matter associated with air pollution from coal fired power stations. In addition to being unsightly, air pollution emitted from coal fired power stations, including particulate matter, nitrogen oxides, sulphur dioxide (SO₂), as well as heavy metals, is believed to induce medically associated respiratory conditions such as asthma, bronchitis and cardio-respiratory mortality (Earthlife Africa, 2009).

Another benefit of CSP has to do with solar energy being a renewable resource, this implies that it has no finite reserve limits and thus offers a sustainable source of energy as it is a flow of energy and not a storage of ancient sunlight as in coal and oil. Due to this fact, all development associated with CSP, including local production, management and jobs, is sustainable and thus falls under the government policy of sustainable development.

Finally a property which is becoming significantly more important is energy security, both in security of supply and security of tariff increase where historical data on solar energy proves its supply and the learning curve property of the technologies meaning cost should decrease as capacity increases

From these benefits it is apparent that there needs to be a further breakdown of what this technology actually requires, how it works and what conditions are needed, to allow a complete analysis of South Africa's prospects of a CSP future.

4.2 Analysis of Concentrated Solar Thermal Technologies

Concentrating Solar Thermal Power (CSP) utilizes direct normal solar radiation, concentrates it multiple times to reach a higher energy density and temperature and thus allows further efficiency and utilization of the resource. The heat generated is used to operate a conventional power cycle, such as a steam turbine or a Stirling engine, which runs a generator.

The technology has three core characteristics:

- It is ideally suited for locations with high power, direct normal solar radiation which are widespread but not universal throughout the globe.
- It has the ability to deliver power on demand, due to its intermediate thermal phase from which thermal storage can be utilized. Heat storage has the potential for continuous solar only power generation.
- Hybridization can occur where CSP can perform in tandem with fossil fuel burning by using the same steam turbines and generators to generate electricity during intermittent conditions.

The ability of CSP to match peak demands is of particularly high value for utilities as peaking power generation is prohibitively more expensive than base load. Large scale CSP expansion is limited by direct normal solar insolation (DNI) and a minimum requirement is often considered to be 2 MWh/m² per year (IEA, 2008).

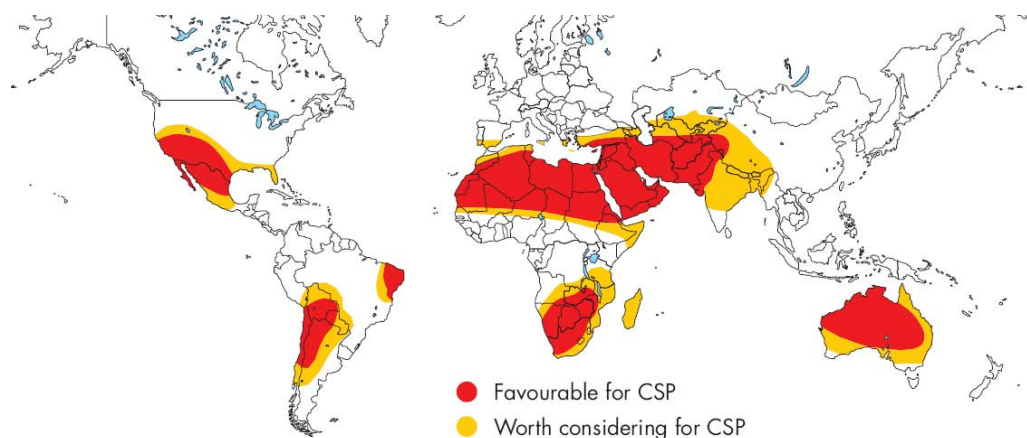


Figure 4.3: The most promising areas for CSP plants. Source: (IEA, 2008)

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

CSP plants are considerable in size and typically designed to several hundred Megawatts in size for efficiency and cost reduction. Due to their size and remote placement, CSP plants require long distance transmission networks and modern DC transmission lines can transmit power at US\$ 30 per MWh (DLR, 2006). CSP additionally has the potential to produce direct heating and cooling for industrial applications such as water desalination or the production of fuels and hydrogen (IEA, 2008). In arid countries, such as South Africa, co generation of heat for water desalination and electricity production could greatly increase the efficiency of the plant while adding a valuable resource to the surrounding inhabitants.

There are four main CSP technologies, Troughs, Central Receiver Towers (Power Tower), Dish systems and the new concept of linear Fresnel concentrators. The concentrated solar radiations varies between them with the troughs and fresnel achieving a flux of between 30 and 100 suns, Central Receiver Towers between 500 and 1000 suns and Dishes between 1000 and 10 000 suns (IEA, 2008)

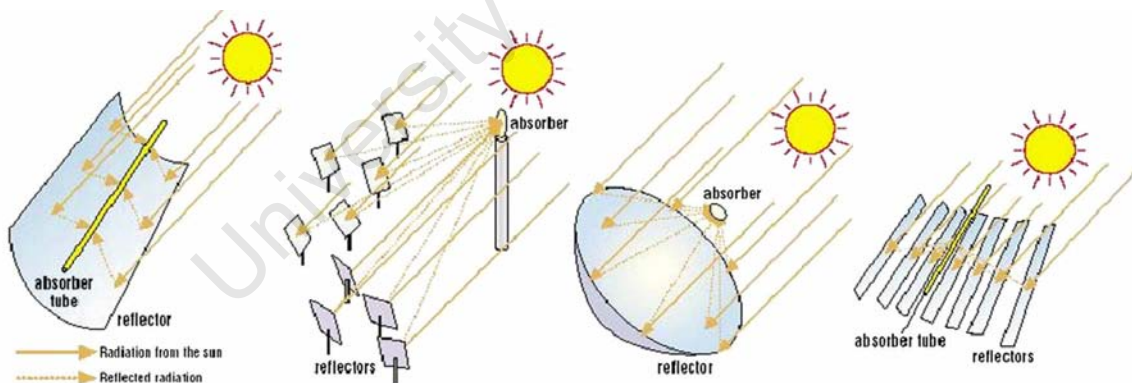


Figure 4.4: The four major CSP technologies, from left Trough, Central Receiver, Dish and Linear Fresnel. Source: (Cavallaro, 2009)

Troughs work by utilizing a parabolic trough shaped mirror reflectors to linearly concentrate incoming direct solar radiation. This radiation is concentrated onto evacuated receiver tubes which absorb the radiation and transfers it to a thermal heat transfer fluid contained within the tubes. Towers utilize multiple independently controlled mirrors called heliostats which concentrate the incoming direct solar

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

radiation onto a central receiver located on top of a tower. Dishes use a parabolic dish to concentrate the solar radiation in two dimensions to a focal point at which a small engine or PV panel is located. Fresnel use multiple, parallel, long mirrors to focus incoming radiation onto receiver tubes located above mirrors.

CSP is evolving away from the small scale, prototype type plants towards larger grid-connected installations, in particular trough and tower designs are showing promise for large scale electricity generation. Compact Fresnel linear collectors and multiple tower Central receiver type plants are new concepts that are showing specific value for large rooftop installations in sunny cities (Mills, 2004). CSP development was expensive in the US during the initial stages in the 1980's. Low fossil fuel prices in the 1990's and the withdrawal of various US state incentives added to this expense and lead to a drop in the interest of the technology (Environment America, 2008). Energy security and global warming have renewed the interest in CSP and resulted in new investments which are reducing the costs and increasing the efficiencies of the technologies.

4.2.1 Parabolic Trough Systems:

Troughs represent the majority of current CSP installed technology and are the most mature out of the four. They have a proven commercial record of 354MW which has been operating in California since the early 1980's in the nine SEGS plants (IEA, 2008). The United States has since constructed one new trough plant, Nevada Solar One, which has a nominal capacity of 64MW and came on line in 2007 (IEA, 2008). Nevada Solar One should not be confused with Solar One in California which is of the Central Receiver Type. The majority of projects under construction or under consideration around the world are based around the Trough concept.



Figure 4.5: Picture illustrating the Trough concept and its scale. Source: (EC, 2007 & REIANM, 2009)

Troughs have utilized various heat transfer mediums such as refined oils, mineral oils, molten salts and water for direct steam generation but current designs are focussing on molten salts for their thermal storage properties. Phase change materials and concrete structures may prove to be more efficient and effective in future plants (IEA, 2008). Trough plants can be mated with fossil fuel plants to form hybrid plants which achieve greater capacity factors. The solar heat, around 400 °C, feeds the bottom of the combined cycle but in practice only achieves 10 – 28% of the output energy (IEA, 2008). Trough systems are said to achieve a maximum temperature of 400 °C under a concentration of 200 suns and a solar to thermal efficiency of 60% and a solar to electric efficiency of 12% (IEA, 2008).

4.2.2 Central Receiver Tower Systems:

Central receiver systems vary in design from country to country however the typical setup consists of a large field of heliostats (dual axis, flat, tracking mirrors), with a centrally located receiver tower which transfers the concentrated solar radiation to the heat transfer fluid. The designs vary according to thermal transfer fluids, thermal storage and the theoretical thermodynamic cycle. Molten salts have been employed for transfer fluids in Solar Two (10MW) in the US and in the Themis (2MW) plant in France and will be utilized in the Spanish Solar Tres (15MW) plant under development by Sener (IEA, 2008). Saturated steam has been employed at the PS10 (11MW) plant in Seville, Spain and is to be used in the two sister plants, PS20 (20MW) under development by Solucar (IEA, 2008).



Figure 4.6: Picture illustrating the Central Receiver concept, and a heliostat. Source: (NREL, 2009)

Eskom, South Africa's utility electricity supplier who provides the majority of South Africa's electricity has been considering a large Central Receiver plant of 100MW size with thermal storage in the Northern Cape region. The plant would potentially consist of approximately 8000 heliostats covering an area of approximately 4km² and include a molten salt transfer fluid and with a thermal storage of 14 hours (Van Heerden, 2009). This project has been in planning since 2001 but progress has all but stalled as of end of 2007, detailed risk assessment, mitigation studies and environmental impact assessments have all been conducted but financial investment decisions are pending (Van Heerden, 2008)

4.2.3 Dish Systems:

Dish systems usually utilize a parabolic dish which focuses the incoming solar radiation onto one focal point where a Stirling engine is located. The dishes continuously track the sun on two axis and develop between 10 and 25kW's each (IEA, 2008). Dish systems have been said to be more suited for decentralised electricity generation however a 300MW plant would consist of approximately 12 000 Stirling Solar dishes and require approximately 3 square miles (IEA, 2008).

One major drawback of the dish system is its inability to easily include a thermal storage system thus yielding a very low capacity factor.



Figure 4.7: Pictures illustrating the Dish Stirling concept. Source: (NREL, 2009)

4.2.4 Fresnel Lens Systems:

Linear fresnel reflector systems use a series of long and flat (sometimes curved) mirrors which focus incoming solar radiation onto an absorber positioned above the reflector field. The absorber may have a small parabolic dish attached to the top of it to increase concentration of light. The benefit of these systems is lower costs due to sharing of receiver, single axis tracking, use of flat or elastically curved mirrors, no complex, rotating heat transfer fluid couplings and less engineered support structures.

Drawbacks however include shading and blocking of solar radiation from adjacent mirrors. This can be reduced by increasing the height of the receiver, above the collector field or increasing the width of receiver, allowing greater distance between the mirrors. These solutions however, both increase the cost due to additional land usage.

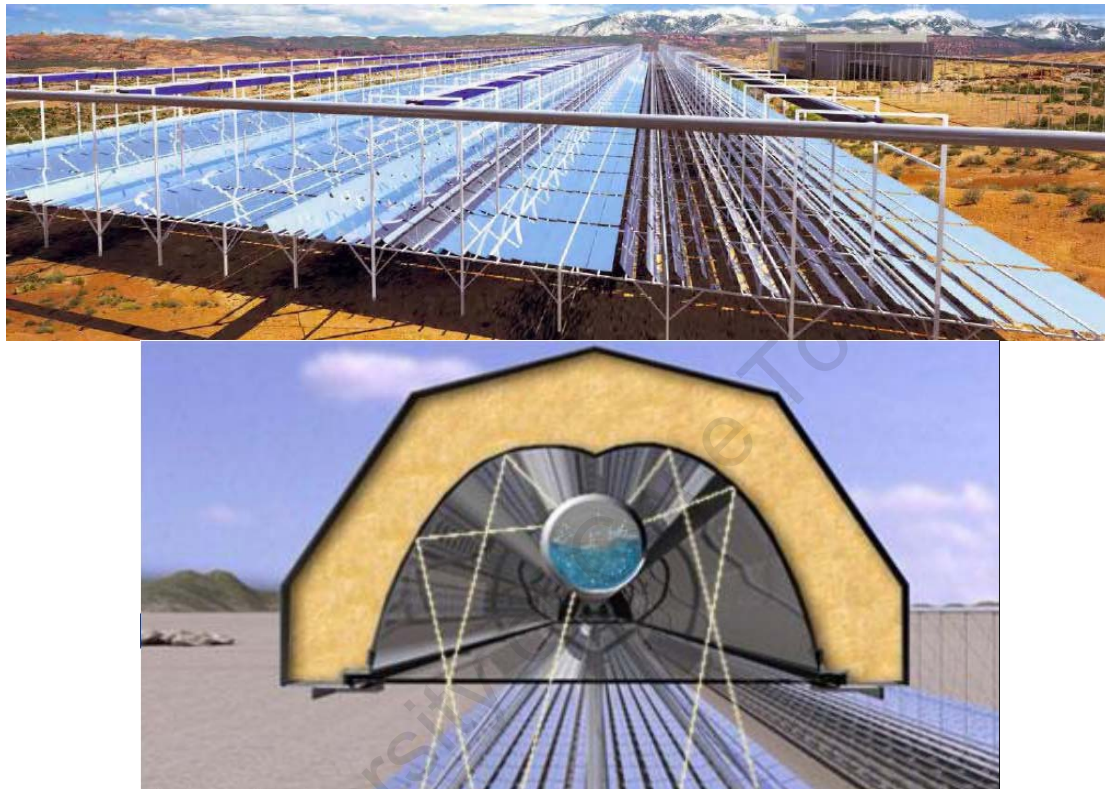


Figure 4.8: Pictures illustrating the linear Linear Fresnel lens concept. Source:

(NREL, 2009 & Van Heerden, 2009)

4.2.5 Comparison:

It is not the purpose of this dissertation to model and select the most appropriate CSP technology, instead research into various past analysis's was compiled, and a paper written by Cavallaro (2009), was selected as the most up to date and in-depth analysis of the technologies.

This paper lays out a very effective method for comparing these technologies on existing and planned plant properties. The paper provides a flexible tool that can be

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

used to bring together a large range of variables and help the decision maker in mapping out the problem (Cavallaro, 2009).

The table 4.1 below states the variables that were used by Cavallaro where P.1-3 are parabolic trough type plants, SCR1-6 are central receiver type plants, H1, 2 are hybrid solar and gas plants and D.S is a Dish Sterling system.

Table 4.1: Table of the variables associated with the different CSP technologies. Source: (Cavallaro, 2009)

Alternatives		Criteria						
		Investment cost	O&M cost	LEC	Maturity of technology	Environmental impact	Temperature	Solar capacity factor
		EURO/kW	EURO'000	c/EURO	qualitative	qualitative	°C	%
		a	b	c	d	e	f	g
P.1	parabolic trough (50 MW)	3530	4,003,490	0.1720	commercial	Very low	391	29
P.2	parabolic DSG(47 MW)	2840	3,515,128	0.1870	experimental	Very low	411	22
P.3	parabolic DSG-Fresnel (50 MW)	2033	2,921,659	0.1620	experimental	Very low	411	22
SCR1	SCR molten salt (50 MW)	3473	5,518,874	0.1545	experimental	Low	560	33
SCR2	SCR molten salt (17 MW)	3708	2,832,888	0.1825	experimental	low	560	33
SCR3	SCR saturated St. (11 MW)	3319	2,175,105	0.2272	under construction	Low	260	26
SCR4	SCR saturated St. (5×11 MW)	3019	4,977,789	0.1681	experimental	Low	260	26
SCR5	SCR Phoebus (10 MW)	4391	2,334,800	0.2342	experimental	Low	680	33
SCR6	SCR Phoebus (5×10 MW)	3989	5,825,666	0.1787	experimental	Low	680	33
H.1	solar hybrid gas (14 MW)	1767	4,554,850	0.1004	under construction	Moderate	800	55
H.2	solar hybrid gas (4×14 MW)	1622	13,814,257	0.0819	experimental	Moderate	800	55
D.S.	dish-stirling	8035	11,451,238	0.2811	under construction	Very low	750	22

With this data, calculations were made and a ranking system was formulated. The ranking showed that alternatives using a hybrid solar thermal system with natural gas are the most efficient and effective options due to their low investments costs and high temperature and capacity factors (See Cavallaro, 2009 for a detailed breakdown of this process). The ranking showed the best performers to be the H1, H2 solar hybrid options followed by the Central Receiver Plants SCR1 and SCR2 which are the 50MW and 17MW plants respectively. Next was the P.3 plant of 50MW which utilized the Fresnel lens concept, followed by P.1, SCR4, P.2 and SCR.3 (Cavallaro, 2009). Bottom of the rank was SCR5, SCR6 and finally D.S. poorly performed due to the poor cost to performance ratio (Cavallaro, 2009). The hybrid case is not however, specified in the REFIT tariff drawn up by NERSA and thus will not be assessed (See Appendix 1 for the tariff breakdown of the REFIT).

In addition to this report, localised research completed by the utility ESKOM was used as it took into account various South African variables that will weight certain

technologies differently. Eskom's report concluded that in addition to the above factors, the ability of local manufacture of the parts for the plant, is of high importance for the country's sustainable development plans and up to 70% of the plant could be locally built (Van Heerden, 2008).

A study, by Sargent and Lundy LLC, completed a thorough analysis of Trough and Central Receiver technologies and the levelized energy costs are summarised by the graph below which show considerable cost reductions with the tower technology:

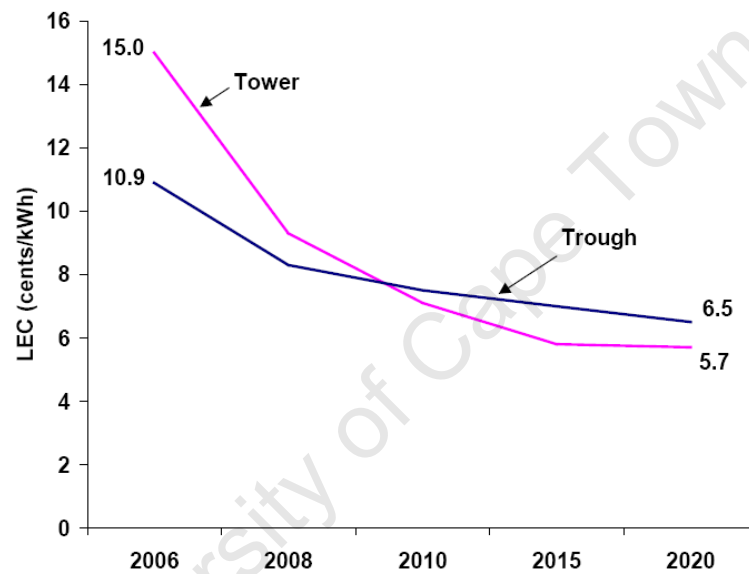


Figure 4.9: Graph indicating the projected levelized energy costs of the two prominent CSP technologies. In US cents/kWh. Source: (Sargent and Lundy, 2006)

From these findings, conclusions were made that in order for this dissertation to answer its core questions, in the required time, analysis of a single technology is needed. The Central Receiver Tower concept was thus chosen as the basis for this analysis, however Trough technologies maturity enables a more diverse range of technical information which will be used where limited data or experience with Central Receiver plants, exists.

4.3 South Africa's Supply and Demand structure and its Role in Global and Local Sustainable Development

South Africa contains approximately 5% of the total world coal reserves and has the 5th largest reserve at approximately 38 billion tons (DME, 2006). The majority of coal produced is used for electricity production, some 44.2% in 2004 shown by the chart below (DME, 2006). Approximately 90% of the electricity produced in South Africa is produced from coal, and the chart below illustrates the remaining coal utilization (Eskom, 2008).

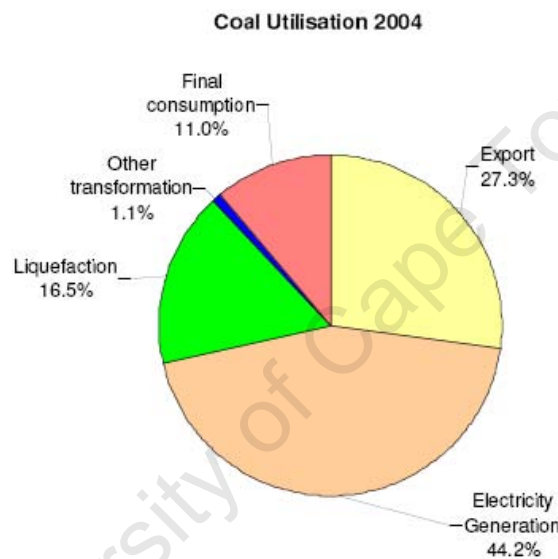


Figure 4.9: Pie chart illustrating coal utilization in South Africa. Source: (DME, 2006)

The national electricity supplier, Eskom, produces approximately 95% of South Africa's supply, some 43MW which is almost half of the continents supply (Eskom 2008). The demand for electricity in South Africa is at a maximum in the winter where it has two daily peaks, in the morning between 7am and 9am, and in the evening between 5pm and 8pm which is taken from the graph below (Eskom, 2008). This demand structure is represented by the following graph which shows a recorded peak demand in June of 2006 of 35GW. A further peak demand of 38.8 GW was recorded in June, the following year.

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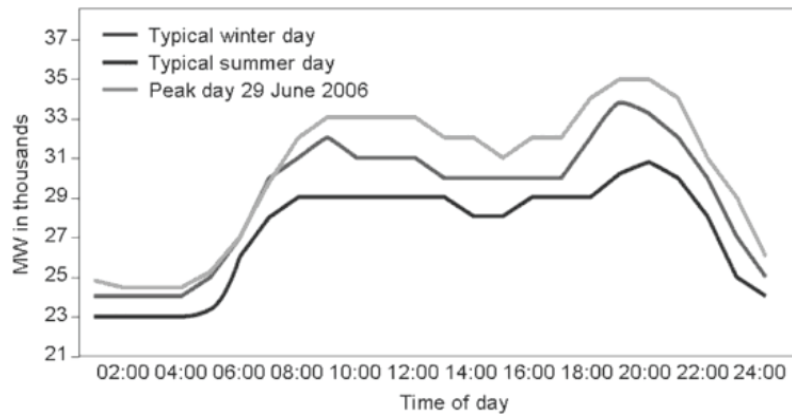


Figure 4.10: Demand pattern for South Africa showing typical winter and summer curves and peak curve of 2007. Source: (Eskom 2008)

The capacity demand for electricity in South Africa is expected to continue increasing and by 2026 it is believed to lie between 60 GW and 102 GW depending on the modelling scenario used (NERSA, 2007 and DME, 2007). These findings were graphically represented by the Department of Minerals and Energy of South Africa with the ASGISA (Accelerated and Shared Growth Initiative of South Africa) model which used an average GDP growth of 4% shown by the line “Position” (DME, 2007). An average of 80 GW demand by 2025 will be used for future calculations and references in this thesis.

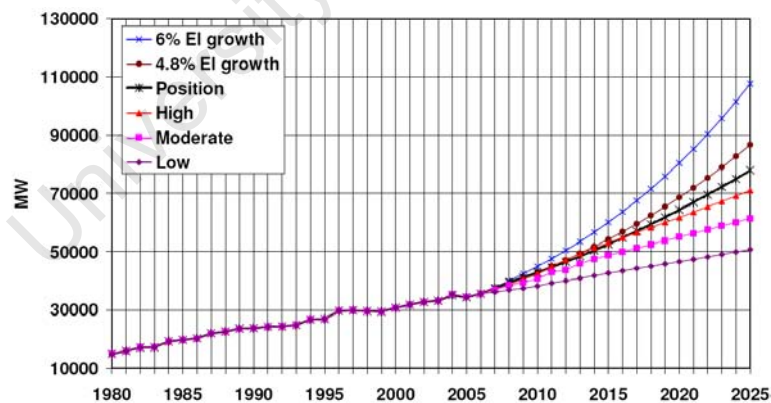


Figure 4.11: Predicted demand pattern for South Africa from 1980 to 2025 showing the various reference models and scenarios. Source: (DME, 2007)

It was expected by energy analogists that South Africa’s demand would outstrip supply between 2005 and 2007 unless demand side management occurs or new plants are built (DME, 2007). This was stated by the DME in the White Papers on Renewable Energy of 1998 and 2003. South Africa’s reserve margin was reduced from 40% in 1990 to 25% in 2002 and to 7% in 2007 which is below the optimum of

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15% that would allow for maintenance, system stability and unplanned outages (DME, 2008). Due to large reserve margins in the early 2000's, a policy decision was made that only allowed ESKOM to build 70% of new power stations with the remaining to be built by Independent Power Producers (IPP's). This policy however failed as the low electricity price and a delay in Eskom's expansion plans resulted in an unfavourable investment environment. Another factor is that the current power stations will begin to reach their decommissioning stage from 2025 and current expansion plans are not sufficient to meet the projected demand (NERSA, 2008 and ERC, 2008). This cascading of old stations can be easily illustrated by the following chart showing the year and the lifetime of the various currently installed power stations, this chart does not however show the new power stations planned and coming online:

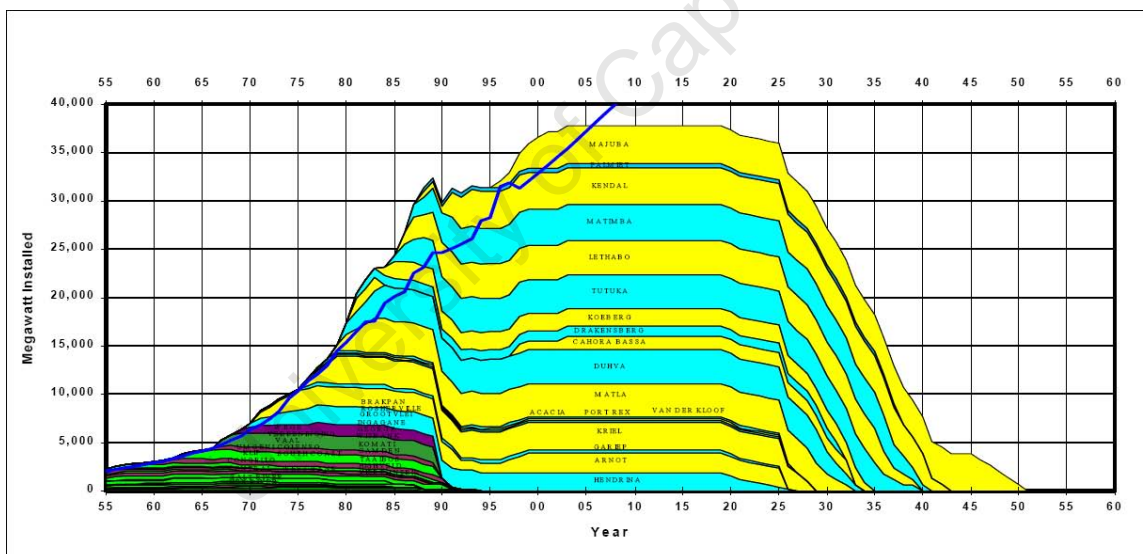


Figure 4.12: Eskom electricity generation as a function of time where the solid blue line represents the actual and projected demand where it outstripped supply at the end of 2007. Source: (DME, 2003)

New Eskom power stations are expected to supply an additional 16.3GW of capacity by 2017 costing approximately R343 billion in nominal terms (ESKOM, 2008). This 16.3 GW is expected to come various new plants, upgrades and return to service (“mothballed”) plants. Three “mothballed” coal fired stations will be coming online within the next four years along with the extensions made in 2007 to two open cycle gas turbines (OCGT's) and an upgrade to the Arnot coal fired station (Edkins, 2008).

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Two, large coal fired plants are expected to come online in 2012, Medupi and Kusile/Bravo representing 4,76 GW and 4,8 GW respectively (ESKOM, 2009). Peaking plants which make up approximately 5,03GW, include Ingula pumped storage at 1.35 GW, OCGT's at 2,05 GW, Tubatse at 1,5 GW, sere at 0,1 GW and finally the return to service stations totalling 3,47 GW (ESKOM, 2009). Despite these plans, ESKOM still appears to heading for an approximate 3GW capacity shortfall, if a reserve margin of 19% is to be used (Edkins, 2008). This shortfall is illustrated by the graph below :

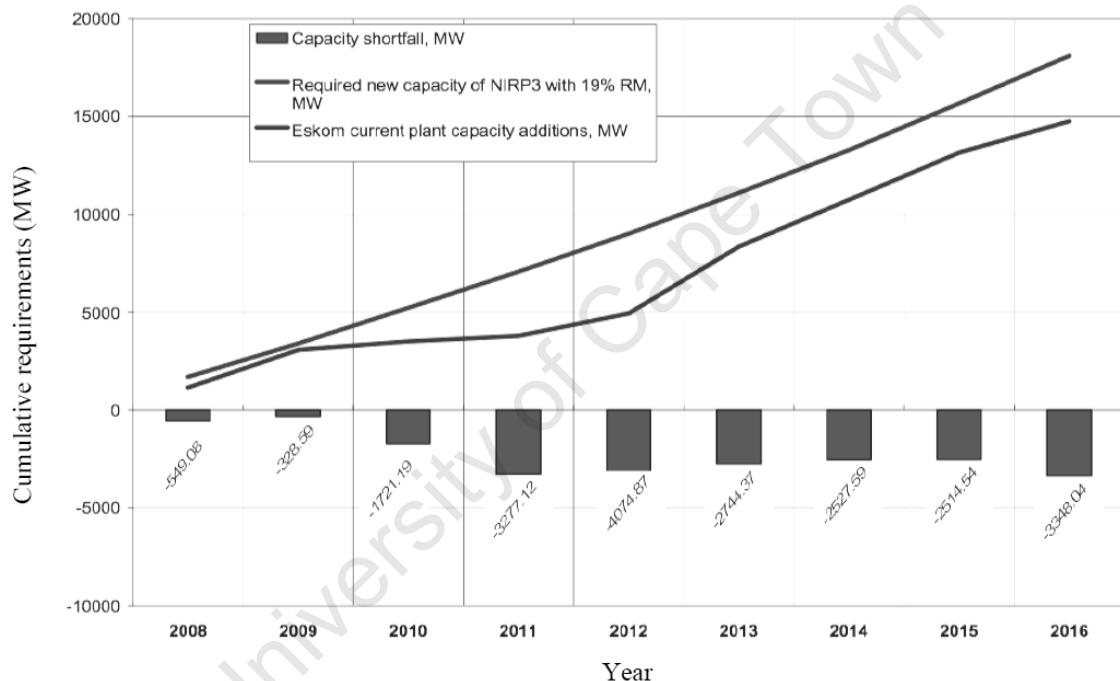


Figure 4.13: Eskom's electricity generation building plan showing a capacity shortfall of approximately 3GW, peaking from 2010 to 2012. Source: (NERSA 2008)

The LTMS was both a facilitated stakeholder calculating process, and a study to address the GHG mitigation options for South Africa's carbon intensive structure. This report found that one of South Africa's biggest mitigation options is its electricity generation, which is heavily reliant on coal (SBT, 2007). The two main mitigation alternatives to the carbon intensive, coal electricity generation are nuclear power and renewable electricity generation technologies (SBT, 2007). Even with a dramatic shift in policy and electricity development plans with nuclear and renewables, it would still

be insufficient to reverse GHG emission growth in South Africa as illustrated by figure 4.14 below. To reach the target of GHG emissions peaking at 2025, other carbon mitigation options will need to be rapidly implemented (DEAT, 2008)

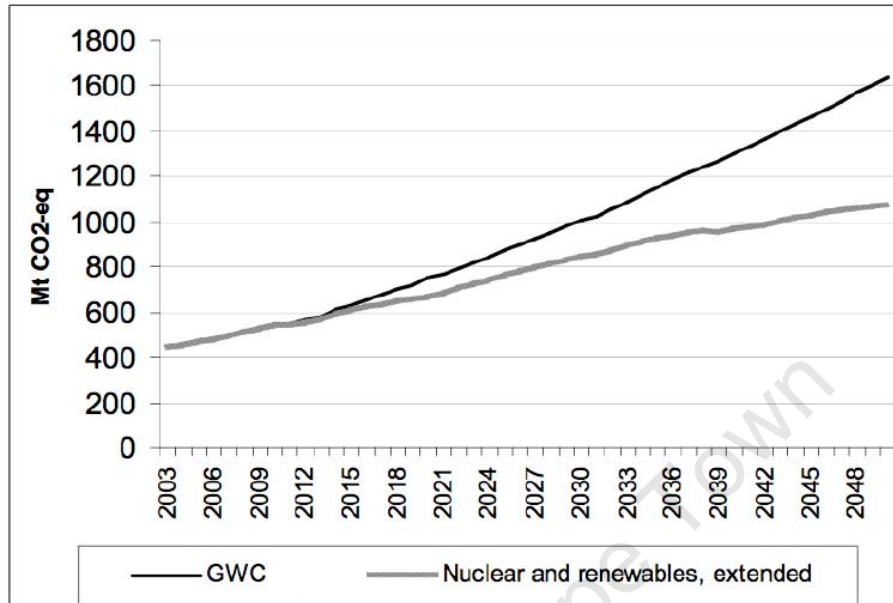


Figure 4.14: Emission growth for South Africa showing Growth without Constraint (GWC) and Nuclear and renewables extended where generation is near zero carbon. Source: (SBT, 2007)

For the world as a whole, global temperature increase over the past century has been undisputedly proven by the scientific community and climate change is with almost certainty induced by anthropogenic activities causing increasing concentrations of GHG's (DEAT, 2007). The negative affects of climate change are already being experienced by both humans and ecosystems and further temperature increases will further amplify these effects. To minimise the possible effects, global emissions need to peak by 2015 and then begin to subside to limit the temperature increase between 2.0 and 2.4°C (DEAT, 2007). This is not just a first world issue but a South African problem too as the effects of climate change will have major impacts on the country itself, especially the poor who are vulnerable to the projected future effects. South Africa has already committed to multilateral negotiations in an effort to mitigate emissions, however being a developing country, it is not constrained under the Kyoto Protocol (DEAT, 2007). These constraints however may be reviewed in upcoming international negotiations where there is increasing pressure on the larger

emitting, developing countries of which South Africa is high up on the list. This means it is imperative for South Africa to begin planning and developing its options to reducing GHG emissions of which electricity generation and its solar resource abundance can be utilized to play a major role.

As stated before, CSP presents one of the best mitigation options to South Africa, however certain barriers exist. One of the largest barriers to the establishment of CSP in South Africa is said to be the cost of the technology, which manifests itself in the price of electricity generated from it, and the approval and distribution of the power purchase agreements (PPAs) which will allow the Renewable Energy Feed In Tariff (REFIT) to play its part (Edkins, 2008). The issue of cost has been thoroughly addressed and a recent paper by Edkins (2008). Edkins addressed the various economical issue of CSP. Another large barrier to CSP deployment is the lack of inspired political will. Therefore, given suitable laws like the feed-in-tariff (REFIT) and others such as carbon taxing, South Africa could rapidly and effectively combat climate change while achieving the crucial local needs of sustainable job creation. The two remaining barriers which were brought to light by the preliminary research of this dissertation, were, the geophysical and electrical infrastructure requirements, and the requirements for creating a local industry. This dissertation thus aims to answer these questions and determine what a large CSP future could look like for South Africa.

5 GEOPHYSICAL AND ELECTRICAL INFRASTRUCTURE REQUIREMENTS FOR CSP

The following chapter aims to answer the first of the two core questions laid out by this dissertation. It aims to answer what infrastructure requirements are required, from South Africa, to allow a large portion of the country's electricity supply, to be fueled by CSP. The infrastructure requirements are separated into three main sections; firstly a geographical analysis of the South African conditions is compiled, where an analysis of solar radiation, land usage and water resources are modeled against the requirements of a large CSP infrastructure. Secondly, the transmission and distribution needs are analyzed, where the current state of South Africa's national grid is presented and the CSP requirements are modeled. From these figures, estimates and recommendations are made for possible national grid expansion to transport CSP energy to the load centers of South Africa. Finally, the technology of energy storage is investigated where the implications and benefits are first stated following which, multiple technologies are reviewed and modelled against both South Africa's and CSP's requirements. From this modelling, recommendations are made for both the immediate technology options and longer term options which are showing particular promise. Ending off the chapter is a summary of conclusions which are drawn on all the infrastructure requirements allowing recommendations to be made.

5.1 Geographical Analysis of Radiation, Land and Water

In planning a low carbon economy, one of the first areas of analysis will be assessing the renewable energy potentials of the country. In South Africa's case, abundant, renewable sources are limited to wind and solar as hydro is restricted by the water scarcity of the nation and likewise for sustainable biomass. The Northern Cape

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region of South Africa is blessed with a very high solar potential and receives an annual Direct Normal Radiation (DNI) of over 2600 kWh/m² (Eskom, 2006). The town of Upington, which has been taking accurate measurements of DNI, is stated to receive more radiation than some of the world leaders in solar energy such as the U.S, Mexico, Jordan, Morocco, Crete, India and Spain (refer to Table 4.2 below)

Table 5.1: International Solar Potential relative to Upington, South Africa. Source: (Eskom, 2006)

Location	Site Latitude	Annual DNI (kWh/m ²)	Relative Solar Resource
South Africa			
Upington, North Cape	28°S	2 955	100%
United States			
Barstow, California	35°N	2 725	92%
Las Vegas, Nevada	36°N	2 573	87%
Albuquerque, New Mexico	35°N	2 443	83%
International			
Northern Mexico	26-30°N	2 835	96%
Wadi Rum, Jordan	30°N	2 500	85%
Ouarzazate, Morocco	31°N	2 364	80%
Crete	35°N	2 293	78%
Jodhpur, India	26°N	2 200	74%
Spain	34°N	2 100	71%

It is important to note that Northern Cape, Upington region is not the only suitable location for CSP in South Africa. In total there is believed to be approximately 550GW of CSP potential in South Africa of which approximately 510GW coming from the Northern Cape region, 25GW coming from the Free State area and a little over 10GW of resource available from the Western Cape (Fluri, 2008). For the purpose of this report, Upington has been used as a reference point to simplify the complexities when modelling multiple variables. Solar thermal plants however require large areas of uninhabited or utilized land. A CSP plant of 100MW or 0.1GW requires approximately 4km² of planar land and a sufficient water source for the condensation

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of the thermal cycle (ESKOM, 2006). 1GW of CSP would require approximately 28km^2 or 5.3km by 5.3km (Fluri, 2009). Fortunately, lands in areas of high solar irradiance are usually sparsely inhabited due to the difficulty in sustainable living. By comparing two independent studies on solar radiation maps of South Africa, we can identify a portion of the Northern Cape with the highest radiation potential and assess the possible land usage from satellite maps (See figures 5.1.1: solar radiation statistical representations below, 5.1.2: satellite image with the size of 30GW of CSP superimposed along with radiation hot spot below, and 5.1.3 a detailed satellite image of the Upington region with CSP facilities of varying capacities, superimposed on suitable areas).

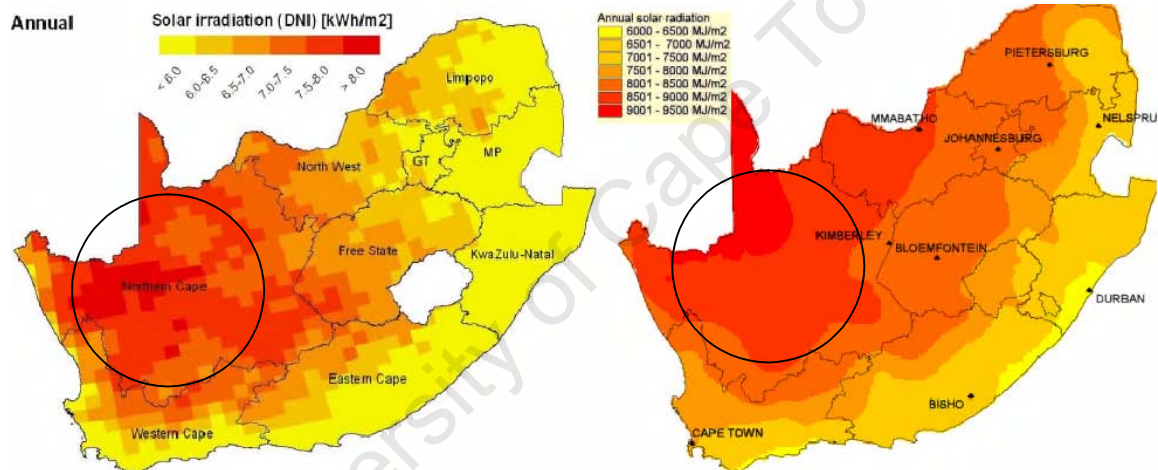


Figure 5.1.1: Two overviews of the annual solar irradiation falling on South Africa in kWh/m^2 on left and MJ/m^2 on the right. Source: (Fluri, 2008 and DME, 2003)

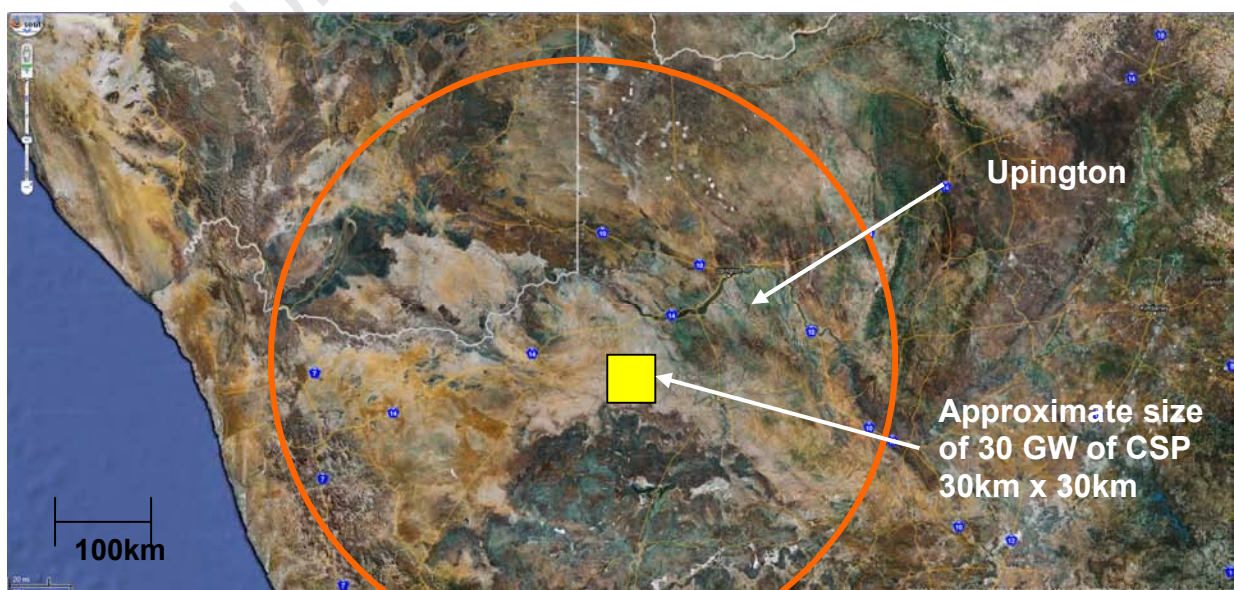


Figure 5.1.2: Satellite image of the Northern Cape region showing baron lands and an estimation on the size of 30GW of CSP. Source: (Google Maps)

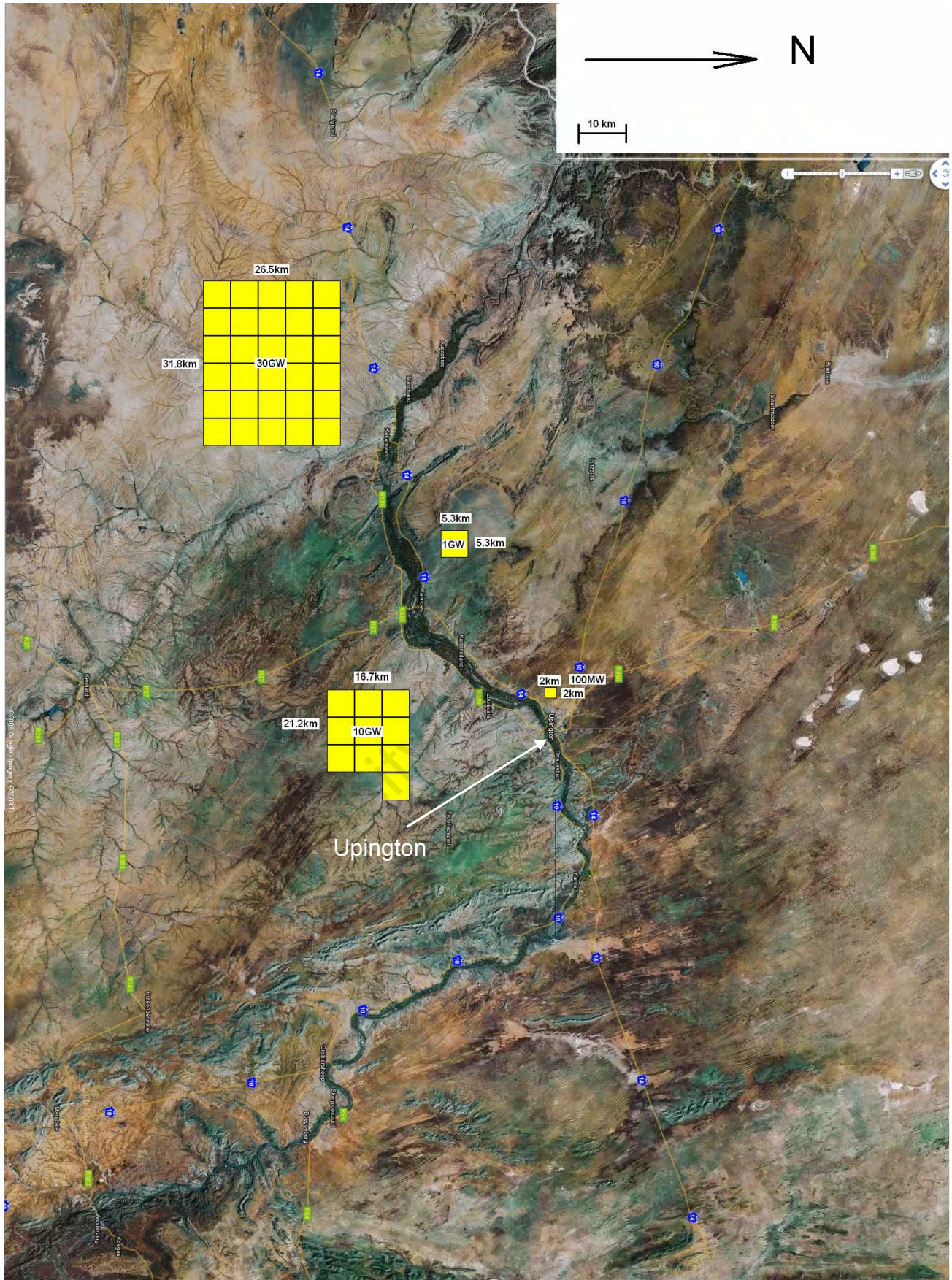


Figure 5.1.3: Enlarged satellite image of approximated sizes on CSP plant near the Town of Upington and Orange river, note the scarcity of land usage other than farms on banks of orange river. Source: (Google Maps).

From these maps it is clearly evident that very little land is being utilized in the very high insolation areas of Upington in the Northern Cape region. The lands required must contain no military bases, no conservation or ecologically sensitive areas, no water surfaces and no airports as the central receiver technology contains towers of approximately 190m in height, thus presented an aviation risk. Farms line the banks of the Orange River and small clusters of settlements have developed adjacent to them. Land should therefore be easily acquirable for the establishment of Concentrated Solar Thermal farms. According to a study, (Fluri, 2009) the generation potential of CSP in South Africa is 3.3 to 5.4 times higher than the total electricity demand predicted by 2025 by NERSA (Fluri, 2009). See the results in the table below:

Table 5.2: Table of the suitable land area in the relevant provinces in South Africa and their associated energy generation potential. Source: (Fluri, 2009)

Province	NC	FS	WC	EC	Total
Suitable Land Area, km ²	14 288	708	294	44	15 334
Power Generation Potential, GW	510.3	25.3	10.5	1.6	547.6
Net Energy Generation, TWh/a	1 734.3	85.9	35.7	5.3	1 861.4

The final question that needs to be answered, with respect to geographical conditions, is the availability of a water source. Like conventional steam power plants, solar thermal plants require a large volume of water for their operation which is often limited in the high solar radiation locations. In order for the thermodynamic cycle of a steam power plant to operate a water source is required to condense the steam to create your high pressure to low pressure zones. This is a fundamental step in the Brayton heat engine cycle which most Central Receiver Towers are based. Mirror cleaning and maintenance also requires water and approximately 4% of a traditional, wet cooling plants water requirements is consumed for the cleaning of mirrors (RENAC, 2008)

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The amount of water required depends on the type of cooling technology being utilized. The two main cooling technologies are wet draft towers, which are very efficient but require vast amounts of water, or dry cooling which relies on a heat exchanger and closed water cycle but is very expensive and lowers the efficiency of the plant. For reference, a 100MW solar thermal plant, utilizing wet cooling, requires approximately 1.2335 million cubic meters of water per year, of which approximately 50,000 cubic meters (4%), is required for cleaning (West Government, 2008; RENAC, 2008).

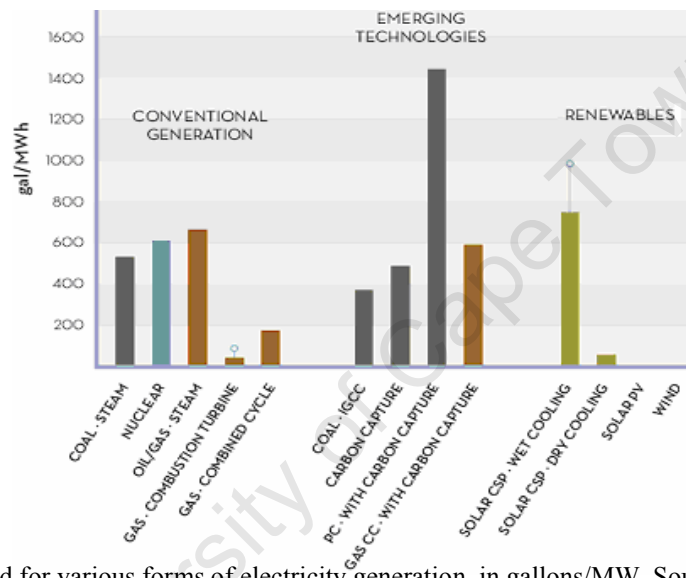


Figure 5.1.4: Water consumed for various forms of electricity generation, in gallons/MW. Source: (Western Advocates, 2008)

This does present an issue for the development of CSP in the Northern Cape region as the only constant source of water is the Orange River. This river is a lifeline to the farms and industry of the area and the town of Upington uses approximately 12.3 million m³ of water per year (DWAf, 2003). This means a CSP plant of 1 000MW or 1GW would consume approximately an equal amount of water as Upington and likewise 10GW of Solar Thermal generation would use 10 times the amount and 30GW would use 30 times Upington's consumption. The Upper Orange River is said to have approximately 900 million m³ of flow annually and the Lower Orange drops down to 150 million m³ (Fluri, 2009). Other rivers such as the Fish River on the East Coast, has 85 million m³ per annum, the Gouritz 110 million m³ per annum and the Olifants Doring 185 million m³ per year (Fluri, 2009). Information on the flow rates

and excess availability of water of the orange at Upington is very limited as precipitation catchment varies from the source at over 2000mm in Lesotho to less than 50mm at the mouth and in some areas it drops below 25mm. Neusberg Weir however is located approximately 75km downstream of Upington and is stated to handle average flow rates of $7.5\text{m}^3/\text{s}$ for its north bank canal and $6.8\text{m}^3/\text{s}$ for its south bank (DWAF, 2003). This equates to approximately 450 million cubic meters of water a year which feeds just under 7000ha of farm lands (DWAF, 2003). It can then be concluded that if South Africa were to develop a CSP capacity of 30GW or over, at least 360 million cubic meters of water would be required per year which would seriously damage the local industries and the general ecological balance of the area. This conclusion leaves one option which has not yet been discussed, and that is of dry cooling, which South Africa is said to be one of the world leaders. The following table shows the required water consumption for each province, depending on what cooling technology is used if all solar resource is used (Fluri, 2009).

Table 5.3: Table of the water requirements for the relevant provinces (Source: Fluri, 2009)

Province	NC	FS	WC	EC	Total
Power Generation Potential, GW	510.3	25.3	10.5	1.6	547.6
Net Energy Generation, TWh/a	1 734.3	85.9	35.7	5.3	1 861.4
Water requirement (wet cooling), million m^3/a	6 399.9	317.1	131.7	19.7	6 868.5
Water requirement (dry cooling), million m^3/a	520.3	25.8	10.7	1.6	558.4

The water requirement for wet cooling requires approximately $3.69\text{m}^3/\text{MWh}$ and dry cooling requires approximately $0.30\text{m}^3/\text{MWh}$, some 8% (Fluri, 2009). Two alternative dry cooling systems have been developed, the indirect (or Heller) concept and the direct (or GEA) concept. The indirect system incorporates a cooling water system, where cooling water circulates between the condenser and the cooling tower. Eskom's Kendal power station is the largest indirect dry-cooled power station in the world (6 x 686MW turbo generators). The direct concept employs an air cooled condenser where steam is condensed inside finned tubes and no cooling water is required. Eskom's Matimba power station uses direct dry cooling (6 x 665 MW

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generators). South Africa's experience with dry cooling thus inspires this avenue of development for Large scale CSP of over 1GW capacity. Dry cooling does however come at a cost an increasing loss of efficiency at high ambient temperatures and thus a causes higher levelized energy cost of between 5 and 10%. Further research is therefore required in the future modelling between the cost of water and increased cost of energy. The water resource is however not the final infrastructure requirement as one of the largest, that requires long term planning, is the state of the national electricity grid in the area of the Northern Cape, Upington region. A full breakdown analysis of this complex engineering project will be undertaken in the following section 5.2 however a brief introduction and current state of infrastructure is described here. The transmission grid is of vital importance to this question of large scale CSP for South Africa. The grid is multifaceted system that allows this energy source to be transported and utilized in every corner of the country but currently very little infrastructure exists in the area of concern. The map below shows the current national grid and expansion plans where the varying coloured lines indicate the different capacities of the lines and substations

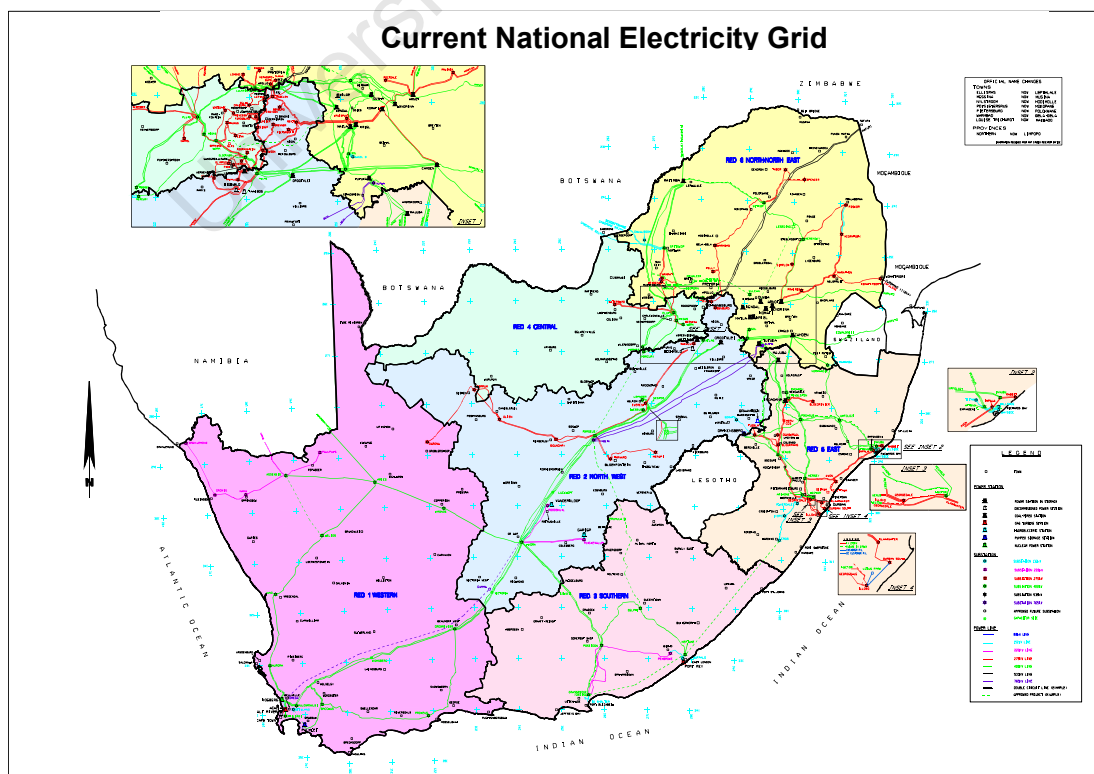


Figure 5.1.5: Diagram of the Eskom national grid showing the power lines and substations. Source: (Eskom, 2007b)

Currently, in the Northern Cape, Upington region, there exists one 275 Kilovolt (KV) line with a 275KV substation at Garona which is 74km from Upington and one 400KV Substation, already handling four 400KV lines at Aries, 125km from Upington.

Fluri (2008) looked at using Geographic Information Systems (GIS) modelling for the most suitable locations for CSP parabolic trough plants. His methodology included solar radiation, vegetation, gradient slope of the terrain for troughs and proximity to available power lines. GIS is a method of using a system of hardware and software used for accumulating, retrieving, mapping, and analysing geographic data. These relevant GIS maps are shown below.

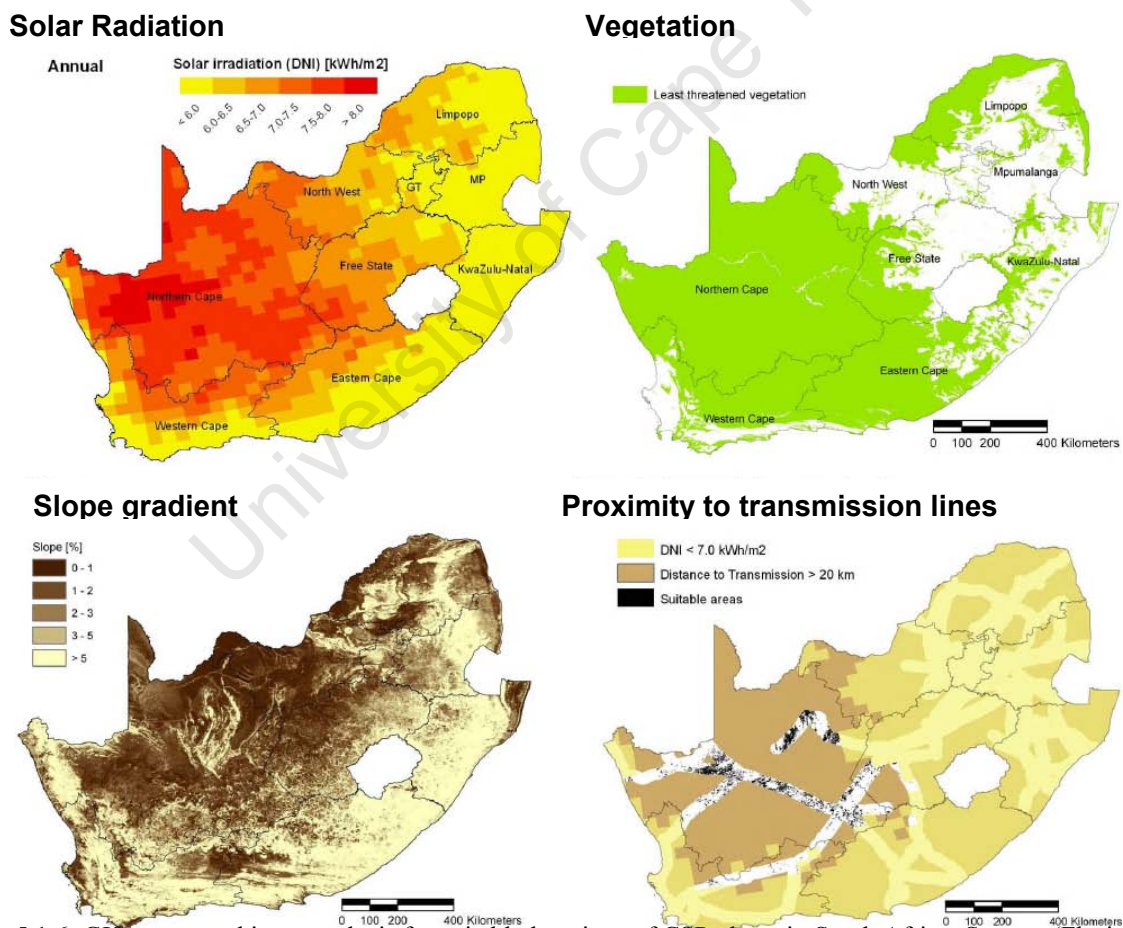


Figure 5.1.6: GIS maps used in an analysis for suitable locations of CSP plants in South Africa. Source: (Fluri, 2009)

This study is very useful for the immediate start-up of CSP plants as it allows the most cost effective locations, with the least environmental influences to be identified.

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This analysis however has not taken into account the large scale grid requirements of 1GW, 10GW or 30GW of solar thermal and has additionally not looked at the water requirements of such scale plants. The results of this GIS study are shown by the detailed map below where the transport roads are shown along with the potential site locations. The criteria for these results is an annual direct normal irradiation of greater than $7\text{kWh/m}^2/\text{day}$, a terrain slope of less than 1% for trough concept, less than 20km distance to high voltage transmission lines, greater than 220kV and no environmentally sensitive areas. The results of this study showed the total CSP power generation potential of South Africa to be 547 600 MW which is indicated in the figure below, split by province (Fluri, 2008).

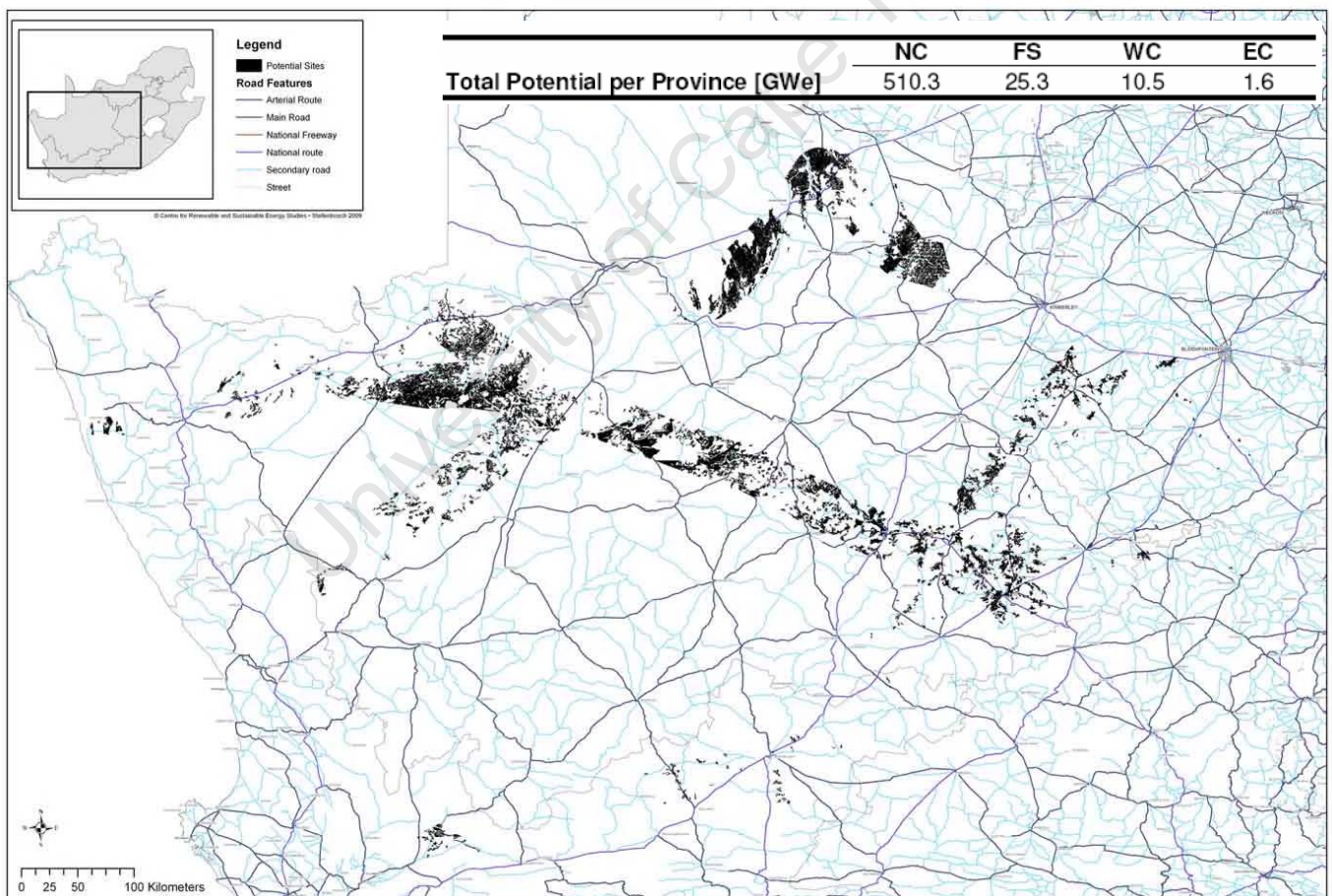


Figure 5.1.7: Map of South Africa, indicating areas which are suitable for the installation of large concentrating solar thermal power plants without significant changes to infrastructure (Source: Fluri, 2009)

Continuing on from Fluri (2008) it is evident that further research is needed into the specifics of transmission and distribution of the large CSP capacities.

5.2 TRANSMISSION AND DISTRIBUTION

Electricity transmission and distribution encompasses all the systems involved in the bulk transfer and conversion of energy from the source to the end user. An electricity transmission network usually connects power plants to multiple substations which convert the power to more usable or efficient forms. The distribution network usually encompasses the wiring between the substations and the end user. The distribution network will thus not be investigated in this dissertation as the majority of this infrastructure already exists. The following diagram shows the transmission (top) and the distribution (below) networks and how the various power stations feed into them. Note the small scale wind and photovoltaic plants can feed into the distribution grid.

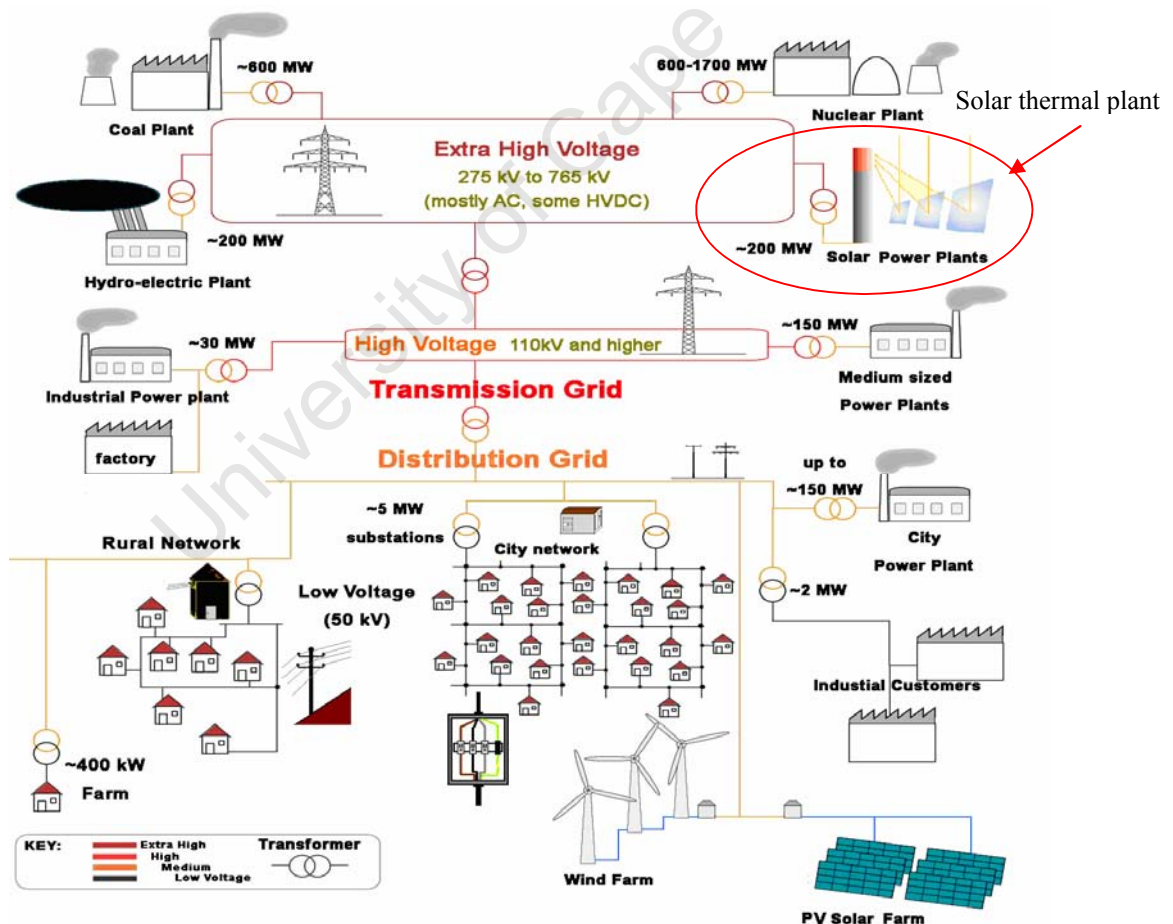


Figure 5.2.1: Schematic of electricity networks showing generation, transmission and distribution Network.

The larger Solar Thermal and Hydro plants require higher voltages for the large power they produce.

Source: (Stefan Riepl-Quark48, 2008)

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However the larger plants (200MW up), such as coal, hydro, nuclear and large scale CSP, require higher voltage power lines and substations. The electricity is transmitted at higher voltages to reduce losses as the longer the length of current carrying wire, the higher the resistance. By increasing the voltage, you reduce the current and hence the losses, as losses are proportional to the current squared.

The main electricity grid backbone from Gauteng to the Western Cape forms the major link between all the power pools, while the major regional corridors allow the flow of power into the major load consumption regions (DME, 2007). Figure 5.2.2 below shows the proposed main backbone and regional corridors which are based on the ASGIA load forecast and generation capacity analysis by 2026 (DME, 2007).

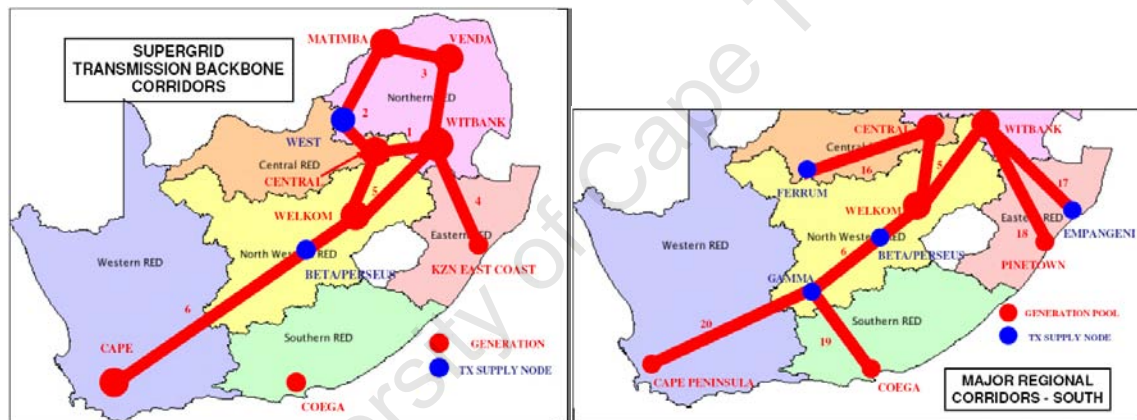


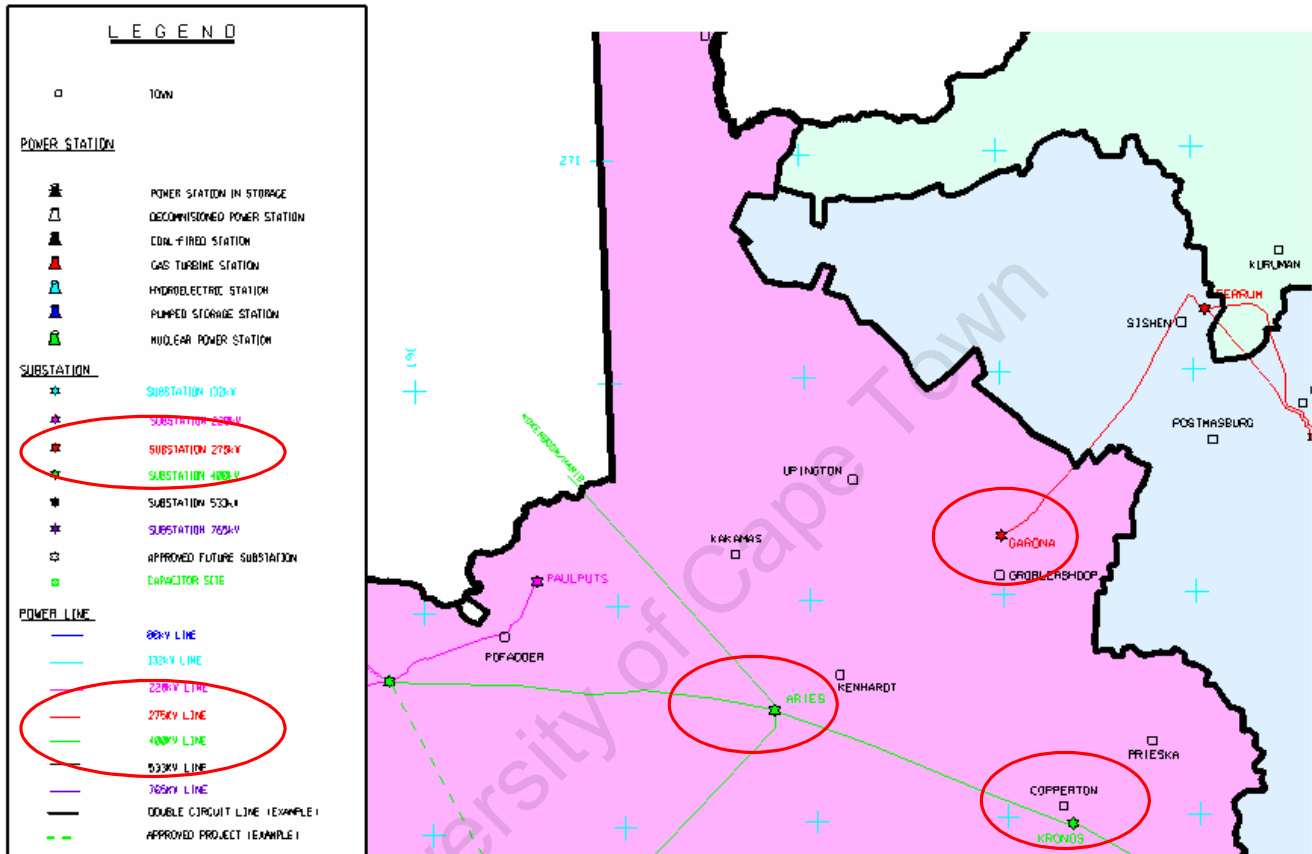
Figure 5.2.2: Planned supergrid backbone and major regional grid corridors. Source: (DME, 2007).

It is important to connect the CSP power plants up to this national grid backbone to allow the electricity to distribute around the country. This process however, is not a simple task where a power line can be quickly constructed from Upington to a convenient location, it requires careful calculations of loads and capacities to maintain grid stability along with minimising costs and losses.

The purpose of this section is thus to analyse and theoretically construct a possible transmission infrastructure concept, required to distribute the electricity generated by hypothetical CSP projects of 1, 10 and 30GW to the main grid. Currently, the transmission infrastructure that exists in the Northern Cape is very limited and

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consists of a 400 Kilo Volt (KV) line that passes from the 400KV substation at Aries, near Kenhardt, into Namibia and a smaller 275KV line and substation at Garona near Groblershdop. An enlargement of the Eskom Transmission map is shown below showing the respective lines and substations.



.Figure 5.2.3: Enlargement of the current Eskom transmission grid in the Upington Northern Cape region. Source: (Eskom, 2007b)

The 275 Kilovolt (KV) line with a 275KV substation at Garona is 74km from Upington and one 400KV Substation, already handling four 400KV lines at Aries, 125km from Upington. The proposal of a 765kv line between Cape Town and De Aar has been approved to strengthen the backbone grid. The only Eskom line cost estimate, found by this dissertation, was published in their 2007 annual (Eskom, 2007c), and stated that a 765kv line costs approximately R1 million per kilometre. When compared to other sources, this estimate appeared to be grossly underestimated and actual costs of the various transmission lines will be evaluated later in the chapter.

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Below is an enlargement of the Eskom transmission grid showing the backbone between Cape Town and Johannesburg, the solar radiation hot spot and the approved 765kV line.

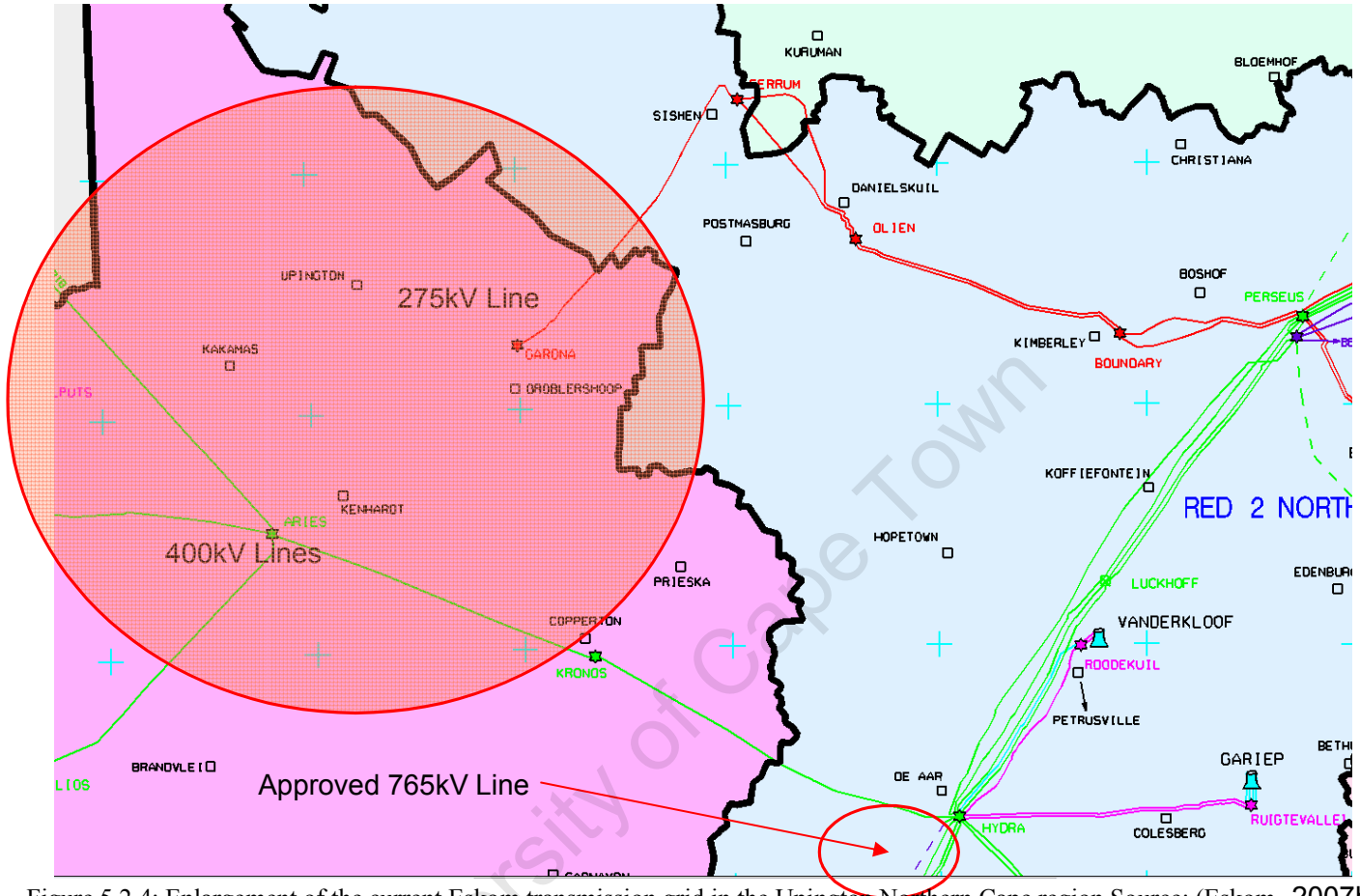


Figure 5.2.4: Enlargement of the current Eskom transmission grid in the Upington Northern Cape region Source: (Eskom, 2007b)

After various interviews and research it became clear that this grid requirement was no simple yes and no, this line, that station answer. A useful rule of thumb is 100MW of power on a 132kV line, the maximum distance without incurring excessive losses, is 100km (Sep Boshoff [Interview with specialist power electrical engineer from Power System Dynamics] pers. comm., 22 May 2009). This is likewise for 200MW down a 275kV line is a maximum of 200km and 400MW down a 400kV line is a maximum of 400km (Sep Boshoff [Power System Dynamics] pers. comm., 22 May 2009). Additionally Mr Boshoff's assessment was that the current local grid in the Northern Cape could only handle another 100 to 300MW and the backbone grid between Cape Town and Johannesburg could handle 1 000MW to 2 000MW with the

new 765kV line installed. For capacities greater than 2GW Mr Boshoff recommended a new High Voltage Direct Current (HVDC) transmission system should be implemented.

A secondary interview was conducted via email with Izak van der Merwe, the Chief Operating Officer of Kutlwano Engineering Consulting. The main points to come out of this source were that the choice of voltage line level is dependant on both the distance from the source and the amount of power needed to be transferred. The more power transferred, the higher the voltage drop and hence the greater the losses (Van de Merwe, 2009). The greater capital investment in 765kV lines will be justified by the reduced losses at some megawatt transferred point (Van de Merwe, 2009). A rough rule of thumb would be to use 400kV for 1 GW with twin 400kV Dinosaur (Type of conductor) equivalent power lines per GW and for greater than 1.5 GW, 765kV lines should be considered (Van de Merwe, 2009). For capacities greater than 4 GW, HVDC should be considered, 275kV should not be considered for any of the 1, 10 and 30GW capacities (Van de Merwe, 2009).

From these interviews, further research was conducted on the differences and requirements of High Voltage Alternating Current (HVAC) lines and High Voltage Direct Current (HVDC) lines.

5.2.1 High Voltage Alternating Current Transmission (HVAC)

In South Africa, high voltage electric energy is mainly transmitted in the form of three-phase alternating current, whose direction and amount changes with a sinusoidal periodicity (sine wave). The frequency of the South African electricity supply network amounts to 50 oscillations per second, which means, that the current flows back and forward 50 times per second. Here, the current is also called three-phase alternating

current because of three time-shifted phases. Single-phase alternating current is mainly utilized in low voltage, domestic and commercial applications.

The main advantage of three-phase, alternating current is its simplicity in regulating voltage and frequency. The voltage can be stepped up and stepped down easily by a transformer and with very few losses. In addition, the electrical actuators or engines that are driven by alternating current can be produced compactly and economically (DLR, 2006). One of the main disadvantages of three-phase is that the consumer and producers needs to be synchronised in terms of frequency otherwise unwanted swings or fluctuations could lead to network instability (DLR, 2006). The failure of one of the phase conductors results in the total failure of the whole circuit. Additionally alternating current is highly susceptible to losses when the distance from source to load increase

Losses of alternating current

Any current-carrying conductor produces a magnetic field around itself. In the case of alternating current, this magnetic field changes constantly and induces a voltage. This effect is called the “inductive reactance” and occurs when the voltage runs in front of the current at a certain phase angle or power factor (DLR, 2006). Alternating current is also amplified due to the capacitive reactance from the voltage running after the current. These resistances cause no heat losses, unlike Ohm’s resistance, but they do create an unusable reactive power which remains between generator and power source thereby reducing the effective power capacity. HVAC lines transmission capacity and length are thus, not limited by the thermal rating of the conductor, but rather the voltage drop along its length (DLR, 2006). In practice, installations are used every 600 kilometres to compensate for these losses in voltage which increases cost.

Losses in Overhead Lines

In addition to current-dependent losses as mentioned above, there are also voltage-dependent losses in the form of ionizations of the gas surrounding the conductor. Gas discharges in areas of heavy curved surfaces and high field strengths are called Corona discharges and can be perceived as a luminous sparks and crackling sounds. The annual average Corona losses amount to approximately 2 - 3 kW electrical capacity per kilometre for a 400 kV system and 2-60 kW electrical capacity per kilometre for a 750 kV system (DLR, 2006). The wide variation in losses depends on the respective atmospheric conditions such as humidity, pollution and ambient temperature.

In summing up, the complete average losses, in HVAC systems is approximately 15 % per 1000 kilometres for a 380/400 kV line and approximately 8 % per 1000 kilometres for a 750 kV line (DLR, 2006). In addition to the line losses, each transformer station can loose approximately 0.25 % of the electrical energy received (DLR, 2006).

Capacities and Associated Costs of HVAC

There are two main high capacity conductor cables utilized in South Africa, namely the Zebra conductor and the Dinosaur conductor. These are usually configured in a twin or quad mounting configuration with capacities including 275kV, 400kV and 765kV (Van der Merwe, 2009). The capacities of these various configurations are shown by the following table:

Table 5.4: Table of the various line configuration capacities and sizes. Source: (Van der Merwe, 2009)

Line Capacities:			
Configuration Name	Transmission Line Size		
	275kV	400kV	765kV
Twin Zebra	0.9GW	1.3GW	-

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Twin Dinosaur	1.2GW	1.8GW	3.4GW
Quad Zebra	1.6GW	2.3GW	4.3GW
Quad Dinosaur	-	3.6GW	6.8GW

From this table it can be seen that at 1GW of capacity can be easily handled by all the conductor configurations where the most economical will be the Twin Dinosaur configuration at 275kV line voltage. 5GW of power can be transferred by the Quad Dinosaur configuration at a 765kV line rating but for 10GW of power, multiple lines will need to be installed. For the bench mark capacity of 30GW, a very large array of 5 of these Quad Dinosaur lines will need to be erected to handle the power capacity. The line costs for the different line voltages increase significantly with the associated voltage increase. Table 5.5 below indicates the costs involved with each line capacity and includes the costs for hardware, labour, transport and commission but not land and rights costs.

Table 5.5: Table of the associated line costs in Million Rand's per kilometre (Van der Merwe, 2009)

Line Costs:	
Line Voltage	Cost / km (R millions)
275kV	R 1.7 million
400kV	R 2.6 million
765kV	R 6 million

As can be seen from the above table, the difference in price increase from each capacity is not linear. This exponential rise can be attributed to the increasing complexities in both materials, in terms of quantity and speciality, and engineering, in terms of insulation, design and mounting structure, all becoming more advanced and specialized to facilitate the higher voltages and capacities.

For lines greater than 100km 80% of the below values can be used (Van der Merwe, 2009). Further costs of lines and substations include transformer costs, transformer

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bays, line bays and busbar costs. These costs are not fixed but can be based on the tables below:

Table 5.6: Tables indicating the associated costs with the various variables of HVAC (Source: Van de Merwe, 2009)

	Transformer Costs:		Transformer Bays	Busbars	Line Bays
Line Voltage	Transformer size and voltage	Cost (R)	Cost (R)	Cost (R)	Cost (R)
275 kV	160MVA	R 28 million	R 6 million	R 1.7 million	R 5 million
400 kV	315MVA	R 50 million	R13 million	R 2 million	R 11 million
765 kV	500MVA	R 55 million	R 25 million	R4 million	R 20 million

The cost for the respective Transformer includes foundations, oil drainage, fire protection, labour, transport and commission. Lands and rights costs, (including EIA's), are not included in these costs. The costs for the Line Bays include foundations, labour, transport and commissioning. The costs for transformer bays include foundations, labour, transport and commissioning. The Busbar (conductor bars that carry heavy currents to supply several electric circuits) costs are R/per bay for a double bus bar. Therefore the cost / bay should be multiplied by the number of bays (feeders + transformers + bus sections + buscouplers + VTs + Reactors + Capacitors) (Van de Merwe, 2009). A reasonable cost approximation is R80 million for a Transmission substation with ± 4 transformers and ± 6 feeder bays. Note, this cost does not include the transformer and feeder bay costs, the transformer and bay quantities are just an indication of the size of the transformer. The cost quoted above includes steelwork, lighting, lightning protection, fencing, earth grid, trenches, relay house, yard stone, transport and commissioning. Lands and rights costs, (including EIA's), are not included. A recent 400/220 kV transmission substation with two transformers, 1 x 400 kV bay and 2 x 220 kV bays had a total cost of R650 million. (This included a 400 kV reactor, protection, DC supplies, communication equipment, etc) (Van de Merwe, 2009). From preceding figures and tables, estimates can be drawn of what is needed for the 1, 10 and 30GW CSP options and what costs are involved.

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For 1GW the most efficient option would be to construct a twin zebra line at 400KV however, this configuration would not allow future expansion in CSP capacity in the Northern Cape area. This lead to the choice of the twin dinosaur, 765kV line configuration to be constructed from Upington to the Hydra station at De Aar. Additionally this line configuration is easily compatible with the planned Eskom 765kV line to Cape Town thereby reducing further costs in future. This expansion would reinforce the backbone grid and offer further expansion capacity, allowing power to distribute anywhere in the country. The line distance was measured to be ~370kilometers, therefore:

$$\begin{aligned} \text{Total cost} &= \text{Line cost} + \text{Transformer cost} + \text{Transformer bays} + \text{Busbar} + \text{Line bays} \\ &= 2 \times (370 \times 6 \times 0.8) + 55 + (25 \times 2) + (4 \times 2) + (20 \times 2) = \mathbf{R3.705 \text{ billion}} \end{aligned}$$

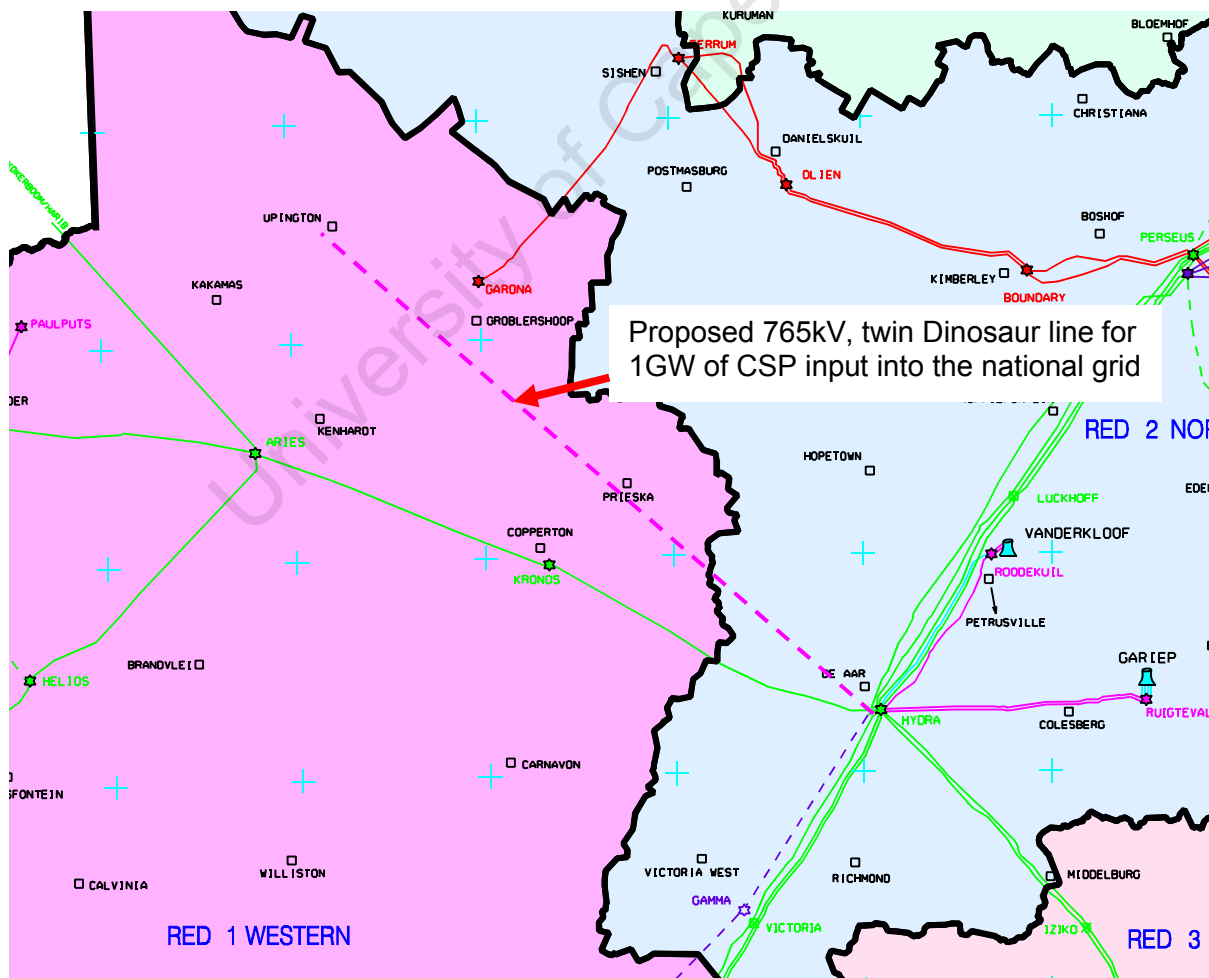


Figure 5.2.5: Grid diagram indicating possible HVAC 765kV line addition for 1GW CSP. Source: (Eskom, 2007b)

For the amounts of 10 and 30GW, the problem becomes significantly more complex. As was quoted before, the main grid backbone is unlikely able to handle more than 2GW additional supply therefore a new grid structure is needed to supply key point sources in the country. To accurately estimate the transmission capacity required the load locations first needs to be understood and projected. The following map from Eskom (2009a) shows the predicted load sizes from 2009 to 2018 of the hotspots:

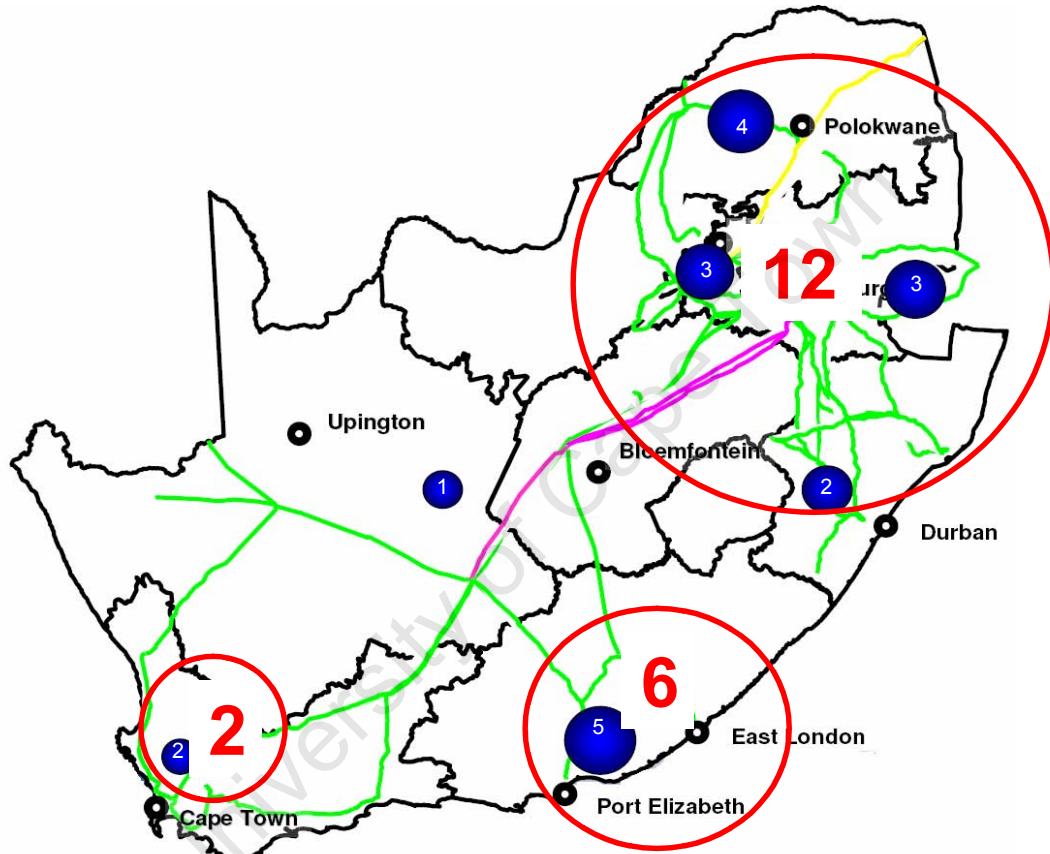


Figure 5.2.6: Grid diagram indicating load centers for 2009 until 2018, numbers are purely for comparative scaling. Source: (Eskom, 2009a)

Actual values of city loads were unfound meaning loads were assessed from the scaling of the above predicted loads for the period 2009 until 2018. The new lines would originate from the Northern Cape Upington region and link up the main load regions of the Western Cape, Eastern Cape and Free State where it will be dispersed to the necessary consumers. The direct distance from Upington to Cape Town is approximately 700 kilometres, Upington to Port Elizabeth 810 kilometres and Upington to Johannesburg is approximately 720 kilometres. Including a safety factor

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of 15% to allow for unforeseen obstacles equates to approximately 800 kilometres distance to Cape Town, 920 kilometres to Port Elizabeth and 830 kilometres to Johannesburg. For 10GW, approximately seven 765kV lines would be required equating to an investment cost of around R25 billion.

Total 10GW cost = Line costs + Transformer cost + Transformer bays + Busbar + Line bays

$$= [(2 \times 920 \times 6) + (4 \times 830 \times 6)] \times 0.8 + (7 \times 55) + (7 \times 25 \times 2) + (7 \times 4 \times 2) + (7 \times 20 \times 2) = \mathbf{R24.879 \text{ billion}}$$

Likewise, 30GW of power would require an infrastructure investment of approximately R76 billion.

$$\text{Total 30GW cost} = [(2 \times 800 \times 6) + (4 \times 920 \times 6) + (12 \times 830 \times 6)] \times 0.8 + (18 \times 55) + (18 \times 25 \times 2) + (18 \times 4 \times 2) + (18 \times 20 \times 2) = \mathbf{R75.906 \text{ billion}}$$

The diagram below shows the possible HVAC grid options.

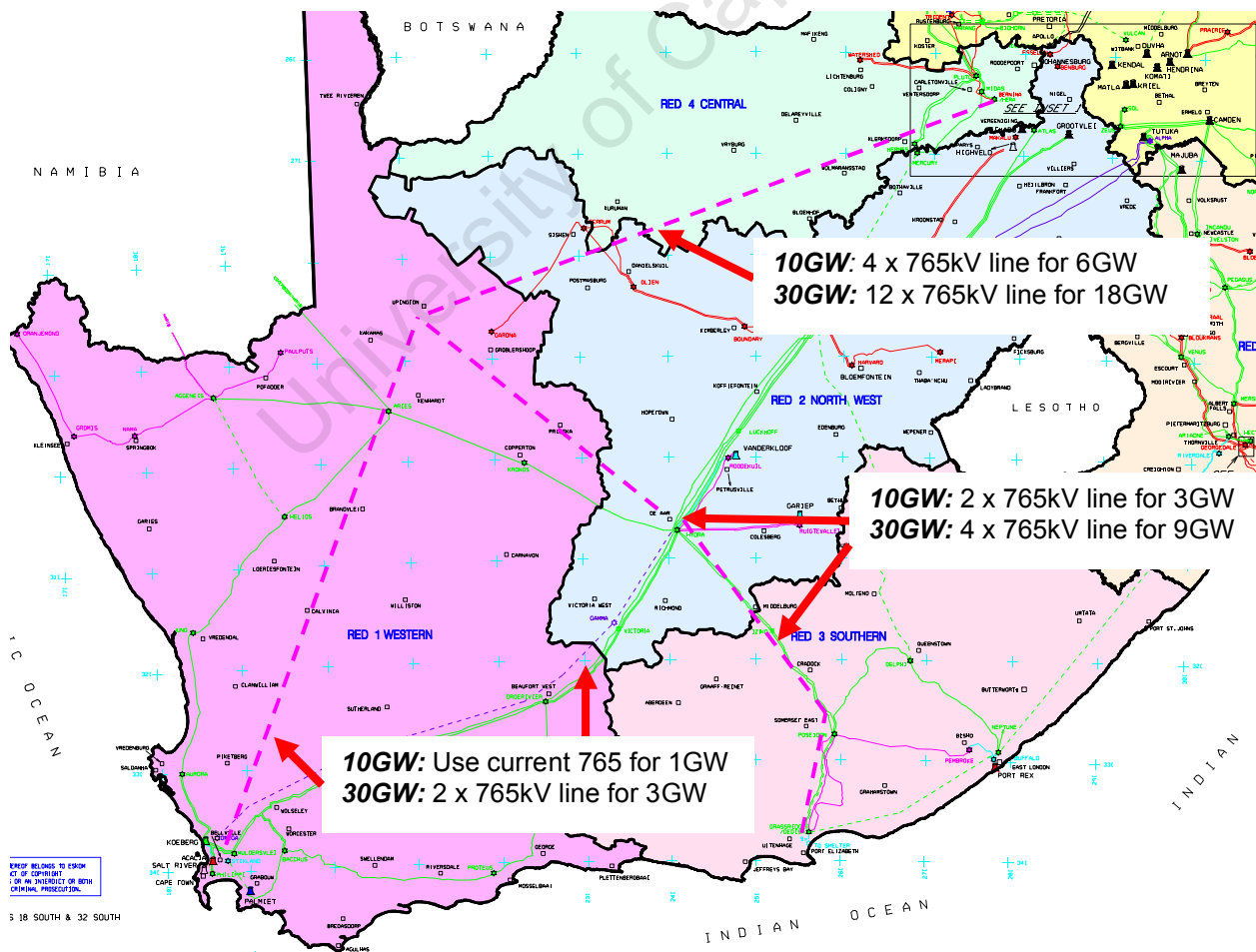


Figure 5.2.7: Grid diagram indicating possible HVAC 765kV line addition for 10 to 30GW CSP. Source: (Eskom, 2007b)

These high investment figures bring the question of more efficient transmission technologies and whether there is a more economical method to distribute the energy. Publications on HVDC are limited, however a very descriptive and informative study, DLR (2006), investigated the Trans-Meridian Interconnection for Concentrating Solar Power. This study investigated the use of HVDC lines to transport CSP power from North Africa into Europe. The majority of the following information was thus extracted from this study and put into perspective of the South African case.

5.2.2 High Voltage Direct Current Transmission (HVDC)

Direct current refers to the continuous flow of electrons, in one direction, at a constant current. It can be generated by electrochemical processes in the form of batteries or by rectification of alternating current (DLR, 2006). In case of rectification the current can be altered by utilizing a rest ripple. This technology is always in demand when conventional AC transmission reaches its technological limits (Schott, 2004). Modern high-voltage DC transmission is a low loss and low cost method that makes it possible to transport electricity for great distances where HVAC becomes costly (Schott, 2004).

Losses of direct current

The utilization of high voltage direct current has a number of diverse advantages if compared with high voltage alternating current. Firstly the transmission distance is only limited by the Ohmic resistance of the conductor, there are no capacitive, or inductive losses which cause a voltage drop along the conductor (DLR, 2006). Unlike HVAC, the entire cross sectional area of the conductor can be used in HVDC until the thermal breakeven point is reached as there are no current displacements at the edge of the conductor (DLR, 2006). A three phase HVAC system requires three conductors whereas HVDC requires only 2 conductors in the bipolar technique and

only one in the monopolar case where current flows back via earth (DLR, 2006). This technique allows greatly reduced line costs, tower size and quantity reduction and decreased land usage as shown in figure 5.2.8 below:

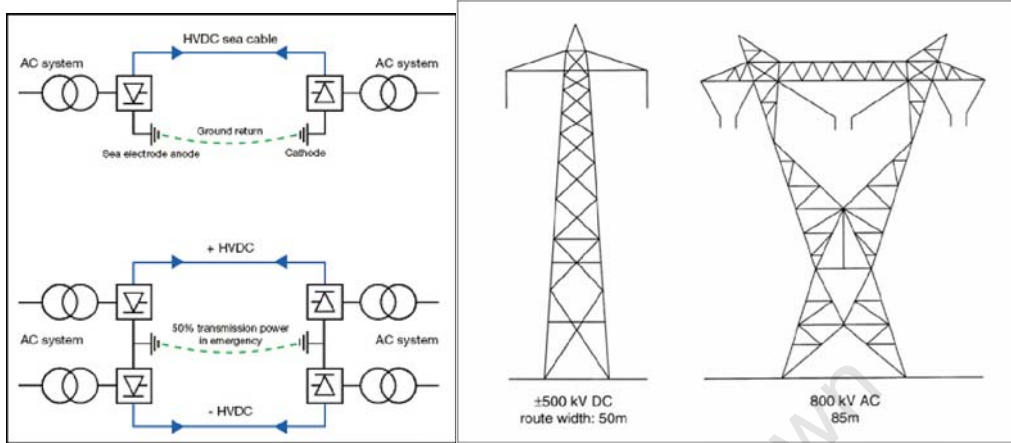


Figure 5.2.8: Schematic diagrams showing the Monopolar and Bipolar HVDC systems along with a comparison of the typical Pylon footprint constructions for HVDC and HVAC overhead lines. Source: (DLR, 2006)

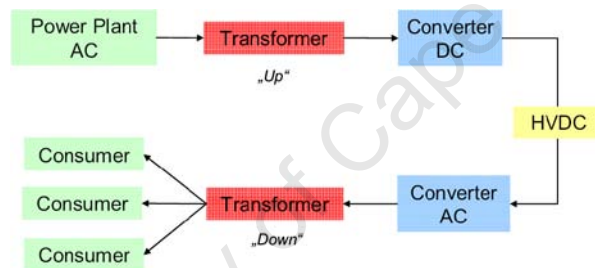


Figure 5.2.9: Schematic diagram of interconnecting HVDC and AC technologies and rectifier placement. Source: (DLR, 2006).

Another advantage of HVDC is that if one conductor fails, a short-term back current of 50% capacity is possible for approximately 10 minutes via the earth allowing more time to bridge and reroute power. Long distance HVDC transmission is said to increase to 800 kV in the near future, allow more efficient transport and improved economics. This is talked about as Ultra High Voltage Direct Current UHVDC and can allow one pole to have 2.5GW capacity.

Disadvantages

Direct current has the disadvantages of not being directly transformable to another voltage and being difficult to disconnect the current with conventional switches at a high network voltage. Additional branching of power is also complicated in an existing

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HVDC system and is only possible with an additional rectifier, increasing the investment costs and space requirements than regular power substations. The final main disadvantage of HVDC is the high initial capital cost when compared to HVAC. HVDC requires large rectifiers which are significantly more expensive than low cost AC transformers.

HVDC, is no new technology and has been in service in various parts of the world for over forty years. The capacity ratings range from a couple hundred megawatts to over 6GW in the Itaipu Brasilia HVDC project. The distances of these lines also range from a few hundred kilometres to 1700km for the Inga-Shaba Congo hydro project. Even South Africa has experience with HVDC where 560MW of hydro power from the Cohora Bassa in Mozambique is transmitted down 1420 kilometres of 500kV HVDC lines. The various HVDC projects around the world are shown by the table below:

Table 5.7: Tables indicating the properties of the various HVDC projects around the world. Source: (DLR, 2006)

HVDC/country	Design	Start of operation	Power [MW]	Voltage $\pm$[kV]	Length [km]	System
SACOI/Sardinia-Corsica-Italy	SC,O	1967	300	200	423	Bipole - multi-terminal
Cahora Bassa/Mozambique-SouthAfrica	O	1977-79	1 930	533	1 420	Bipole - 2 lines
Inga-Shaba/ Congo	O	1982	560	500	1 700	2 x Monopole
Itaipu/ Brasilia	O	1984 - 87	6 300	600	800	Double Bipole
Québec-New England/Canada-USA	O	1990 - 92	2 000	450	1 480	Bipole Multi terminal
BalticCable/ Swe-Ger	SC	1994	600	450	250	Monopole
SwedPol/ Sweden-Poland	SC	2000	600	450	260	Monopole, metallic return
Italy-Greece	UC,SC,O	2001	500	400	310	Monopole
Murraylink/Australia	UC, SC, O	2002	220	150	177	Bipole, HVDC light
NorNed/Nor-NL	SC	2007	700	450	580	2x Monopole

O – Overhead line, SC – Submarine Cable, UC – Underground Cable

Performance, Economy and Impacts of High Voltage Transmission

The cost of transmitting electricity is governed by the investment cost of the transmission lines and by the losses of energy during transmission. Presently, overhead lines are the most common form due to their cost amounting to only 15 -20 % of the cost of underground ground or sea cables (DLR, 2006). The cost of overhead lines is similar for HVDC and HVAC at the lower voltage level, but for UHVDC levels of 800kV, HVDC lines are much more competitive than the comparable HVAC lines. The catch however is that the rectifier stations of HVDC links are substantially more expensive than the simpler transformer stations of HVAC systems. This leads to the fact that for shorter distances and lower voltages HVAC is the more economical and preferred choice, whereas HVDC lines are appropriate for distances over 500 km (DLR, 2006). The reason for HVDC being more suited for long distances is that the transmission losses of HVAC overhead lines are roughly double the amount HVDC overhead line losses (DLR, 2006). The table below compares the associated losses and investment costs of the various HVDC and HVAC options while transmitting 5GW of power.

Table 5.8: Cost and performance variables of HVDC and HVAC options transmitting 5GW of power.
Source: (DLR, 2006)

Parameter	Unit	HVAC		HVDC	
Operation Voltage	kV	750	1 150	600	800
overhead line losses	%/1000 km	8%	6%	5%	2.50%
sea cable losses	%/100 km	60%	50%	0.33%	0.25%
terminal losses	%/ station	0.20%	0.20%	0.70%	0.60%
overhead line cost	Billion R/1000 km	4.5 - 8.5	11.3	4.5 - 5.1	2.8 -3.4
sea cable cost	Billion R/1000 km	36.2	66.7	28.3	20.3
terminal cost	Billion R/station	0.9	0.9	2.9 – 4.0	2.9 – 4.0

The phrase 'Break-Even-Distance' is a term for the shortest distance when the investment costs of a HVDC transmission are identical with the costs of HVAC transmission system. It is a rough rule of thumb and should only be used as such as

it varies according to the transmission capacity and topography land being utilized (DLR, 2006).

The next two graphs indicate the difference in investment costs for an increasing transmission line length at 5GW capacity:

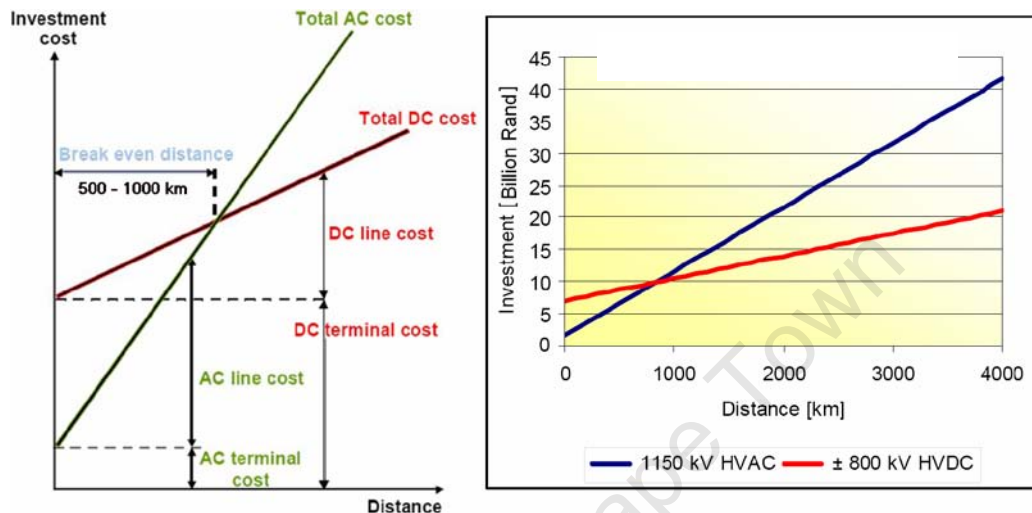


Figure 5.2.10: Comparison of HVAC and HVDC investment costs (Left) and cost model used for Trans Meridian Interconnection for 5 GW overhead line (right). Break even point is at 830 km distance. Source: (DLR, 2006).

In the initial stages, high investment costs of the HVDC rectifier make a substantial difference compared with the lower cost of HVAC transformers. Increasing the transmission length allows the cheaper cost of HVDC conductor lines and their higher efficiency to be an advantage over HVDC. The break even distance can occur between 500 and 1000 kilometres, but this is dependant on the total capacity transmitted (DLR, 2006). The greater the capacity the more advantageous HVDC becomes as the losses are significantly less. Finally, a further advantage of HVDC is that the maximum capacity transmitted is not limited by the thermal limit of the conductors, but by the stability of the along the line (DLR, 2006). This contrasts the option of HVAC where additional costs are added for compensational measures every 600 kilometres (DLR, 2006).

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In the TRANS-CSP model the following assumptions were made for costing HVDC:

- Voltage ± 800 kV, Unit Capacity 5GW
- Overhead Line Investment 350 M€/1 000 km
- Converter Stations Investment 350 M€/Station
- Overhead Line and Cable Losses 2.5 %/1 000 km, Stations 0.9 %/Station
- Economic Lifetime 40 years
- Discount Rate 5 %/y
- Operation & Maintenance Cost 1 % of Investment per year.

The exact costs of the various HVDC components were unfound, thus by using the above trans-meridian model and up scaling it to the South African case of 10 and 30GW, at distance of 800 kilometres, the estimated HVDC costs can be calculated. The 1GW capacity case was seen as uneconomical for HVDC as the transmission distance of 370km is too short to reach the “break even” mark of between 500-1000km stated on the previous page in figure 5.2.10. For the requirements of the 10GW and 30GW cases, the numbers from the Trans CSP model have been adapted and converted to suit the South African situation. The capacity lines have been calculated to match the demand centres and are indicated by the diagram below which shows the HVDC and HVAC hybrid solution.

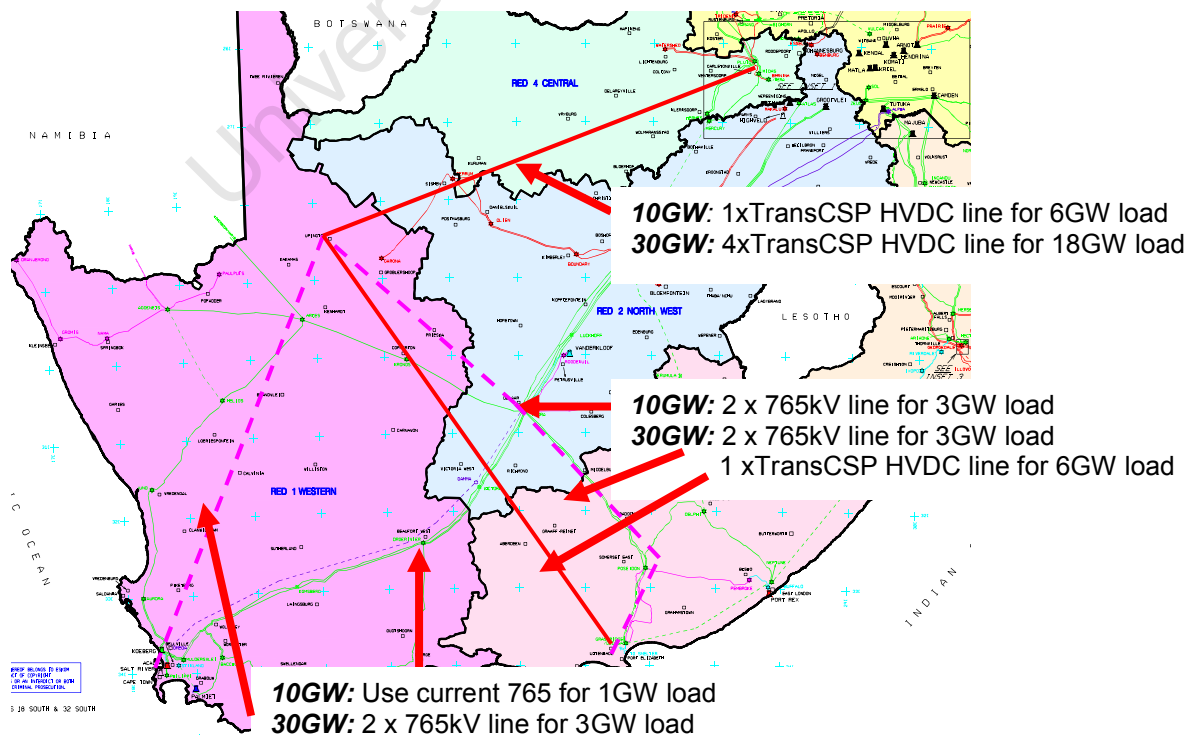


Figure 5.2.11: Grid diagram indicating possible HVAC and HVDCV line additions for 10 to 30GW CSP. Source: (Eskom, 2007b)

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Therefore for the 10GW case the only additional HVDC line would be from Upington to Johannesburg, supplying the 6GW load. The HVDC cost can be worked out to be:

Investment 350M€/1 000km = R3 850million / 1 000km (Exchange 1€ = R11)

= (R3 850 x 0.83)million /830km = R3 195.5 million line investment cost.

Add converter stations at 350 M€/Station = 2x (350x11) = R7 700 million stations

Total HVDC cost = R11.655 Billion which is substantially less than R15.936 billion calculated for the quad HVAC to Johannesburg

Total Grid costs for 10GW capacity are thus HVAC lines + HVDC line

= Line costs + Transformer cost + Transformer bays + Busbar + Line bays +HVDC

= [(2 x 920 x 6)x0.8 + (7 x 55) + (7 x 25 x 2) + (7 x 4 x 2) + (7 x 20 x 2) + R11 655

Total 10GW grid cost = R20.598 billion some R4 billion less than full HVAC

For the 30GW case, the existing 10FG infrastructure is used and additions are made: four Trans CSP HVDC lines would be from Upington to Johannesburg, supplying the 18GW load and 1 from Upington to Port Elizabeth. The HVDC cost can be worked out to be:

Investment 350M€/1 000km = R3 850million / 1 000km (Exchange 1€ = R11)

Johannesburg HVDC lines:

= (R3 850 x 0.83)million /830km = R3 195.5 x 4 = R12 782 million line cost

Add converter stations at 350 M€/Station = 8x (350x11) = R30 800 million stations

Port Elizabeth HVDC lines:

= (R3 850 x 0.91)million /910km = R3 503.5 million line cost

Add converter stations at 350 M€/Station = 2x (350x11) = R7 700 million stations

Total HVDC cost = R54.79 Billion

Total Grid costs for 30GW capacity are thus HVAC lines + HVDC line

= Line costs + Transformer cost + Transformer bays + Busbar + Line bays +HVDC

= [(2x800x6)+(2 x 920 x 6)]x0.8 + (4 x55) + (4x25x2) + (4x4x2) + (4x20x2) + R54 785

Total 30GW grid cost = R73.8 billion only some R2.1 billion less than full HVAC

Another positive of HVDC is the reduced profile compared to HVAC. The profiles of HVAC and HVDC line options for 10GW would look as follows:

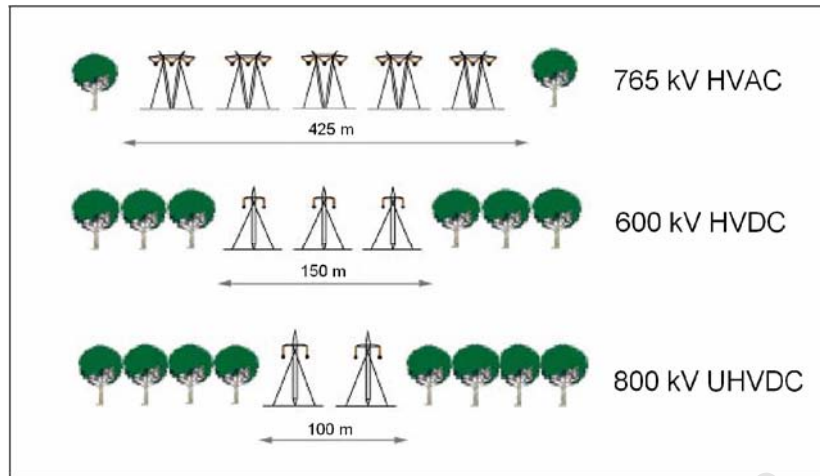


Figure 5.2.12: Comparison of the required number of parallel pylons and space to transfer 10 GW of electric capacity. Source: (DLR, 2006).

While a 765kV HVAC line would require a land width of 425 meters over the total length of a transmission line of 10GW, a HVDC transmission line, of the same capacity, would need only 100 meters of land width (DLR, 2006). These reductions in land usage lead to considerable differences in the environmental impact assessments of both high voltage technologies (DLR, 2006).

The cross sectional profile of 30GW of high voltage transmission would look similar to the figure below:

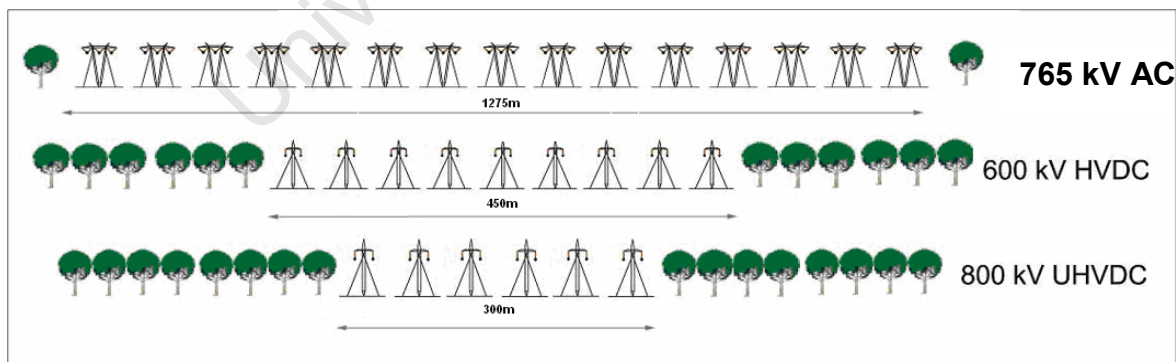


Figure 5.2.13: Comparison of the required number of parallel pylons and space to transfer 30 GW of electric capacity. Source: (DLR, 2006).

For a given transfer capacity, the land requirement of HVDC overhead lines can be up to four times less than that for HVAC lines. As a conclusion, High Voltage Direct Current (HVDC) technology is the best choice for long distance solar electricity

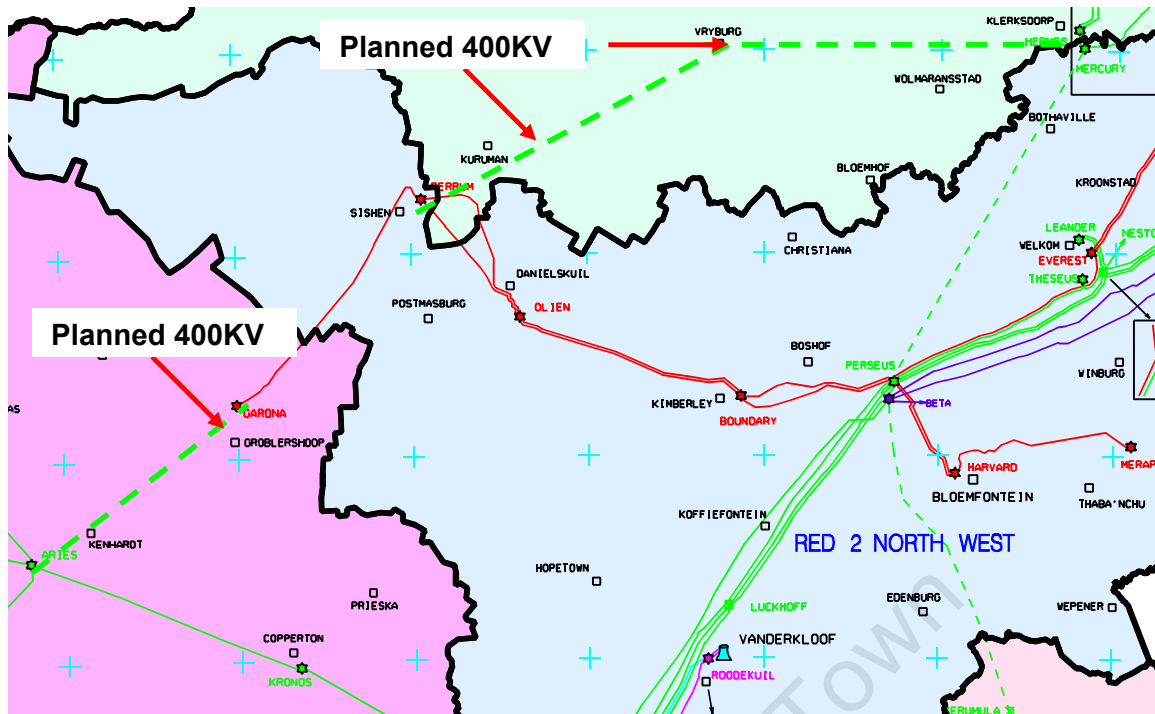


Figure 5.2.15: Eskom's planned capital grid expansion projects for Northern Cape. Source: (Eskom, 2008).

The 2026 grid planning review focused mainly on the development of the main backbone and regional corridors in order to supply the future demands of the main load centres. It took into account that there is some uncertainty with regard to power generation up until 2018 but has not planned for the large capacity of CSP plants, as discussed in this dissertation and as required by the country. These planned capacity lines are likely to allow an additional 500MW to 800MW into the grid, based on the findings from section 5.2, at least 10GW below the required planning by 2026 (Marquard, 2009). It is therefore the recommendation of this dissertation, that future grid infrastructure planning has to take into account the serious probability of a large amount of future generation coming from the Northern Cape region. In addition to the national electricity grid, there is another important technical, infrastructure question that needs to be addressed and that is of energy storage for the intermittent solar energy.

5.3 ENERGY STORAGE

The following section will focus on the energy storage options where an investigation into the importance of energy storage shall be carried out, followed by an analysis on all the relevant technologies. This analysis will encompass capacities, efficiencies, and requirements as well as economic breakdowns which shall conclude the most effective technology under current circumstances along with predicting possible future storage technologies for large scale CSP.

Energy storage for CSP refers to a process of either converting electricity from a power network into a form that can be stored for converting back to electrical energy when needed, or by storing the collected thermal energy before it is converted to electricity and only converting it when needed (Chen, 2009). The implementation of a large number of renewable energy sources is limited by their intermittency such as wind, wave and solar. Most electricity storage options involve losses of 40% to 50% during the conversion process, and are often limited by geographic factors, required by the storage technology which will be explained in further chapters (IEA, 2008). An alternative storage option for CSP is to store the thermal energy generated, and not the electrical energy, and convert it to electricity at times when the intermittent renewable is unavailable. Thermal storage losses are said to normally be held at less than 7% per unit of energy stored (IEA, 2008). Thermal storage is not the only storage option for CSP, as will be demonstrated in the following section, but it does appear to be the most popular option in the research conducted for this dissertation.

Adding storage to a CSP plant, even in fairly low capacities, can allow the plant to increase its average capacity factor from below 25% to above 60% (Baxter, 2008; Palgrave, 2008; Jones, 2004). This depends on the capacity of the storage facility and the number of additional solar collectors from which it can then sell that power at

the most profitable time. This property can significantly increase the value of the plant and electricity produced by optimizing the power produced to address the peak load profile or even the base load of the South African demand profile (Baxter, 2008). Decoupling the production and delivery of solar energy allows a time shift in the supply of electricity from midday, when peak generation occurs, to the typical South African peak which occurs between 5pm and 8pm (Refer to section 4.3). In addition, this stored energy no longer has to compete with the relatively cheap base load stations but with the peaking stations such as gas turbines and pumped storage stations whose running costs are significantly higher than base load.

An additional asset, of thermal storage in particular, is that it is a zero emission solution during operation. An alternative option is to hybridise the solar plant with a fossil fuel back up (Eg. natural gas) that uses the same steam cycle and turbine equipment as the CSP plant. The fact that a CSP plant only requires an additional burner and not a full additional turbine system makes this a greatly more viable economic option for CSP than for other renewables (IEA, 2008). This approach can provide these hybrid facilities with capacity factors approaching 100%, excluding maintenance, but do however increase the carbon dioxide emissions of the plant (Baxter, 2008)

In addition to enhancing the value of the electricity produced, energy storage can help reduce overall expenses by optimising the capital investment made on the turbines. This reduction in cost, however, is limited by the capital expense of the storage system, and the fact that the biggest area of cost in a CSP plant is the heliostat field and not that of the conventional steam turbine part. A CSP plant that operates continuously requires a much larger solar field for a given power capacity than running only during day-time (IEA 2008).

5.3.1 ENERGY STORAGE FORMS

There are two main criteria to categorise electrical energy storage and these are function and form (Chen, 2009). In terms of function, electrical energy storage (EES) technologies can be grouped into those that are intended for power quality control and those that are designed for energy management purposes (Chen, 2009). Power quality control or uninterrupted power supply (UPS) have high power ratings but a relatively small energy content whereas energy management systems also have high power ratings but vary up to large energy contents.

These functions can be split by the following diagram where capacitors, superconductive magnetic energy storage (SMES), flywheel and battery storage are used in power quality and reliability.

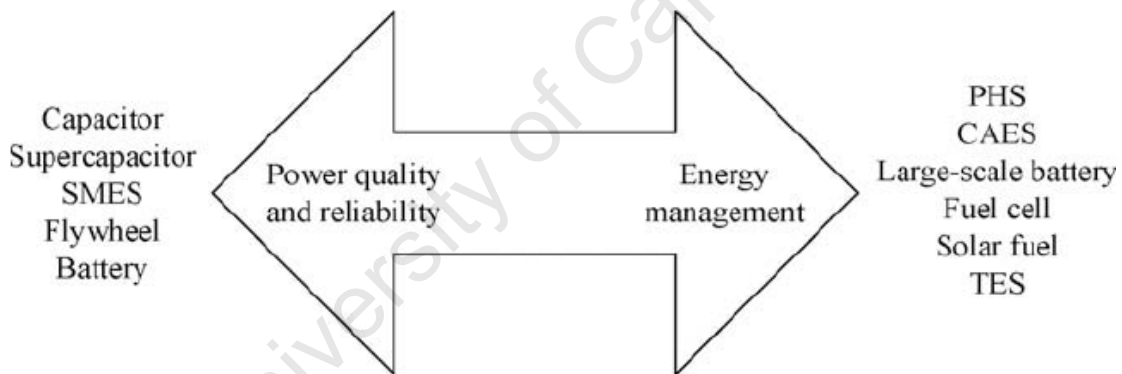
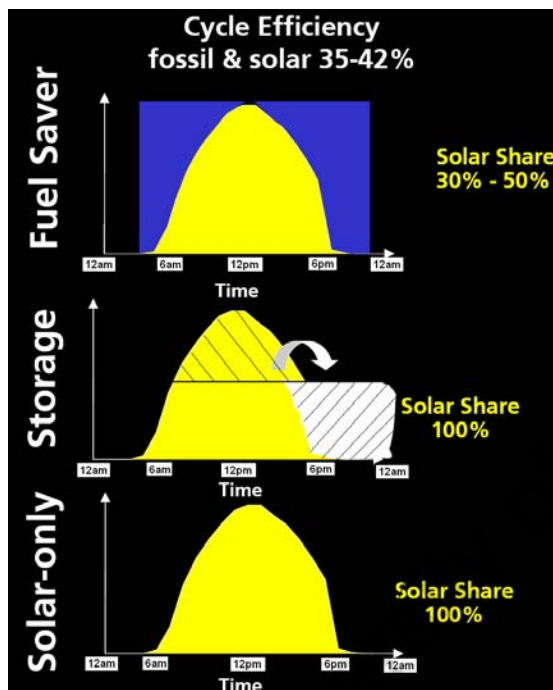


Figure 5.3.1: Energy storage with respect to function. Source: (Chen, 2009)

Energy management function is comprised of pumped hydroelectric storage (PHS), compressed air energy storage (CAES), large scale battery, fuel cell, solar fuel and thermal energy storage. This division is, however not fixed as several manufacturers of batteries and flywheels are developing high energy to power devices (Chen, 2009). Electricity is widely accepted to be difficult and expensive to be stored directly, i.e. as electricity, however it can be easily converted, stored in other forms and converted back to electricity when required.

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

The outputs of the different CSP plant setups, hybrid with fossil fuel, six hour storage or solar only, can be represented graphically on output vs. time graphs. The three options are the hybrid method, where the solar plant is supplemented by a natural gas cycle, the solar plant with storage, where the solar field will need to be considerably larger to match the other two's peak output, and the basic solar plant with no storage are shown below. These graphs are not to scale and numbers are only for illustrative purposes.



1. Hybrid Case

Operates at constant 100MW of which solar energy supplements 30 to 50% of the total output

2. Solar thermal plant with 6 hours storage

Solar capacity can probably reach 100MW at noon however plant will only be rated at 50MW where excess energy will be stored for use at night. Note the cross hatched areas will be the same size excluding ~7% losses.

3. Solar thermal plant with no Storage

The solar plant will be rated at 100MW but will have a very low capacity factor as the rated energy can only be produced for approximately 2 hours

Figure 5.3.2: Diagrams based on Muller-Steihagen, 2008, showing the output vs. time of three CSP plant layouts

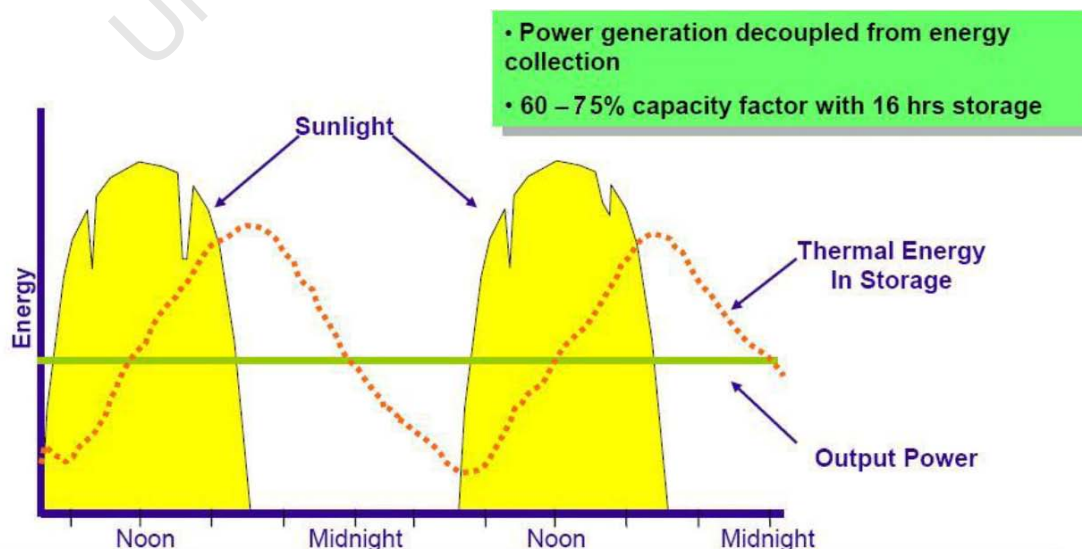


Figure 5.3.3: Graph showing the incoming solar radiation over 2 days, the relevant power output and the respective thermal energy storage capacity of 16hours. Source: (Van Heerden, 2009)

There are multiple methods for storing energy and each will fall under its specific form. The storage technologies can be categorized by they're four forms:

- 1. Electrical Energy Storage:**
 - i) Electrostatic (capacitors and supercapacitors)
 - ii) Magnetic and current (SMES)
- 2. Mechanical Energy Storage:**
 - i) Kinetic (Flywheels)
 - ii) Potential (PHS and CAES)
- 3. Chemical Energy Storage:**
 - i) Electrochemical (Batteries)
 - ii) Chemical (Fuel Cells, Metal air batteries)
 - iii) Thermo-chemical (Solar hydrogen, solar metal, solar ammonia and solar methane)
- 4. Thermal energy Storage:**
 - i) Low temperature (Aquifers, cryogenic)
 - ii) High Temperature (Steam/water, graphite, rock/concrete, phase change materials, salts)

5.3.1.1 Electrical Energy Storage

I) Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) is the only available storage technology that stores electrical energy straight into electric current (Cheung, 2007). It stores the energy through flowing current in a circular, superconducting coil that can hold the electric current virtually indefinitely, with almost zero losses. Additionally the energy can be stored as a magnetic field in the inductor which is submerged in liquid helium in a vacuum insulated cryostat. The conductor coil is typically made from niobium-titanium and the cryogenic liquid can be helium or super fluid helium which are at 4.2 Kelvin or 1.8 Kelvin respectively (Chen, 2009). The system has three main components, a superconducting coil, a cryostat refrigerator and vacuum vessel which is insulated and the power conversion system (Cheung, 2007). These components are shown by the figure below

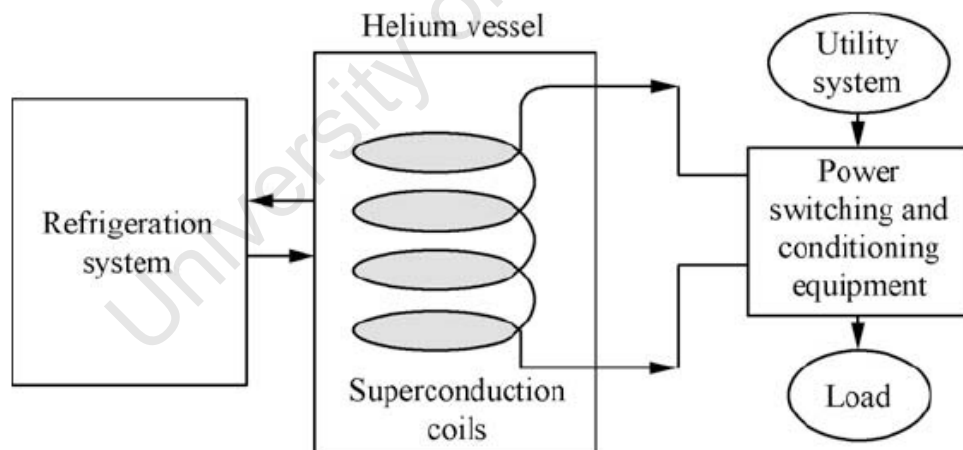


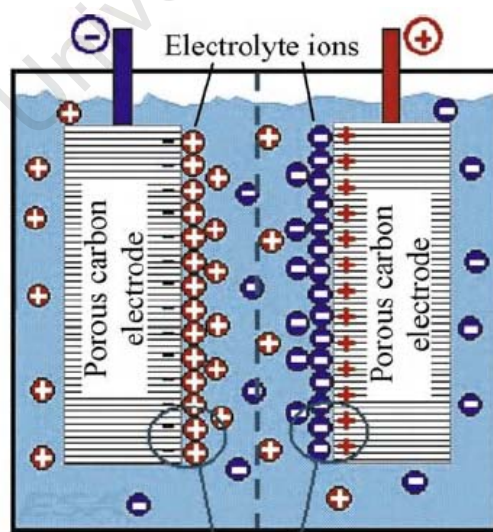
Figure 5.26: Schematic diagram of a SMES system. Source: (Cheung, 2007)

The main advantages of SMES systems is that they have very high storage efficiencies of typically greater than 97% and rapid response times of a few milliseconds. Additionally SMES systems have a very high cycle life and can be charged and discharged repeatedly, this suits it for applications that require full cycling, continuously such as voltage stability and power conditioning. SMES systems are typically rated between 1 and 10MW with a

storage capacity of seconds but research is looking at larger systems of 10 to 100MW with a storage of minutes. This property alone renders SMES not suitable for CSP large scale storage however additional issues such as high capital and running costs along with the negative environmental effects associated with powerful magnetic fields causes this system to be unsuitable.

II) Capacitors and Supercapacitors

Like superconducting magnetic energy storage, capacitors store electrical energy directly but not as current but rather as induced potential energy or voltage. A capacitor can be simplified down into two metal plates, positioned very close together and separated by a non-conductive layer called a dielectric. One plate is charged by an electric current which induces an opposite charge on the other plate forming potential energy between the two. Capacitors have the ability to be charged rapidly and like flywheels, they can cycle tens of thousands of times between charged and discharge with high efficiencies. Capacitors have been used for daily peak loads of less than 1 hour and small capacities of a few kilowatts however, their low energy density renders larger capacities uneconomical and bulky (Chen, 2009).



Double Layer Capacitors
(Adsorbed layers of ions and solvated ions)



Photo Courtesy of ESMA

Figure 5.3.5: Schematic diagram of a capacitor and supercapacitor. Source: (Chen, 2009)

These properties have developed research into supercapacitors which theoretically have a far greater energy density than conventional capacitors meaning more compact designs (Chen, 2009). Supercapacitors store their charge in an electrolyte solution between the two electrodes. The electrodes are generally made from porous carbon which drastically increases the surface area (up to 2000 m² per gram) and substantially increase the capacitance and storage capacity (10 to 100's of kW's) (Chen, 2009).

The negatives associated with capacitors however, is similar to flywheels in their short discharge durations and high self charge losses due to energy dissipations. This limits their uses to power quality control applications and not energy management needed by large scale CSP which requires a six hour, full load storage as stipulated in the REFIT.

5.3.1.2 Mechanical Energy Storage

I) Flywheels

Fly wheels are one of the oldest forms of energy storage where their energy is stored in the angular momentum of a spinning mass (Cheung, 2007). The same motor is used to charge (spun by motor) the flywheel and discharge (motor acts as a generator) where angular momentum is converted into electric current. The total energy and capacity of a flywheel system is based on the mass, size and angular momentum of the rotor and the power rating is based on the capacity of the motor/generator. Modern flywheel systems have containment vessels that are under a high vacuum to reduce windage losses and to provide protection from external disturbances (Cheung, 2007). New designs are utilizing magnetic bearings to further reduce friction losses.

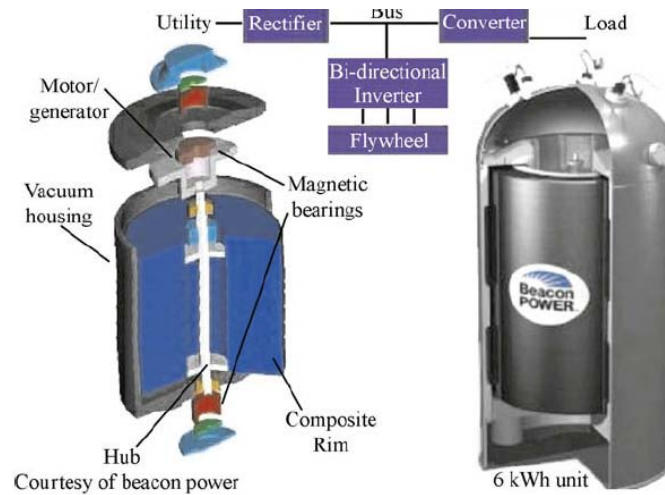


Figure 5.3.6: Schematic diagram of a flywheel system. Source: (Lazarewicz, 2005).

Unlike batteries, the main advantage of flywheels is their long life ability to produce full charge to discharge cycles in the hundreds of thousands (Lazarewicz, 2005). Additionally they have a very high efficiency of between 90 and 95% and they are currently being demonstrated to smooth the output of wind turbines or in general power quality control. In terms of energy management however, flywheels have relatively short energy durations, high frictional losses and low energy densities when compared to other energy storage technologies. These properties render this technology unsuitable for large scale CSP storage as CSP requires long term, high energy capacity of the management storage type, not quality and reliability.

II) Pumped Hydroelectric Storage

Pumped hydroelectric storage is one of the most widely utilized forms of large scale energy storage. The typical design of the system consists of two reservoirs located at different altitudes, a pump to transfer water from the lower reservoir to the above reservoir during off peak periods, thus creating potential energy, and a turbine to extract the kinetic energy when water is allowed to flow back into the lower reservoir during peak load requirements. The pump and turbine are usually designed as one unit that works in reverse when pumping. This layout is shown by the figure on the next page:

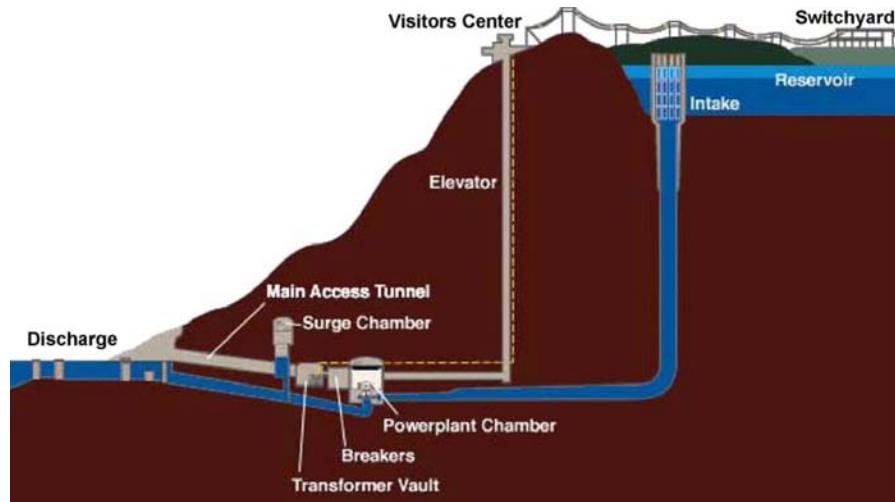


Figure 5.3.7: Schematic diagram of Pumped hydroelectric storage. Source: (Hadjipaschalis, 2009)

The potential energy that can be extracted is fundamentally defined by the difference in height between the two reservoirs and the volume of water that can be transferred in the system. Site location is thus a limiting factor with pumped hydro but there are examples that could use flooded mines or open sea as the lower reservoir (Chen, 2009). The advantages with pumped hydroelectric storage are that it is a very mature technology with very large storage capacity and long available storage period. Additionally it has a relatively high conversion efficiency with low losses and a low initial cost per unit of energy (Chen, 2009). Storage can occur from hours to days and even to years depending on the rate of evaporation, precipitation and river run-off. Losses due to evaporation and conversion cause the system to have an efficiency of between 71% and 85% (Chen, 2009). Pumped hydroelectric storage can range in capacity 100MW up to 3 000MW and is widely accepted to have the highest rating over the available energy storage options. There are however some drawbacks with pumped hydroelectric storage: Firstly an appropriate site needs to exist for two large reservoirs of a sufficient difference in altitude. Finally, large capital costs and long lead times of typically ten years from environmental issues and construction. The various properties of each storage option will be comparatively assessed in section 5.3.2.

III) Compressed Air Energy Storage

Like pumped storage, compressed air storage is the only other commercially proven technology for very large scale energy storage of over 100MW per unit (Chen, 2009). It has to be hybridized with a natural gas turbine as the air acts as a supercharger of sorts. The general layout for the system consists of five main components

- 1) The motor/generator unit that utilizes clutches to engage either the compressor or turbine systems.
- 2) The air compressor consisting of one or two stages consisting of intercoolers and aftercoolers to achieve high efficiency and removal of moisture from the compressed air.
- 3) The turbine system consisting of both high and low pressure turbines.
- 4) A large cavity or container vessel for storing the compressed air. Underground rock caverns of suitably hard and impervious rock formations created by excavation are suitable. Salt caverns formed by solution or dry mining of salt formations can be utilized. Porous materials, such as sandstone and fissured lime, left by depleted gas or oil fields and aquifers bearing water have been employed.
- 5) Control equipment for the fuel storage and heat exchanger units

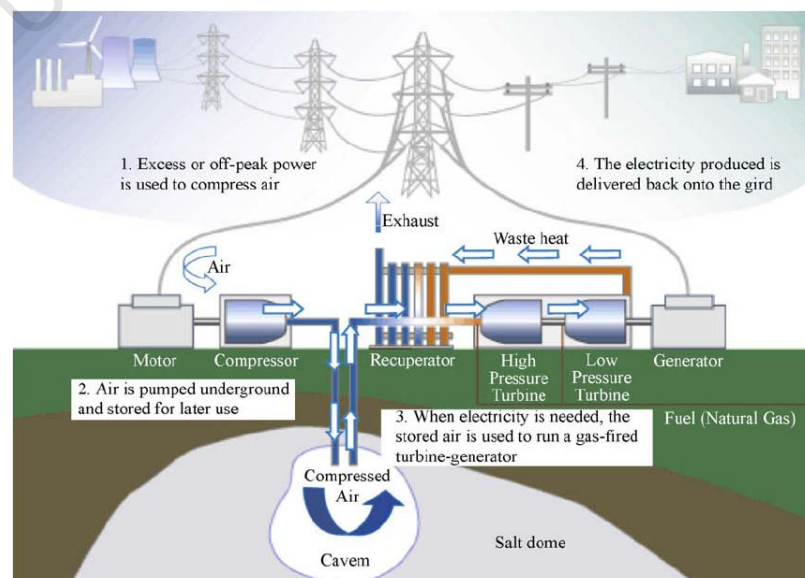


Figure 5.3.8: Schematic diagram of a compressed air storage energy storage system. Source: (Hadjipaschalis, 2009)

Compressed air energy storage systems function on the fundamentals of conventional gas turbine electricity systems. The compression and expansion phases of the traditional gas turbine are separated, where the energy after the compressor is stored in the form of elastic potential energy. During off peak periods, excess electrical energy is used to compress air into the airtight cavern usually between four and eight Mega Pascal's (Chen, 2009). To recapture the energy, the compressed air is released, heated and expanded through a high pressure turbine which extracts some of the energy, however losses occur due to the fundamentals and inefficiencies of the turbine engine. The air is then combined with fuel, combusted and expanded through a low pressure turbine which is connected to the high pressure turbine and generator to produce electricity. The waste heat is used in the recuperator to preheat the compressed air, essentially capturing the waste exhaust heat. Compressed air systems are able to shift from generation to compression quickly and easily, benefiting utility systems whose loads fluctuate, i.e. wind power. The systems are designed to cycle daily and operate efficiently during partial load conditions. Environmental characteristics are favourable with compressed air systems when comparing them to intermediate generating technologies however they still require the combustion of fossil fuels to operate. The storage period is relatively long, over 1 year, and its high efficiencies are said to be between 70 and 89% (Chen, 2009). Low capital costs, between \$400 and \$800 per kWh, and high energy charge/discharge capabilities, between 50 and 300MW, render this technology favourably above other storage technologies however it does have its barriers.

Like pumped hydroelectric storage, compressed air storage is reliant on favourable geographic formations, rock mines, salt cavers, aquifers etc, to be in the near vicinity of the power plant. Additionally, compressed air storage is

not an independent system and has to be associated with a gas turbine system. Steam plants, coal fired, nuclear, wind, solar photovoltaic and thermal plants cannot be used with this design unless a hybrid plant containing a gas turbine is available. Finally the requirement of combusting fossil fuels and the associated emissions with this render the design highly unfavourable in the strictly renewable field.

5.3.1.3 Chemical Energy storage

I) Batteries

Rechargeable batteries are one of the oldest forms of electricity storage in the form of chemical storage (Mclarnon, 1989). The typical battery consists of one or more electro-chemical cells which are made up of an electrolyte (liquid, paste or solid) an anode (+) and a cathode (-). During operation, electro-chemical reactions take place at the two electrodes inducing a movement of electrons through the completed circuit. These reactions are reversible, enabling an external voltage across the electrodes to recharge the battery (Chen, 2009). Batteries are very well suited for electricity storage due to their fuel flexibility, low environmental effects and rapid response to fluctuating loads (Chen, 2008). Batteries efficiencies are said to range between 60 and 95% and they have very low standby losses when fully charged (Kondoh, 2000). Additionally, construction has short lead times and the technology is very modular meaning units can be stacked together to achieve the required output and energy content.

Batteries do have a fair amount of negative properties which may cause them to be an unsuitable option for CSP. Up until recently, batteries suffered from relatively low energy densities, low power capacities, high running and

maintenance costs, short life spans and restricted discharge capabilities. Additionally many batteries contain heavy metals meaning the disposal of spent cells needs to be restricted to avoid ecological damage (Dti, 2004). Batteries that have either been proven or are potentially suited for utility electricity storage include: Lithium Ion, Lead Acid, Sodium Sulphur, Nickel Cadmium and Sodium Nickel Chloride (Karpinski, 1999)

II) **Fuel Cell**

A fuel cell is a device that performs an electrochemical conversion to create a current. The conversion produces electricity from external sources of fuel supplied to the anode side, an oxidant on the cathode side and an electrolyte facilitates the reaction (Dti, 2004). Fuel cells can theoretically operate continuously if the required flows are maintained. They differ from batteries (5.3.1.1) in that they expend the reactants, which need to be restocked, whereas batteries store the electrical energy chemically in a closed system. Additionally, a battery's electrodes react and alter during discharge and charging whereas a fuel cell's electrodes are the catalyst in the reaction and are fairly stable. A fuel cell can be comprised of a wide variety of fuels and oxidants including hydrogen and oxygen, hydrocarbons and air, alcohols and air/chlorine, and metals and chlorine/chlorine dioxide.

For the purpose of energy storage in a CSP system, hydrogen fuel cells are the most promising fuel cell technology as hydrogen production from CSP is achievable in multiple processes from thermo-chemical or photochemical processes (Refer to 5.2.1.9 for detailed conversions). The hydrogen is thus used as the energy storage medium.

In a hydrogen fuel cell, hydrogen and air react to produce electricity and water. These systems are receiving a lot of interest for their possible integration into renewable, intermittent power sources. The fuel cell comprises of the hydrogen storage system and a hydrogen conversion system which converts the stored chemical energy into electricity. These ideas are shown by the figure below

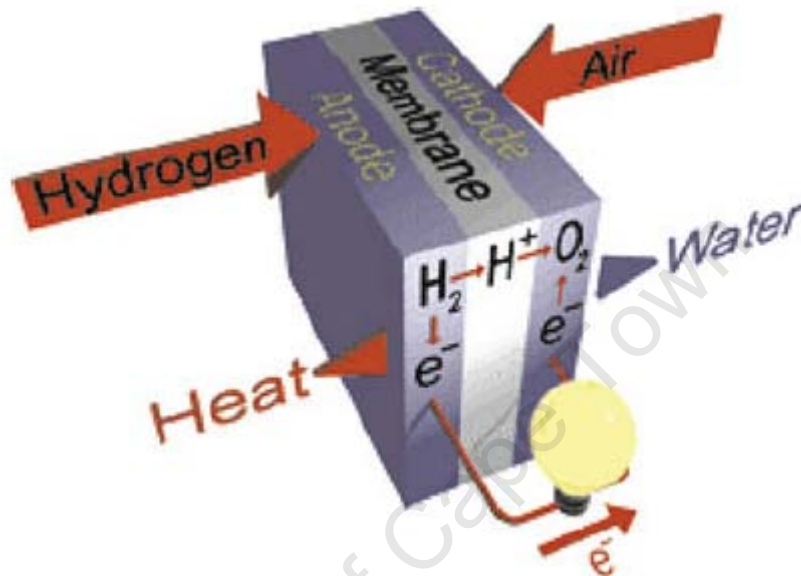


Figure 5.3.9: Schematic diagram of a hydrogen fuel cell. Source: (Dti, 2004)

Hydrogen fuel cells enjoy a couple of inherent advantages, these include a high energy density of between 0.6 and 1.2 kWh/kg, can be implemented in a wide range of scales from kW's to multi-MW in capacities, modular design enabling multiple units to be added and reconfigured and their positive environmental operating characteristics. These advantages do however come with some disadvantages, these include: high costs of between \$6-20/kWh and very low round trip efficiencies 20-50% (Chalk, 2006).

III) Flow Battery

A flow battery is almost a hybrid of a battery and fuel cell and works by using an electrolyte that contains one or more electro-active chemicals which flow through a reactor causing the chemical energy to be converted to electricity (Linden, 2006). Unlike a battery however, the electrolyte, which contains the energy, is stored in external tanks and is pumped through the reactor where the battery can be charged, discharged and recharged (Chen, 2008). The general layout for a flow battery is indicated by the figure below:

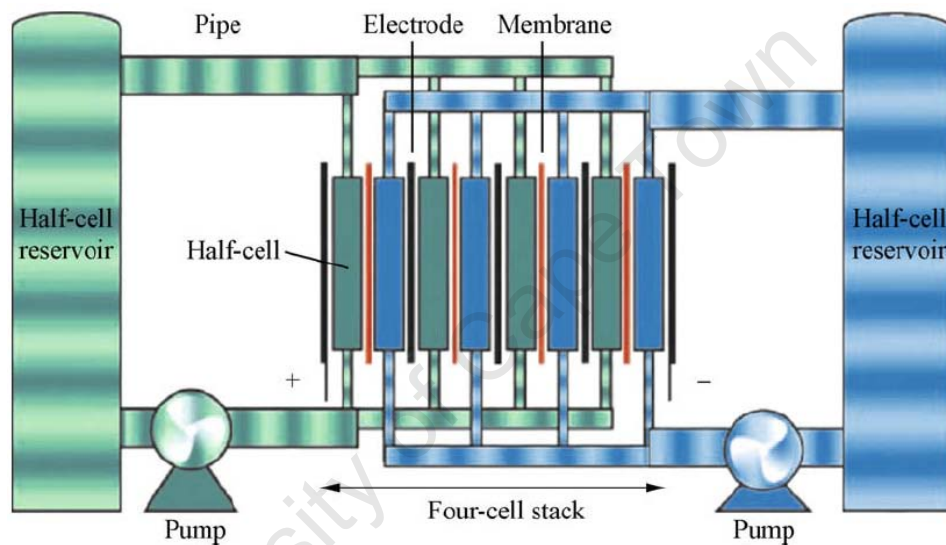


Figure 5.3.10: Schematic diagram of a Flow battery. Source: (Linden, 2006)

The power and energy content ratings of flow batteries are independent of the storage capacity, which is calculated by the quantity of electrolyte used, and the power rating, which is determined by the active surface area of the reactor stack (Linden, 2006). They are able to continuously release large amounts of energy for extended periods of time, ten hours, and are differentiated from fuel cells in that they can be operated in reverse and be recharged. Due to being still in the development stages, flow batteries have very little statistical information on efficiency but costs of the electro active substances are said to be the main limiting factor.

IV) Solar Fuels

Solar fuels are of particular interest to CSP as they theoretically promise an ability to create a transportable fuel for power generation by concentrating the intermittent renewable resource of solar radiation, converting it, and storing it for use when required. They are currently in the early stages of development but are attracting a lot of attention from scientists and energy planners. The theory is shown by the figure 5.30 below where solar radiation is concentrated by parabolic mirrors onto a receiver. The heat generated allows endothermic chemical reactions which produce a transportable and storable fuel (Steinfeld, 1998). These fuels can either be stored on site or transported to more suitable locations for electricity generation.

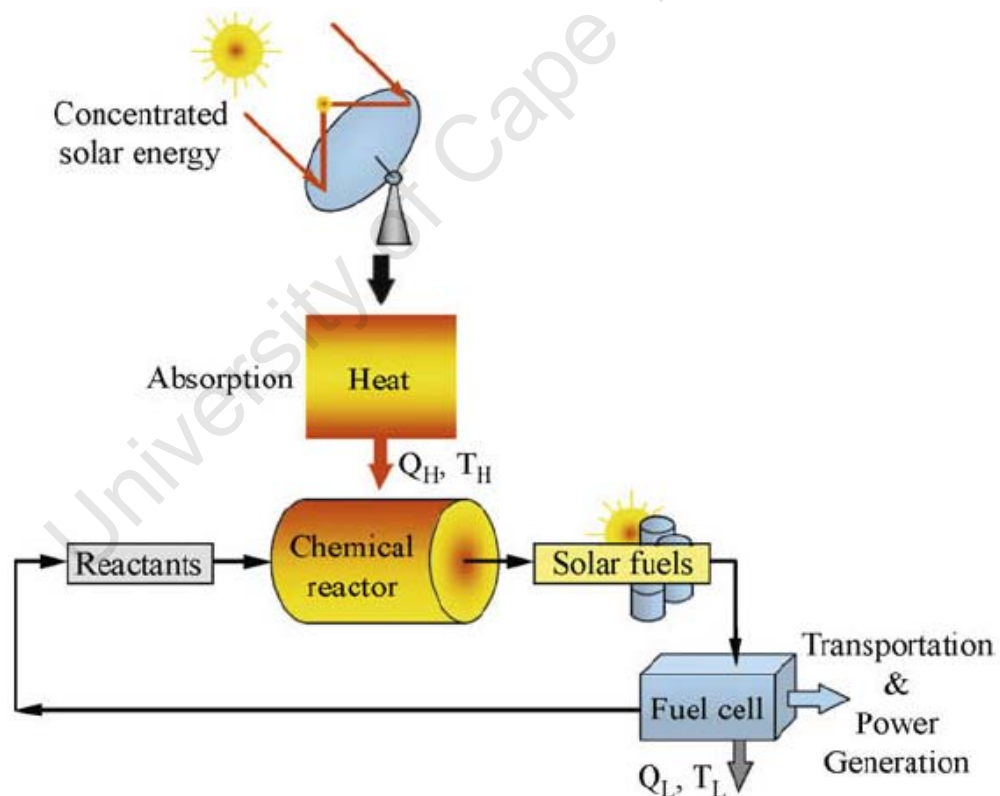


Figure 5.3.11: Schematic diagram of solar energy conversion into transportable fuels. Source: (Steinfeld, 2004)

It is theoretically possible to use electricity as the energy input to convert the solar fuel however, the round trip efficiency of the steam Rankin cycle would be relatively low. The advantage of the solar fuel system is that the change in

conversion efficiency of solar to electric becomes close to zero and the storage efficiency comes close to 100% (Chen, 2009). The storage becomes part of the system and not an external unit.

There are a number of fuels that can be produced by concentrated solar power such as Solar Hydrogen, Solar Metals, and Solar chemical heat pipe.

Solar hydrogen: There are five thermo chemical routes for the production of hydrogen which all use solar radiation as the source for high temperature process heat energy. They include: Solar thermolysis and solar-thermo chemical cycles which use water, fossil fuels can be used in solar cracking, and water and fossil fuels are used in solar reforming and solar gasification (Steinfeld, 2004). These processes are depicted by the figure below

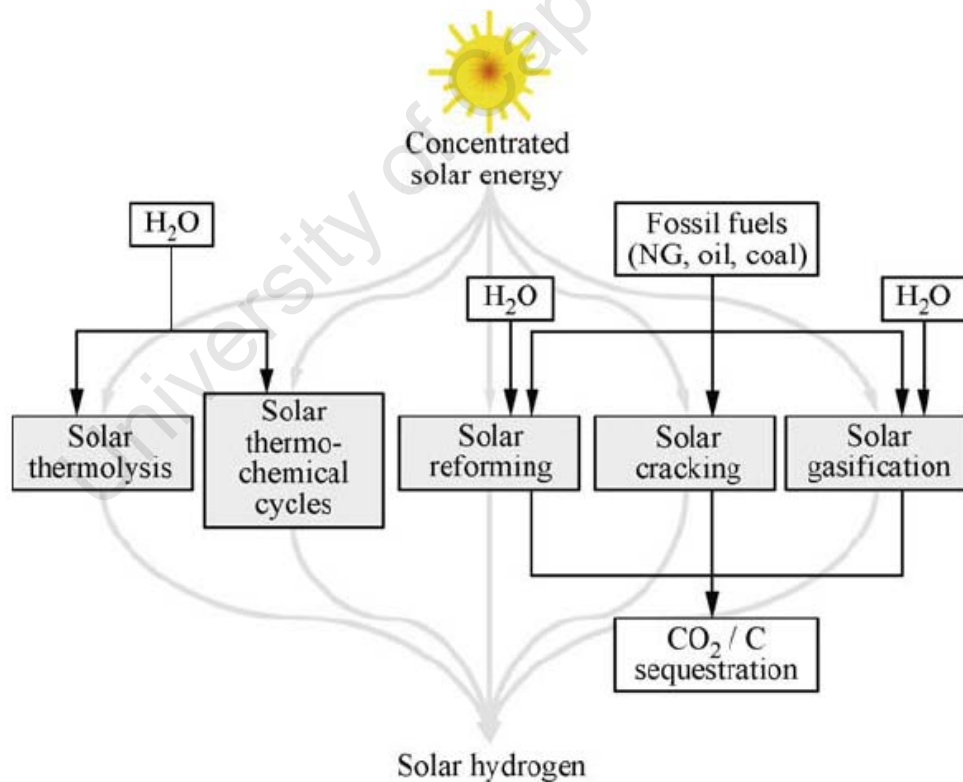


Figure 5.3.12: Schematic diagram of solar energy conversion into hydrogen. Source: (Steinfeld, 2004)

Solar Metals: Metals, which would seem strange as a source of energy, are actually an attractive method for the storage of energy as the metallic bonds release a large amount of energy when broken. The metals can either be

combusted to generate high temperature heat or via fuel cell and batteries, mentioned in the previous sections, to directly generate electricity. The by-products of these processes are the formation of metal oxides which need to be recycled. This is traditionally done by energy intensive carbothermic and electrolytic reactions which are associated with high environmental pollution (Chen, 2009). These issues however, can be dramatically reduced by the use of concentrated solar energy as the heat source (Steinfeld, 2004). The most promising of the solar metals is the dissociation of Zinc-oxide, ZnO , as a relatively low heat source is needed for the reduction reaction into zinc (Wieckert, 2007).

Solar Chemical Heat Pipe: Involves a high temperature heat to power an endothermic, reversible reaction in a chemical reactor where concentrated solar energy is the heat source. The benefit over hydrogen is that the product can be easily stored and transported over long distances to where it is needed as a heat source. The product goes through an exothermic reaction where the heat yielded is equal to the heat required in creation. The by-product is then returned to the solar reactor where the process is repeated. Two products are being thoroughly investigated which are methane, CH_4 being reformed by methanation, and NH_3 by dissociation synthesis (Lovegrove, 1999).

5.3.1.4 Thermal Energy Storage

Thermal energy storage (TES) is of particular interest to CSP as it allows the thermal energy concentrated in the CSP system to be directly stored as thermal energy without the need to convert it to another energy form. The thermal energy is stored in insulated containers and is recovered through a heat engine which generates electricity. There are a couple of low temperature TES technologies which are either being utilized or under development. These include: Aquiferous low temperature thermal energy storage (AL-TES) where water is frozen by a refrigeration cycle during off peak periods and stored for the cooling requirements of industry during peak times. Cryogenic Energy Storage (CES) is another form of low temperature energy storage and is currently under development. It works by generating liquid nitrogen during off peak periods or renewable power which is stored in an insulated container. During peak demand, the ambient outside temperature boils the liquid nitrogen which is passed through a cryogenic heat engine from which electricity is generated.

Of greater interest to CSP storage however, is High Temperature Thermal Energy Storage (HT-TES). There are five main technologies under research and development. (I) Molten Salt Storage represents the most mature of the technologies and is currently being utilized in various small scale CSP plants around the world. (II) Concrete Storage uses the thermal properties of concrete to store and release the energy when required and is currently under prototype development. (III) Saturated water Thermal storage, a non salt solution, is being utilized in PS10 in Spain. (IV) Graphite blocks are the fourth method of HT-TES and are being used in Cloncurry in Australia. (V) Phase Change Materials represent the final major thermal energy storage option under research. Due to their infancy, results and properties on some of these new thermal storage options are very limited and thus direct comparisons are problematic.

1) Molten Salt Storage

The most matured and well known variant on the molten salt storage platform is the indirect thermal energy storage technique which utilizes a molten potassium and sodium nitrate salt in two separate hot and cold storage tanks. The heated, heat transfer fluid from the solar collector transfers its thermal energy to the salt from the cold tank which is transported to hot tank. The heated salt is then passed through an exchanger, where it heats the oil which is used to create steam for electricity generation, following which it is transferred back to the cold tank (Palgrave, 2008). This system is called the indirect method as the heat transfer fluid for storage is different from the heat transfer fluid in the collector. The molten salt is comprised of a ratio of 60% sodium nitrate and 40% potassium nitrate and is generally called saltpetre (Sandia, 2006). Benefits with the molten salt include it is non-toxic, non flammable and experience exists as it is used in the chemical and metal industries (Sandia, 2006). The salt changes phase into liquid at 221 °C, is kept as a liquid in the cold storage tank at 288 °C, is heated to 566 °C by the collector and is stored in the insulated, hot storage tank (Sandia, 2006). A 100MW plant with 4 hours storage would need tanks of approximately 9 meters in height and 24 meters in diameter or a cubic capacity of 4072m³ (Sandia, 2006). The Andasol 1 plant, which is based on the parabolic trough system, uses this method to power its 50MW turbine for 7.5 hours after sunset and requires 28 000 tons of salt (Palgrave, 2008).

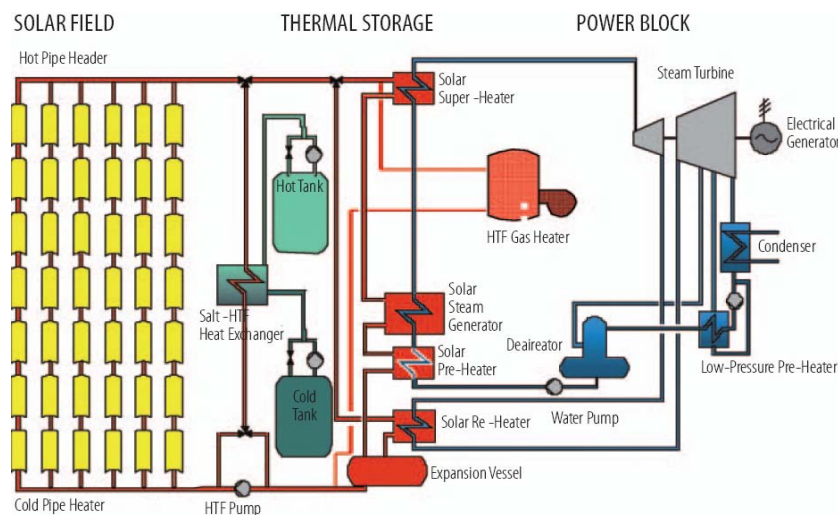


Figure 5.32: Schematic of a trough power plant with molten salt thermal storage. Source: (EC, 2007)

The Central Receiver Tower concepts have an advantage to the indirect method as it is possible to have the heat transfer fluid as the molten salt itself. By heating the salt medium directly instead of using oil and expensive heat exchangers allows greater efficiency and lower capital costs. This is due to the fact that synthetic heat transfer oils have a limit of 400° C where as salts can be heated safely up to 570 ° C (Palgrave, 2008).

With this greater difference in temperature (i.e. approximately 300°C compared to 130° C) between the cold storage tank and the hot storage tank, less heat transfer fluid/storage salt medium is needed for the same return on energy (Palgrave, 2008). Abengoa Solar and Sener are both companies in Spain performing tests on this storage and plant setup.

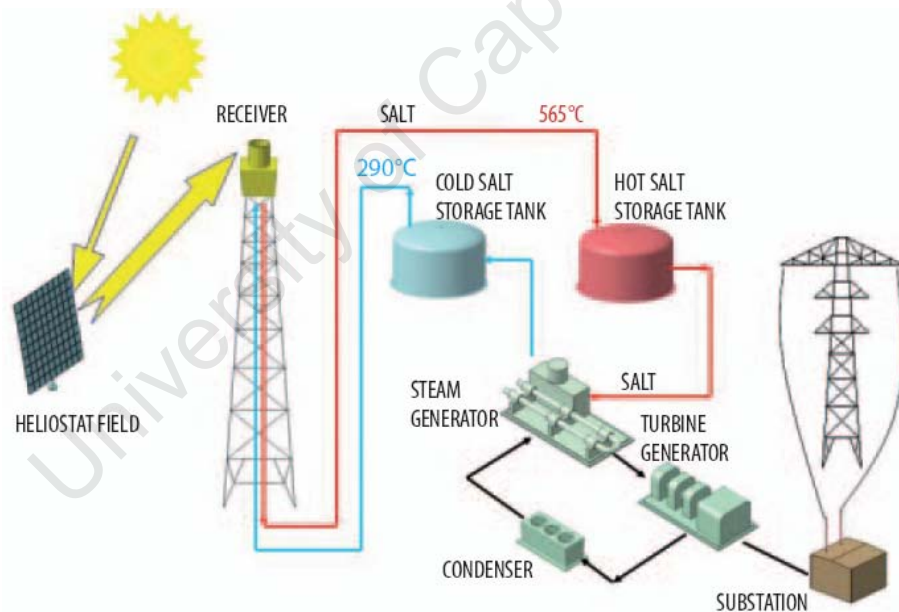


Figure 5.3.14: Schematic of a Central Receiver plant with molten salt thermal storage. Source: (EC, 2007)

The two tank direct method, where the heat transfer fluid is also the storage medium, is the most mature and advanced thermal energy storage option for CSP plants (Herrmann, 2004). The cost of two tank molten salt storage is in the range of \$30 to \$40 US dollar per kWh (Thermal) (Herrmann, 2004).

A method which further reduces the cost of the two tank storage system is the single tank, thermocline storage system. This system uses a one tank which contains the hot fluid at the top and gradients in temperature down to the coldest at the bottom of the tank (NREL, 2009).

An additional advantage of the thermocline system is that most of the volume of the storage vessel can be replaced by a filler material which possesses better thermal properties and has a lower cost than the heat transfer fluid. The research institute of Sandia National Laboratories has developed a 2.5MWh backed bed thermocline system which utilizes a binary molten salt heat transfer fluid with quartzite rock and sand as the filler materials (NREL, 2009).

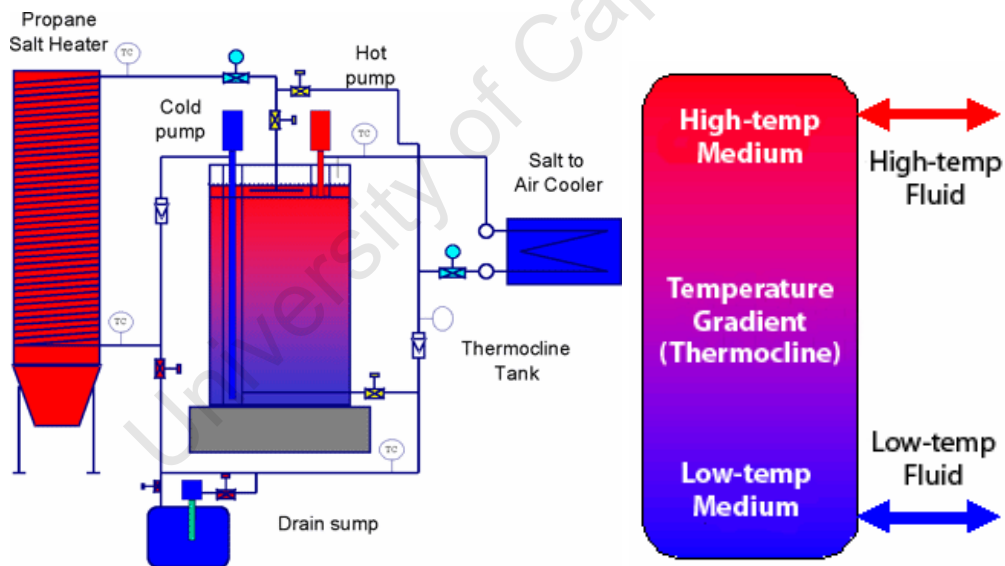


Figure 5.3.15: Thermocline test system at Sandia National Laboratories. Source: (NREL, 2009)

II) Concrete Storage

Concrete storage has been investigated in some European trough projects. The concrete, or castable ceramic, stores the high thermal energy which is transferred from oil as the heat transfer fluid. The standard heat transfer fluid from the trough field is passed through an array of pipes which are imbedded in the solid concrete or ceramic medium which transfers the thermal energy (Palgrave, 2008). Numbers for efficiencies of the technology are not yet available. Both the materials, castable ceramic and high temperature concrete have been tested to be suitable as a heat storage system however, high temperature concrete has the advantages of being lower in cost, greater strength and ease of handling (Laing, 2006). The systems are modular and scalable to 1000MWh or a 100MW plant running for 10hours and a HTF rating of up to 400 / 500°C (DLR, 2008). The introduction of these systems is said to be realizable within 5 years or less (Chen, 2009). The main advantages of these systems are their low cost of the solid mediums when compared to the molten salt solution (Palgrave, 2008). Issues however, include maintaining a good contact between the concrete and the fluid piping, this lowers the efficiency of the system, and maintaining the heat transfer rates entering and exiting the storage medium (NREL, 2009).



Figure 5.3.16: Pilot scale concrete storage system. Source: (DLR, 2008)

III) Direct Steam Thermal Storage

A direct steam thermal storage system or saturated water thermal storage operates by diverting some of the steam generated at the top of the tower during full load into the thermal storage system. The storage system comprises of four tanks which are sequentially operated, depending on their relevant charge status.

When energy is needed during cloudy periods, the energy is recovered from the saturated water at 20 bar which is able to drive the turbine at 50% load (Palgrave, 2008). This simple system is used in the PS10 central receiver plant in Seville Spain which has an energy content of 20MWh lasting 50min at 50% load (EC, 2007; Palgrave, 2008). The PS10 system is made up of four insulated storage tanks that are operated in a sequential order in reference to their charge status. During operation under full load, a percentage of the 250°C, 40 bar steam produced is diverted to load the thermal storage system. When a transient or cloudy period arises, energy is recovered from the saturated storage water at 20 bar which can run the turbine at 50% load for 50min. Steam accumulators are only economic as a buffer storage (DLR, 2008)

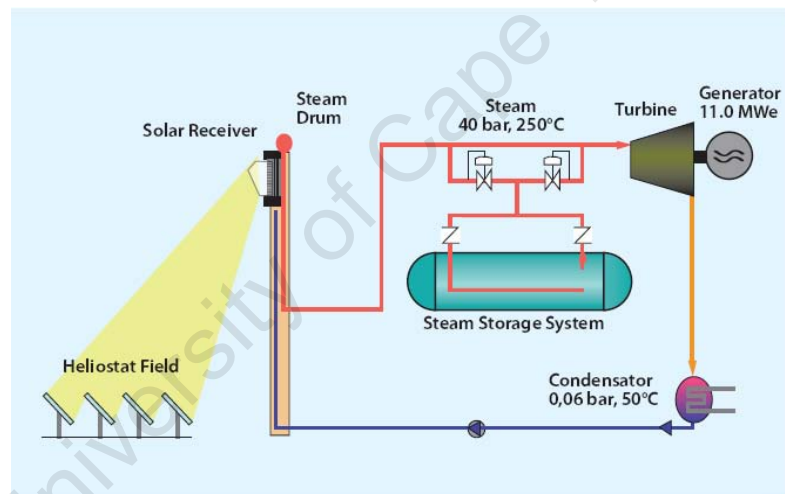


Figure 5.3.17: Schematic diagram of the saturated steam storage system. Source: (EC, 2007)



Figure 5.3.18: The four storage tanks of the ps10 plant. Source: (Solarpaces, 2008)

IV) Graphite Storage

A 10MW central receiver plant in Cloncurry in Queensland, Australia is using graphite blocks at the focal point of the central receiver field. Steam is generated by running water through pipes which are encased in the 540 tons of graphite (Palgrave, 2008). The thermal capacity of the graphite is said to run the turbine at full capacity for 8 hours and will come online early 2010 (Palgrave, 2008). The plant will comprise of 54 energy storage towers at 17 meters in height and have approximately 8 000 mirrors or 60 000m² to concentrate the sunlight onto the graphite blocks (Lloyd, 2008). Each of the storage towers holds 10 tons of the graphite material which totals 540 tons giving the system 8 hours of storage at 10MW of power or 80 000kWh's electrical (Lloyd, 2008). Water is then pumped through the blocks which generate steam which is injected into turbines to generate electricity.

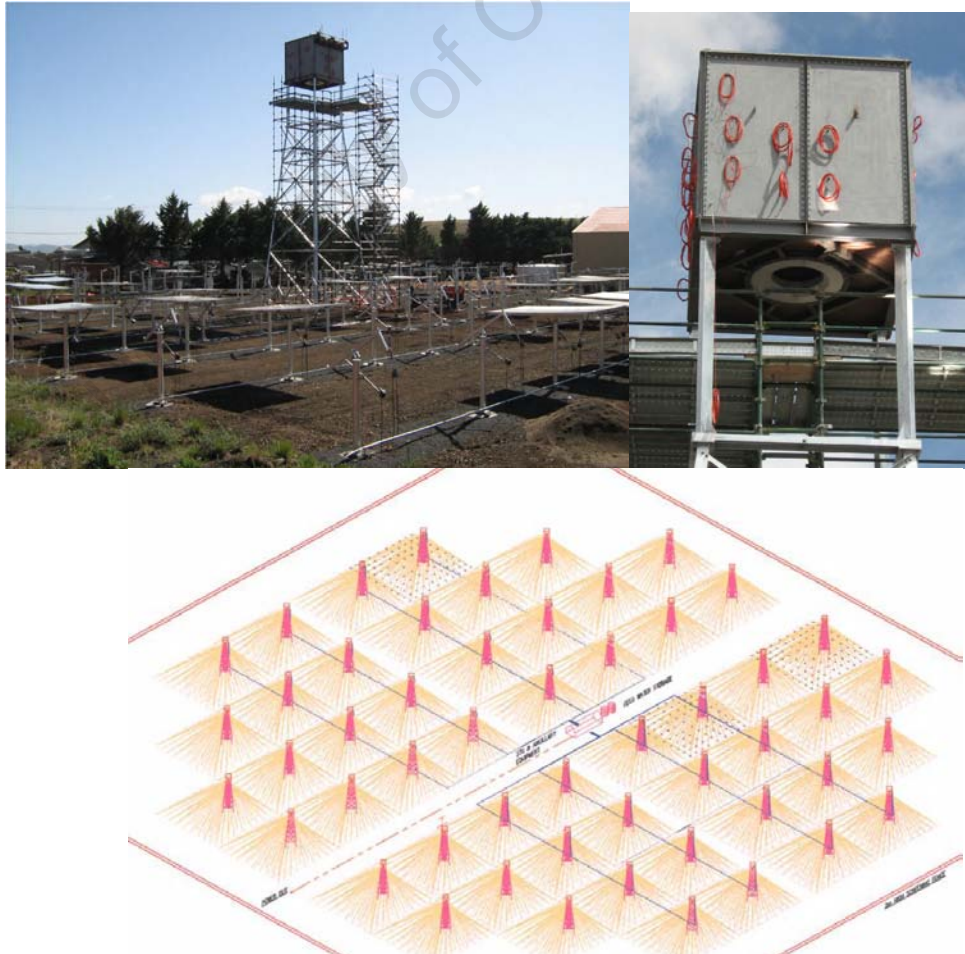


Figure 5.38: The graphite thermal energy storage prototype in Cloncurry Australia. Source: (Lloyd, 2008)

V) Phase Change Materials

Phase Change Materials (PCM's) have been considered to be a good candidate for trough plants that utilize direct steam generation (Palgrave, 2008). The phase change material is selected to have its phase change match the thermal input source, usually from a solid to liquid (Chen, 2009). Phase change can offer a high latent heat meaning higher energy density of the storage system than conventional storage forms. Two main methods are under development, firstly by embedding the PCM in a matrix of expanded graphite or a highly thermal conductive solid and secondly by microencapsulating small amounts of the phase change material in a matrix of expanded graphite (EC, 2007; Chen, 2009).

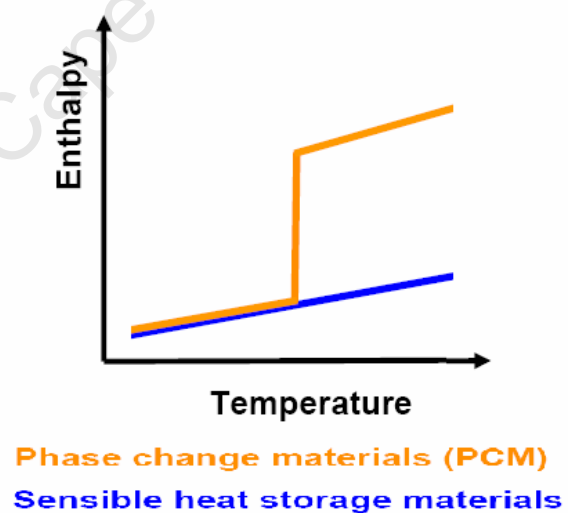


Figure 5.3.20: Phase change Pilot salt storage exchanger. Source: (Muller- Steinhagen, 2008; Bauer 2006)

The Distor project is focussing their research on phase change materials to produce a more efficient form of energy storage (EC, 2007). Their research is based on the microencapsulation of PCM in an expanded graphite matrix and aims to select the most efficient form of heat transfer energy storage and demonstrate the projects feasibility through a 100kW prototype module (EC, 2007).

Phase Change materials' main advantage is that they allow a large amount of energy to be stored in a relatively small volume allowing some of the lowest storage media costs out of the storage concepts (NREL, 2009)

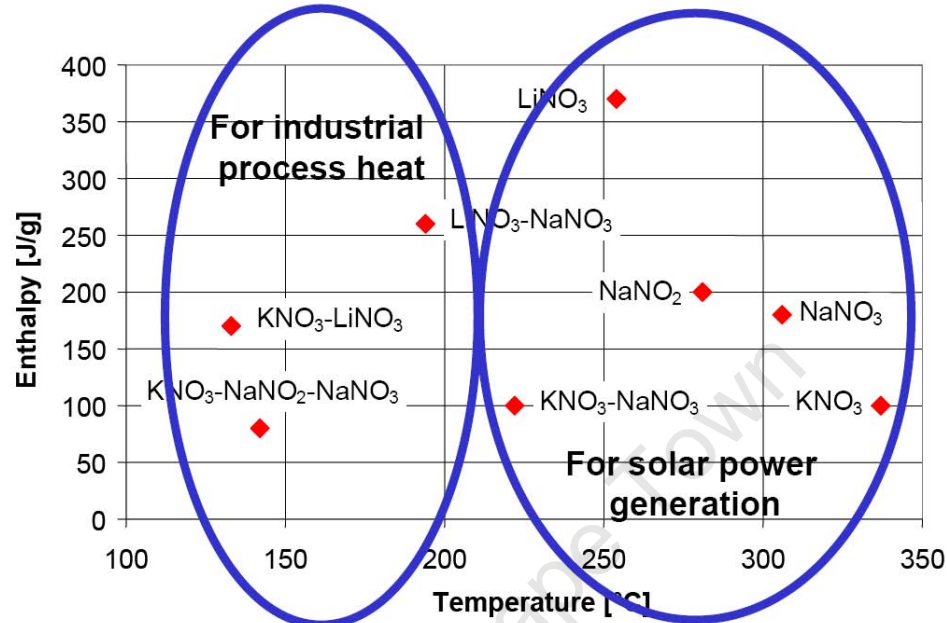


Figure 5.3.21: Selection of phase change materials and their properties. Source: (DLR, 2008)

A final theory for thermal storage, which is fundamentally different from the above, has come from Professor Reuel Shinnar of New York's Clean Fuel Institute. His theory is based on the principle that the thermal efficiency of the power plant rises, the operating temperature rises and the cost of the power produced decreases (Palgrave, 2008). CSP plants can operate at much higher temperatures however, the heat transfer fluids are restricting these temperatures. His concept utilizes pressurized gas, possibly CO_2 , as the heat transfer fluid which flows from the collector through storage, directly to the power plant. The pressurized gas has no thermal limit, as is the case with other thermal transfer fluids, and will pass through a storage container of Alumina pebbles which can function at temperatures up to 1 650°C (Palgrave, 2008). This storage design, he claims, will cost 3 to 10 times less than the molten salt method due to the higher thermal efficiency and greater temperature difference (Palgrave, 2008).

5.3.2 COMPARISON OF ENERGY STORAGE TECHNOLOGIES

As mentioned before, a comparison of the various energy storage technologies is difficult when the technologies are at different points of their respective maturities. Comparing a mature technology, such as pumped hydro electric which has almost 100 years experience, to a thermal energy storage option, such as the prototype graphite plant, will not yield any quantitative results that are of particular use for the South African issue. Thus the question of “*what storage technology is required in the large scale implementation of CSP in South Africa*” needs to be broken down and defined to more specific conditions. An initial analysis of: “*What are the immediate energy storage options for the first gigawatt or 5 years of CSP?*” followed by a broader long term question of “*what are the most promising future energy storage technologies*” is more informative. Additionally this approach does not rule out the possibility of future breakthroughs or the possibility of leapfrogging certain technologies. To begin this selective process, certain criteria and constraints need to be stated which will allow the comparative process to rule out unsuitable options.

5.3.2.1 Criteria for energy storage compatibility

- 1) **Size:** The standard capacity of a CSP plant taken in this dissertation analysis is 100MW, plants decrease in Rand's/kW capacity when plants increase in capacity from 10MW to 200MW and as such the storage capacity is required to have the ability to be up scaled to these sizes.
- 2) **Storage duration:** According to the South African Renewable Energy Feed In Tariff (REFIT), for a CSP plant to be eligible for this tariff of R2.10 / kWh, it needs to have at least 6 hours of storage (NERSA, 2009) (See appendix A1).

- 3) **Geographic conditions:** Some energy storage technologies require specific geographic conditions of which the general Upington / Northern Cape region needs to possess.
- 4) **Maturity:** The maturity of the technology is important for cost stability, reliability and security of supply for the initial uptake of the plants to be successful.
- 5) **Cost:** Finally the relative cost of the technology is of particular importance as it will either allow or disallow the economic viability of the plant as a whole

5.3.2.2 Storage Technology Selection for Immediate applications

To comply with the first restriction the various storage technologies capacities and storage durations was investigated. Pumped hydro electric's capacities range from 100MW to over 5 000MW and are thus suited for the standard 100MW plant (Chen, 2009). Compressed air storage has capacities of between 5 and 300MW, batteries of lead acid and Nickel Cadmium has capacities of between 0 and 20MW and 0 and 40MW (Chen, 2009). Fuel Cells have capacities of between 0 and 50MW and solar fuels between 0 and 10MW (Chen, 2009). Super conducting magnetic energy storage has a range from 100kW to 10MW (Chen, 2009). Finally the various thermal energy storage technologies vary drastically in capacity from a couple kW's to 10's of MW. This is due to the prototype phases some of the technologies are going through however, the most mature thermal technology is the molten salt method whose capacity ranges from 0 to 60MW followed by Cryogenic Energy Storage whose capacity is between 100kW's and 300MW (Chen, 2009). Various energy storage technologies have been unable to handle these capacities and have subsequently been eliminated from the options. These technologies are more suited for power quality control and reliability security and include: Zebra Batteries and Lithium Ion batteries,

capacitors and super capacitors and flywheels. Thus the technologies of pumped hydro, compressed air, batteries of lead acid and nickel cadmium, fuel cells, solar fuels, molten salt, and the other thermal energy storage technologies, all comply with the first constraint of the 100MW capacity CSP plant size.

To comply with the second criteria of the REFIT, 6 hours of energy storage is needed to allow the approval of the plant. Failing this is superconducting magnetic energy storage, flywheels, capacitors and super-capacitors all with storage capacities of only milliseconds to minutes. This has left pumped hydro electric storage, compressed air energy storage, large scale batteries, fuel cells, solar fuels and the thermal energy storage technologies as the remaining options.

The third criteria for CSP storage is suitable geographic conditions which are imperative to pumped hydro electric storage, which requires two reservoirs of appropriate height and distance between them, and compressed air energy storage, which requires very large underground formations that are too vast in scale to be economically viable. The research conducted in this dissertation did not yield any suitable reservoir locations for pumped hydro storage nor did it find any depleted gas fields, salt caverns or aquifers. The possibility however, of these conditions should not be ruled out as the scope of this dissertation cannot perform an in-depth analysis for these geographic formations and as such pumped hydro electric will remain in the comparison for reference but not specified as an option. Compressed air however, can be ruled out due to the REFIT (Appendix A) not specifying whether hybridization of the CSP plant is encompassed and thus compressed air energy storage requires a gas turbine to function. This is not a technology reason for elimination but rather a national policy clause rendering the technology unsuitable.

The fourth constraint stated in the beginning of this comparative analysis was the property of technical maturity. This property indicates the stability of the technology in terms of performance development, cost reductions and how far it is along the learning curve. In essence the maturity scale shows the risk involved in investing in a particular technology, mature technologies have a lower risk whereas developing technologies may have large performance improvements, reliability issues or cost reductions in the near future thus a large investment could mean high costs or substandard performance. The maturity can be divided into three criteria namely:

- I) Commercial mature
- II) Near commercially mature
- III) Greater than 10 year development required

The following graph indicates some of the technologies discussed and their relevant maturity:

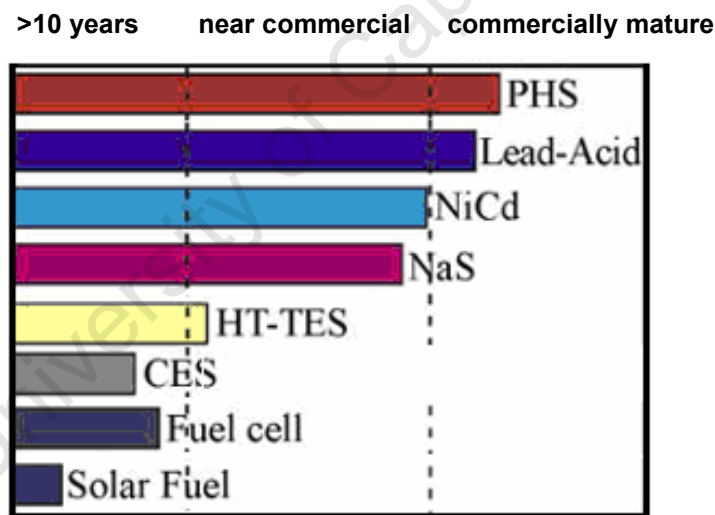


Figure 5.3.22: The relevant technical maturity of the remaining storage options for immediate utilization. Graph modified from original. Source: (Chen, 2009)

Pumped hydro electric storage and lead acid batteries are the most mature and fall under commercially mature. Nickel cadmium and sodium sulphide batteries are close reaching maturity and are currently high up on the developed scale, falling just under commercially mature. Rounding off the near commercially mature technologies is high temperature thermal energy storage which in this case refers to the most mature of the thermal technologies, molten salt. Fuel cells, cryogenic energy storage and

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solar fuels are still in the developing stage and have deemed to be an unwise investment for the immediate requirement of CSP storage however, future developments may yield these technologies superior and therefore will be included in the future predictions scenario where energy costs and environmental concerns take heavy preference (Chen, 2009).

Finally the fifth constraint which is arguably the most important property of these technologies, is the issue of cost. Capital cost, levelized energy costs and running cost are the main factor in which the economists decide whether the technology is feasible and in essence whether the plant is feasible. Cost estimates for mature technologies are fairly accurate and are thus easy to compare, however cost estimates for developing and developed technologies are either unavailable or vary drastically from source to source. The following table is the most up to date:

Table 5.9: Table of the relevant storage technologies, their capacity range, their associated costs, Life time and cycle life and their influence on the environment. Source: (Chen, 2009)

Comparison of technical characteristics of EES systems.

Systems	Power rating	Capital cost			Life time and cycle life		Influence on environment	
	Power rating	\$/kW	\$/kWh	¢/kWh-Per cycle	Life time (years)	Cycle life (cycles)	Influence	Description
PHS	100–5000 MW	600–2000	5–100	0.1–1.4	40–60		Negative	Destruction of trees and green land for building the reservoirs
CAES	5–300 MW	400–800	2–50	2–4	20–40		Negative	Emissions from combustion of natural gas
Lead-acid	0–20 MW	300–600	200–400	20–100	5–15	500–1000	Negative	Toxic remains
NiCd	0–40 MW	500–1500	800–1500	20–100	10–20	2000–2500		
NaS	50 kW–8 MW	1000–3000	300–500	8–20	10–15	2500		
Li-ion	0–100 kW	1200–4000	600–2500	15–100	5–15	1000–10,000+		
Fuel cells	0–50 MW	10,000+		6000–20,000	5–15	1000+	Negative	Remains and/or combustion of fossil fuel
PSB	1–15 MW	700–2500	150–1000	5–80	10–15			
Solar fuel	0–10 MW	–	–	–	–	–	Benign	Usage and storage of solar energy
SMES	100 kW–10 MW	200–300	1000–10,000		20+	100,000+	Negative	Strong magnetic fields
Flywheel	0–250 kW	250–350	1000–5000	3–25	~15	20,000+	Almost none	
Capacitor	0–50 kW	200–400	500–1000		~5	50,000+	Small	Little amount of remains
Super-capacitor	0–300 kW	100–300	300–2000	2–20	500–5000			100,000+
AL-TES	0–5 MW		20–50		10–20		Small	
CES	100 kW–300 MW	200–300	3–30	2–4	20–40		Positive	Removing contaminates during air liquefaction (Charge)
HT-TES	0–60 MW		30–60		5–15		Small	

➔ Note the massive running costs per cycle of the various batteries, fuel cells and other storage technologies. From this table it is clear that pumped hydro, compressed air and thermal storage are the most economic options.

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These results yield the following graph which clearly shows the cost benefits of molten salt and pumped hydro storage over the battery options. Additionally it should be noted that if compressed air energy storage was an option, its cost per kWh range is the lowest of all the technologies.

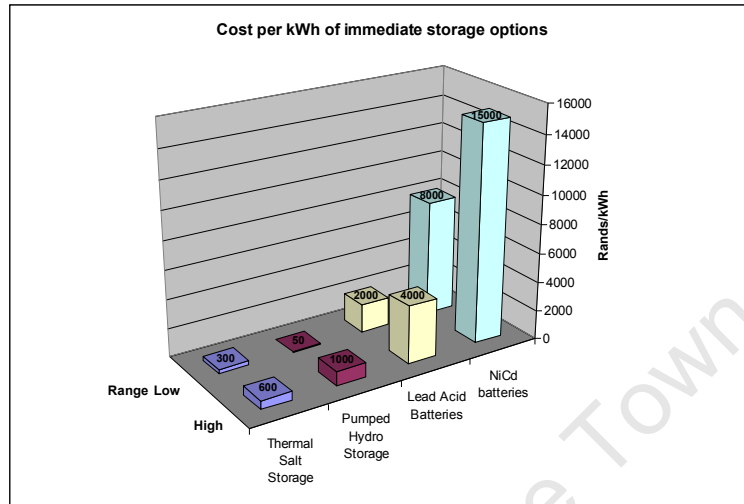


Figure 5.3.23: Graph indicating the cost per kWh of the various applicable technologies. All the cost estimates have taken into account the relevant storage efficiency of the specific technology to give a cost per output of useful energy. The per cycle costs are said to be the best evaluation of the relevant cost of energy storage however data for thermal storage technologies is unavailable so no comparison could be made. The following table shows a detailed breakdown of the associated costs in the varying storage capacities of Molten Salt storage along with the percentage of each system.

Table 5.10: Table of the varying capacity storage costs for 50 MWmolten salt components. Source: (Herrmann, 2004)

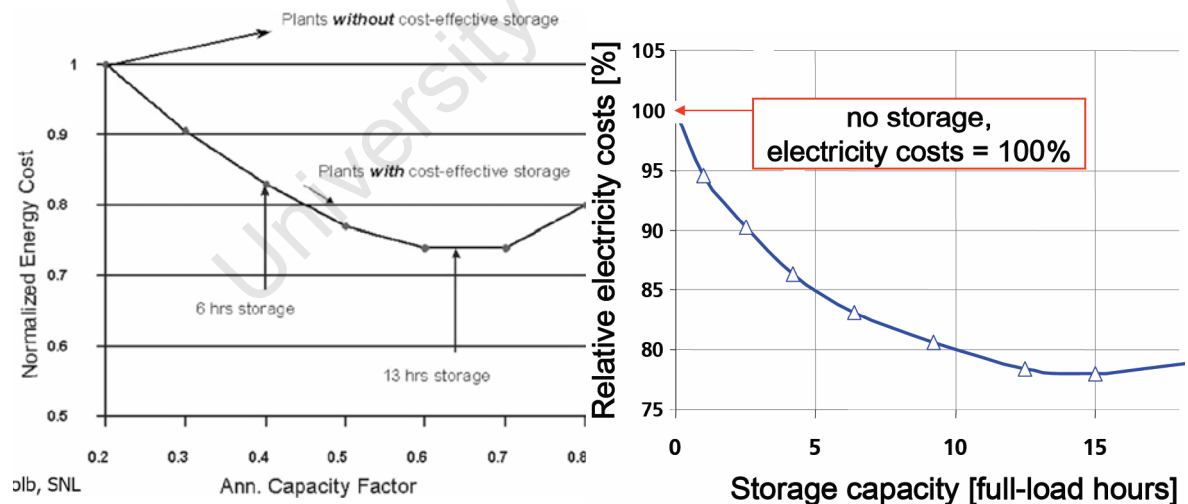
Item	Storage Capacity and percentage of total cost in Million Rands											
	1 hour		3 hours		6 hours		9 hours		12 hours		15hours	
Salt inventory	R 18	23%	R 52	38%	R 104	46%	R 156	48%	R 208	47%	R 260	48%
Storage Tanks	R 7	9%	R 19	14%	R 37	16%	R 55	17%	R 74	17%	R 92	17%
Tank insulation	R 2	3%	R 5	4%	R 8	3%	R 10	3%	R 16	4%	R 18	3%
Tank Foundation	R 4	5%	R 8	6%	R 13	6%	R 18	6%	R 26	6%	R 31	6%
Salt pumps	R 34	44%	R 34	25%	R 34	15%	R 44	13%	R 59	13%	R 74	14%
Heat exchanger	R 6	7%	R 6	5%	R 11	5%	R 13	4%	R 17	4%	R 21	4%
BOS	R 7	9%	R 12	9%	R 21	9%	R 30	9%	R 40	9%	R 50	9%
Total	R 77		R 137		R 228		R 326		R 439		R 546	

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From this table it can be noted that the majority of the molten salt storage solutions cost come from the actual salt inventory followed by the storage tanks and then the salt pumps. It should be noted that when increasing storage capacity, the large capital cost of the salt pumps gets relatively less compared to the other system components. The actual salt relative costs increase at a predictable linear rate while the storage tanks relative cost increases at a much lower rate.

From these figures it can be deduced that it is more economically viable, on a capital component verse storage duration perspective, with the added benefit of increasing capacity factor, to increase the storage duration size.

The minimum 6 hour duration of the storage, set out in the REFIT, is not the most optimum length of storage time for Molten Salt in terms of normalized energy costs. The most optimum storage duration is between 13 and 15 hours as indicated by two independent studies shown below



Figures 5.3.24: Optimum storage durations for Molten Salt as calculated by two independent studies between 13 and 15 hours. Source: (Jones, 2004; Muller-Steinhagen, 2008)

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In concluding this section the following summary table show a numeric rating comparison of the various storage technologies for the immediate implementation into CSP plants in South Africa:

Table 5.11: Summary table indicating the various requirements for immediate, large scale CSP storage and the performance of each storage technology

Technology	Key Requirements (5 = good, 1 = poor, 0 = fail, U = unknown)						
	Size	Duration	Geography	Maturity	Cost	Efficiency	Total (30)
Superconducting	3	0	5	3	1	5	Fail
Supercapcitors	0	3	5	3	2	5	Fail
Flywheel	1	0	5	4	1	5	Fail
Pumped Hydro	5	5	U	5	4	4	Unknown
Compressed Air	5	5	U	4	5	4	Unknown
Batteries (Lead, NiCd)	3	4	5	5	2	4	23
Fuel Cells	4	4	5	2	0	2	Fail
Flow Batteries	3	4	5	3	U	4	Unknown
Solar Fuels	3	5	3	1	U	1	Unknown
Molten Salt	5	5	5	3	5	3	26
Concrete	4	4	5	2	5	U	Unknown
Direct Steam	3	2	5	2	4	U	Unknown
Graphite	4	5	5	2	4	U	Unknown
Phase change	4	4	5	2	4	U	Unknown

It should be noted that data made in this estimate is preliminary and can significantly change depending on breakthroughs in the technologies, construction duration, location of the storage plant, and the total capacity of the system. Although there are various available commercial energy storage systems, no single system meets the ideal requirements of being mature, long life, low cost, high efficiency and benign environmentally. It is the finding of this paper however, that the most effective form of storage for the immediate deployment of CSP plants is the molten Salt method.

5.3.2.3 Storage Technology Options for Future Large Scale CSP Infrastructure

The second part of this comparison aims to predict which storage technologies are going to be available and suitable for large scale CSP plants in the future. Projections on future technology trends are difficult and uncertain as a wide variety of variables can come into the equation that can drastically influence the direction of storage as a whole. These variables include current technology breakthroughs, completely new technology breakthroughs, policy alterations, cost fluctuations in materials, unforeseen environmental impacts etc.

For this analysis a similar set of criteria needs to be drawn up. Maturity is not an issue by definition but rather a progression scale of what is suitable for the first 10 years, 25 years and 50 years.

- Storage capacities are again important as the optimum size of a plant is said to lie somewhere between 50MW and 400MW therefore the storage technology needs to be scalable to this size (Taggart, 2008).

The cost reductions of increasing plant size are shown by the graph below:

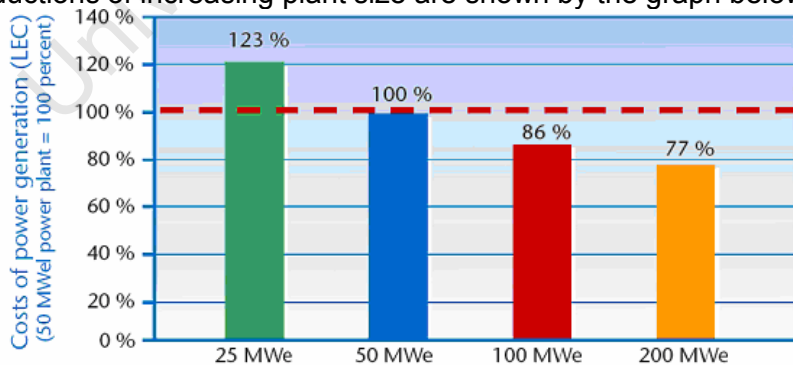


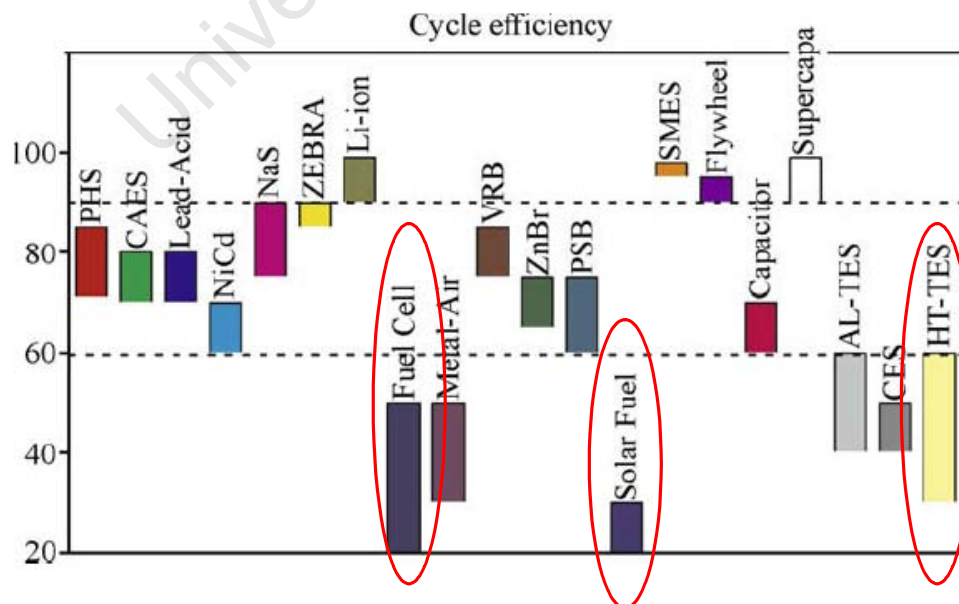
Figure 5.3.25: Power plant sizes relative cost, lowest at 200MW (Source: Schott, 2004)

- Reliability and affordability become ever increasingly important as scale increases.
- Storage duration is again important as the larger scale of CSP installed, the higher its load/capacity factor needs to be. This is to keep the grid stable, security of

supply, as the base load power generation shifts away from coal to more emphases on CSP.

- Pumped Hydro electric storage and compressed air energy storage have been ruled out as large scale storage options for 10+GW. This is due to the fact they require specific geographic conditions near the point of generation and as of yet, no small scale, ~100MW options have been identified.
- Environmental impact of the technologies will become of greater concern as the scale of the storage increases and full life cycle assessments need to be taken into account.
- Finally, efficiency will play a bigger role as maximising the energy collected and converted, allows more electricity to be generated from the single plants.

The cycle efficiency is the roundtrip efficiency of the system, defined as energy out divided by energy in. There is a trade off between capital cost and round trip efficiency where a storage technology with a low capital cost and low efficiency may be more competitive than a high cost and high efficiency technology. The following table represents the current effective efficiencies of a couple of the storage technologies and where their future efficiencies are likely to lie:



Figures 5.3.26: Graphical representation of some energy storage technology efficiencies from current efficiencies to projected efficiencies (Chen, 2009)

The list of foreseeable future storage technologies into the next 50 years is as follows:

- ✓ Molten salt
- ✓ Large scale batteries
- ✓ Fuel cells and hydrogen
- ✓ Solar Fuels
- ✓ Concrete thermal storage
- ✓ Graphite thermal storage
- ✓ Saturated water
- ✓ Phase change materials
- ✓ Compressed gas with filler material

To comply with the first criteria of sizes, it is assumed that plants will now be built to the most cost effective sizes of 50 to 100MW in the initial 10 to 25 years and 200MW to 400MW from the 25 to 50 year timescale. For the initial 0 to 10 years, it is expected that molten salt will continue to dominate, however new salts, with better thermal and corrosion characteristics, are expected to become commercially viable (Angelino, 2008). Carbonate salts seem suitable for operating temperatures of up to 850°C and fluoride salts, which are free of water, exhibit excellent corrosion resistance with some standard metals and alloys, mild steel and pure nickel, at temperatures of 900°C (Angelino, 2008). Lithium fluoride operating at a temperature of 800°C and cycling of 250°C stores approximately 1025kJ/kg while molten salt between 550°C and 300°C only stores 387kJ/kg (Angelino, 2008). Lithium is currently expensive however there is said to be a vast amount of reserves if it was extracted from sea water, current estimates state 100tons of lithium exist in approximately 1km³ of sea water (Angelino, 2008).

Large scale batteries may have their place in other renewable storage options, i.e. wind, where the energy captured is immediately converted to electricity. However, for the case of CSP their negative influence on the environment and relatively small scale do not seem appropriate for large scale storage.

Fuel cells and the general hydrogen economy are still very early in their development stage which means there are still some major drawbacks that need to be addressed before large scale implementation. The biggest issue with hydrogen is the storage, the energy per unit volume is very low and the costs to handle highly compressed gas and cryogenic storage are prohibitively expensive (Bennett, 2008). Fuel cells are also still in development stages and are thus very expensive. Additionally the complete round trip efficiency of hydrogen is one of the lowest of all the energy storage options (Chen, 2009).

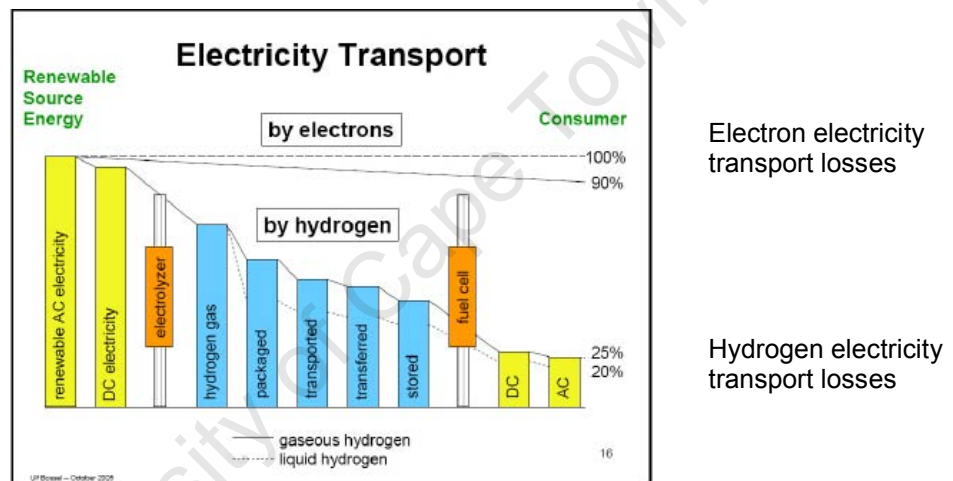


Figure 5.3.27: Losses associated with hydrogen storage and conversion into electricity. Source: (DLR, 2006)

Hydrogen's round trip efficiency is between 20 and 50% due the combination of the electrolyser's efficiency and the re-conversion efficiency back to electricity being low (Chen, 2009). The environmental benefits of the hydrogen fuel cell economy are great, and large scale storage of hydrogen gas in depleted gas or oil fields is said to be economically and technically feasible (Bennett, 2008). The safety issues are the major hindrance to its deployment which will take a long time to overcome, thus as an attractive proposition hydrogen is, there is much evolution the technology needs to undergo and therefore is most likely deployable in the 25 to 50 year timescale.

Solar fuels benign environmental effects are a major asset to the technology, additionally the roundtrip efficiency of the technology is low. However, the storage efficiency, as explained in the previous chapter, can come close to 100% making this

technology every attractive. The storage and transportation of the solar fuels is easy and with the development of batteries and fuel cells the technology is gaining popularity at a rapid rate. Limited information exists on actual prototype examples of solar metal fuels and solar chemical heat pipe but if the theory proves to be practically sound, this technology could provide a major solution in the next 25 years.

Concrete thermal storage has been proven on a small scale to offer a relatively low cost and high efficiency thermal storage solution, however small technical issues still exist which needs to be addressed to improve the reliability and life time of the technology. These issues include cracking and loss of mechanical resistance in the concrete matrix, gap formation between the concrete and tubes, heat exchanger rupture due to expansion and contraction cycles and heat exchanger failure due to corrosion (DLR, 2003). The technology is estimated to be achievable in the next 5 years, has a very low environmental impact and is scalable to any size required (Chen, 2009). These facts yield concrete thermal storage an attractive, low cost option, for the 10 year time scale.

Very little information is available on the graphite thermal storage technology but its said to be very efficient, has rapid heat conductivity properties, can be heated to 1800°C and requires very little water (Peak Energy, 2008). Graphite has two big advantages, firstly, carbon is very abundant and common, meaning it is a virtually limitless resource thus scale is not an issue, and secondly, its thermal property allows it to increase its storage capacity, as the operating temperature is increased (Peak Energy, 2008). At 1800°C it is able to store 1MWh thermal per ton of graphite. Ideally the graphite should be positioned at the focal point, thus being more favourable to the central receiver concept. The graphite storage technology possesses all the properties favourable for large scale implementation where maybe the Beam Down method might be more suited to avoid the large tower structure.

Further testing and prototypes will need to be done to assess the reliability which place this technology in the 10 to 25 year implementation period.

Saturated water or direct steam is not seen as a large scale option as its short duration capacity yields it uneconomical at large scales. This is due to the physical size of the storage vessels, the pressures they need to handle and the degradation of the steam quality during discharging (Peak Energy, 2008). This storage is rather suited as a buffer during cloudy periods and not as long scale storage provider. The utilization of an encapsulated phase change material in the storage vessel can however, increase the storage capacity significantly allowing the latent heat to reduce the rate of decrease in temperature and pressure. Further research is needed to prove the economics and reliability of this Phase Change Material concept but the direct steam technology is ready for commercialization.

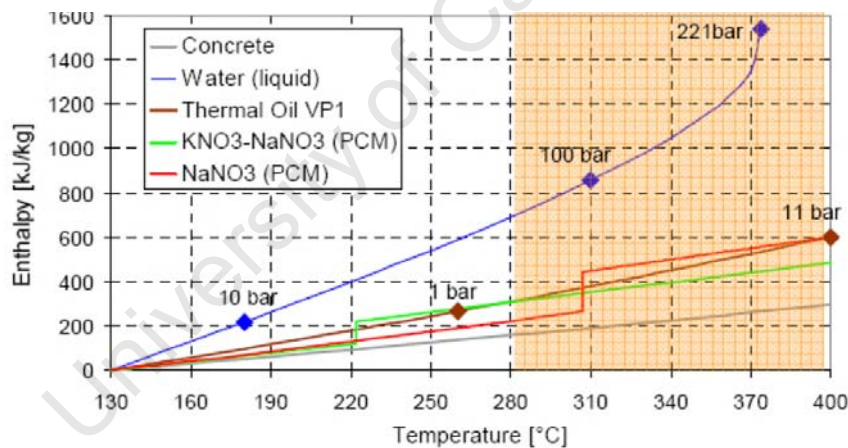


Figure 5.3.28: Relative enthalpy of various energy storage mediums (Source Dracker, 2008)

The final technology which presented itself as a viable option is the compressed gas or air with filler material in the storage vessel. This method significantly increases the working temperatures and thus the conversion rates and efficiencies offering a very cost effective storage option (Palgrave, 2008; IEA, 2008). Alumina pebbles are being assessed for the filler heat storage material in the storage vessel and development and implementation is said to be within ten years (Peak Energy, 2008).

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Table 5.12: Summary table indicating the various requirements for future, large scale CSP storage and the performance of each storage technology

Technology	Key Requirements (5 = good, 1 = poor, 0 = fail, U = unknown)						
	Size	Duration	Geography	Maturity	Cost	Efficiency	Total (30)
Superconducting	3	0	5	5	1	5	Fail
Supercapcitors	0	3	5	5	2	5	Fail
Flywheel	1	0	5	5	1	5	Fail
Pumped Hydro	5	5	U	5	4	4	Unknown
Compressed Air	5	5	U	5	5	4	Unknown
Batteries (Lead, NiCd)	3	4	5	5	2	4	23
Fuel Cells	4	4	5	5	0	2	Fail
Flow Batteries	3	4	5	5	3	4	24
Solar Fuels	3	5	5	5	3	3	25
Molten Salt	5	5	5	5	5	3	28
Concrete	4	4	5	5	5	4	27
Direct Steam	3	2	5	5	4	4	23
Graphite	4	5	5	5	4	4	28
Phase change	4	4	5	5	4	4	26

In concluding the future storage options, energy storage is a key issue to the successful, large scale implementation of CSP into South Africa's electricity supply. Steam accumulators are only economic as buffer storage and should not be viewed as large scale, high capacity options (DLR, 2008). Molten salt technology is available and proven, but further cost reductions are needed. Concrete storage technology is an attractive and simple, alternative but more, large scale demonstrating pilot plants are needed to fully assess the technology. PCM storage is the most promising technology for direct steam generation (DSG) plants, but again more research and pilot plants are needed (DLR, 2008). Continuous research and development effort is needed especially for higher process temperatures greater than 400°C and for further cost reduction (DLR, 2008). These comments, as stated before, are to serve only as a guide. Publications on energy storage technologies and in particular, high heat, thermal storage technologies, is very limited, thus opinions from energy specialists have been taken into consideration.

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The following graph is a graphic representation of the findings of this dissertation in terms of the possible availability of the various storage technologies for the large scale, long term, future implementation of CSP in South Africa. Conventional Potassium Sodium Nitrate along with various large scale batteries, are ready for immediate implementation due to their maturity. Saturated Water is already proven through steam storage but with phase change materials as filler materials, it should take some testing before introduction likewise for concrete thermal storage whose slight technical issues need to be solved before infiltration. Compressed gas or air systems using filler materials along with pure graphite thermal storage need more time to mature but both offer ideal properties for storage and can be seen as long term solutions. Improved salt storage is expected to take over where conventional left off which allows cheaper storage and improved efficiencies. Solar fuels and fuel cells with hydrogen production are long term options who offer not only solutions to electricity production but many other energy needs but major research and technical innovations are still needed before they can be fully integrated.

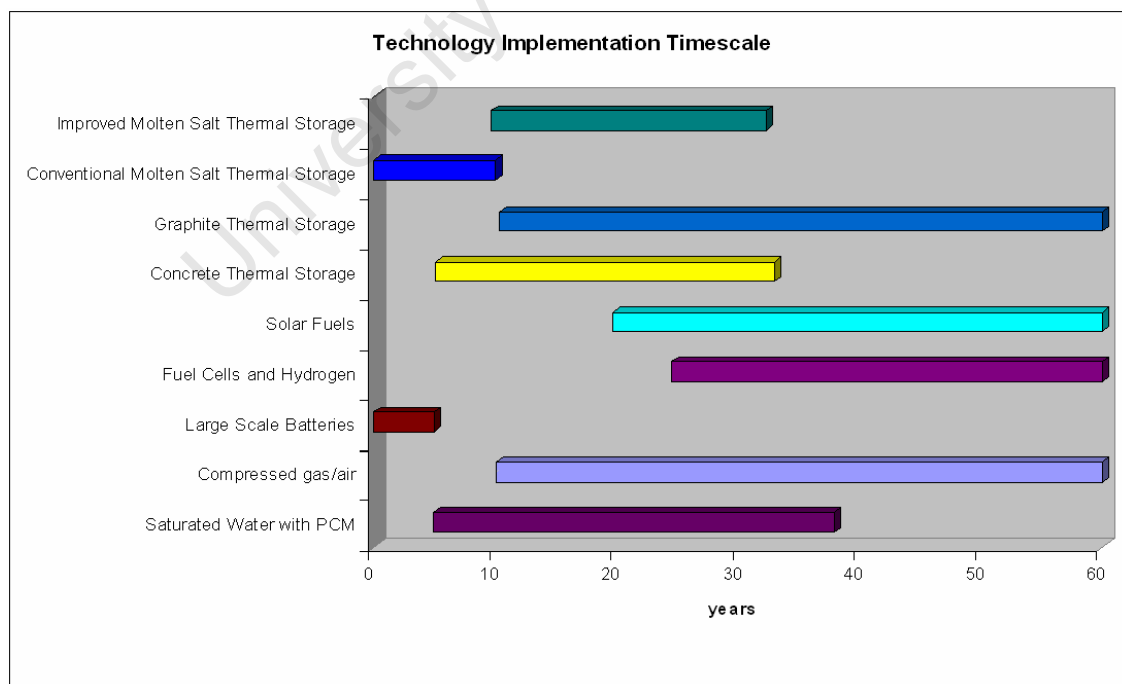


Figure 5.3.29: Graphic showing possible implementation timeline of the various storage technology options for large scale CSP in South Africa

5.4 CONCLUSIONS

In concluding, the geographical, infrastructure and storage requirements are summarised. In terms of the required geographical conditions for a large scale CSP infrastructure, it is clearly evident that South Africa is blessed with abundant solar radiation and available, open land in the Northern Cape region. The only foreseeable geographical barrier for is the limited water resources of the Northern Cape where 1GW of wet cooled CSP would consume the roughly the same quantity of water as the entire town of Upington. This presents a problem for the local farming communities and general ecological balance of the area, thus it is the recommendation of this dissertation that Dry Cooling should be a mandatory requirement once the initial pilot plants have proven concept.

One major infrastructural question that this dissertation aimed to answer is the transmission grid required to distribute the vast electricity capacity generated from the large scale CSP plants. The National transmission grid, its capacity, current state and planned development was assessed along with recommendations where planning is inadequate or non-existent. It was evident that initial start-up and pilot plants would require little additional infrastructure however the process of connecting to the national grid and the Power Purchase Agreements (PPA's) with Eskom were seen by many industry professionals, as a major barrier to CSP start-up. Based on this finding this dissertation recommends that this process be re-evaluated by government to become more transparent and user friendly to allow start-up CSP plants the security of demand, required by investments.

Minimal grid infrastructure was found to be needed for capacities of up to 500MW, if the additional 400KV planned lines are implemented. For around 1GW of CSP capacity, a 765KV HVAC line is recommended to extend from Upington to the Hydra

substation, where the planned 765KV HVAC line to Cape Town, begins. For CSP capacities above 2GW it was found that the stability of the “backbone” of the national grid could be compromised thus additional, high capacity lines would need be required to the key demand point sources. Cost and capacity analysis was performed on the HVAC and HVDC options and it became apparent that HVDC’s properties yielded it to be a superior choice in terms of capacity, losses, cost, land usage and appearance. What this analysis has shown is that current grid planning is becoming rapidly insufficient, if the required capacity route of at least 1GW CSP capacity per year, is taken.

The second major challenge that was projected to form a barrier to the large scale implementation of CSP was the technical issue of energy storage. It was evident that if South Africa were to rely on a large quantity of electricity to be generated from the intermittent source of solar energy, there needs to be a mechanism to match this intermittent source with the demand profile of the country. Various storage technologies were investigated, assessed and modelled against each other. This process drew out the options that were available for immediate to near term plants and which are suited to the South African conditions. Additionally it investigated where the research is heading and which technologies are showing promise in terms of efficiency, cost and ease of use from which informed decisions can be made on possible “leap frog” technologies. Molten Salt stood out as the obvious immediate choice due to its maturity. However, volumetric air/gas, concrete, graphite and phase change materials are all showing promise in pilot plants around the world therefore there does not appear, as of yet, to be a “silver bullet” solution. Out of a possible fourteen storage technologies this dissertation was able to highlight seven technologies for large scale CSP energy storage however, further observation and analysis is recommended to allow a fuller understanding of the implications and requirements of these advanced technologies.

6 REQUIREMENTS FOR A LOCAL CSP INDUSTRY AND ITS EMPLOYMENT POTENTIAL

The purpose of this chapter is to analyse the requirements to create a local industry and its potential to create employment if South Africa were to evolve towards a large focus on CSP. Employment potential is of particular interest to South Africa where the current unemployment rate for the first quarter of 2009 was 23.6% (Statistics South Africa, 2009). Additionally South Africa has a very strong manufacturing sector, which is being crippled by the current economic climate, and a switch in the direction of focus could inject new life to this sector. Eskom's feasibility study showed that up to 70% of an initial, locally built, 100MW, Central Receiver type plant, could be placed within the local industry (Van Heerden, 2008). This number can only increase if an industry is created to supply this infrastructure. This chapter will thus analyse what CSP needs from skills to materials to factories.

6.1 EMPLOYMENT POTENTIAL OF CSP

The economic downturn in 2008-09 should be viewed as an opportunity for South Africa and all countries to shift to a low carbon energy structure and economy, rather than seeing it as an barrier to change. The world wide economic slow-down may be causing job losses and businesses to collapse, but avoiding mitigation actions, to reduce climate change, would result in far greater hardships and costs to society in the long term. It would be reckless and irresponsible to divert back to a fossil fuel based economy as it will have to be abandoned in future anyway. South Africa should use this opportunity to redevelop its heavily carbon dependant infrastructure and economy by creating a new industrial revolution that develops, manufactures and is powered by low carbon technologies (Earthlife Africa, 2009). By changing its development path, South Africa can create a sustainable employment platform and a secure future (Winkler and Marquard, 2008). South Africa has a desperate need to

create jobs, particularly in the semi skilled and unskilled sectors and renewable technologies can offer a serious contribution to this employment vacuum (Earthlife Africa, 2009). Agama (2003) identified direct job creation potential through the implementation of the various renewable technologies for power generation, thermal and transport energy services. The study compared the employment opportunities with other traditional forms of energy generation such as coal, natural gas and nuclear. The stipulated government target of 15% of total electricity generation to be sourced from renewables by 2020, was used in the study and was predicted to create some 36,400 direct jobs from the renewable technologies by 2020 (Agama, 2003).

The results of this study have been tabulated in table 6.1 below.

Table 6.1: Approximate direct job creation of various energy technologies. Source: (Agama, 2003)

Conventional Energy Technologies	Direct jobs per MW capacity	Direct jobs per GWh generated	Renewable energy technologies	Direct jobs per MW capacity	Direct jobs per GWh generated
Coal (current)	1.7	0.3	CSP	5.9	10.4
Coal (future)	3	0.7	Solar PV	35.4	62
Nuclear	0.5	0.1	Wind	4.8	12.6
Nuclear PBMR	1.3	0.2	Biomass	1	5.6
Gas	1.2	0.1	Landfills	6	23

As is evident from these numbers, the jobs created per MW of capacity are the least under the fossil fuel energy sources and the greatest under the renewable technologies (Agama, 2003).

Job creation can be separated into three different forms:

- (I) Direct jobs are those jobs that result directly from the renewable energy project or installation. They include the entire production cycle from fuel production and component manufacture to waste management.

- (II) Indirect jobs are the jobs that appear in addition to the direct jobs, and include services and inputs to the direct processes involved in the project or installation.
- (III) Induced jobs are the jobs created through the increased cash flow which occurs from the wages of those employed in direct and indirect jobs.

An optimistic source said that a 100MW CSP plant could create 4000 direct and indirect jobs (Stoddard, 2006). The choice of source of energy thus has a direct influence on the amount of employment positions available to the economy (Earthlife Africa, 2009). Using these numbers, some simple calculations can be made on the CSP job creation potential. For the smallest capacity analysed in the previous sections: 1GW installed CSP capacity could lead to 5 900 direct jobs being created. For 10GW of CSP installed capacity, 59 000 direct jobs could be created. Finally for the 30GW capacity that was used in previous sections, 177 000 direct jobs could be created. Indirect jobs, could be as high as three times this figure (Agama, 2003), 531 000, meaning a total of 708 000 total jobs for 30GW CSP capacity.

6.2 BREAKDOWN OF PLANT

In order to assess what is needed from an industry and labor perspective, a detailed breakdown of the plant is required. For the purpose of this thesis and due to time constraints, only one plant and storage technology will be assessed. The technologies chosen are the standard Central Receiver where power generation is generated through the Rankine, steam turbine, cycle and the molten salt heat transfer fluid and storage medium of Sodium and Potassium Nitrate in a 60:40 ratio. These technologies were chosen for their maturity and accessible technical data. Central receiver systems can be roughly divided into four main subsystems shown in figure 6.1 below: the heliostat field, the receiver and tower, the energy storage system and the energy conversion power block. Not shown is the remaining balance of system (BOS) costs which includes engineering, civil works and other expenses.

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

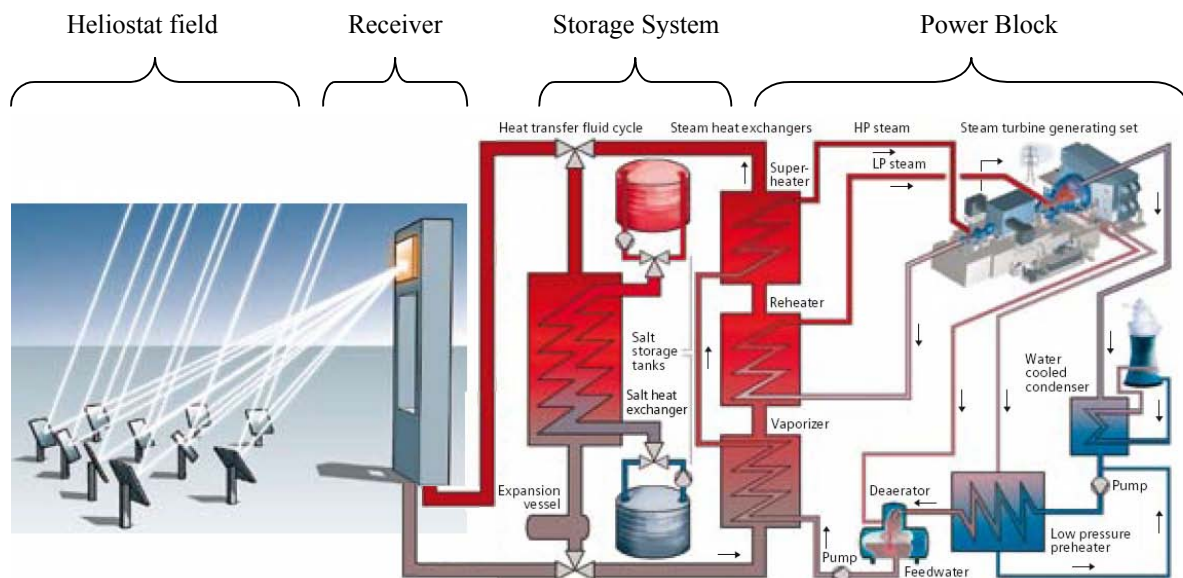


Figure 6.1: Rough breakdown of the four main subsystems of a central receiver plant. Source: (Siemens, 2008)

The heliostat field represents the majority of the costs involved in a central receiver plant and is stated to account for between 35% and 42% of total investment costs (Muller-Steinhagen, 2008; Caldes, 2009). The receiver and tower lie between 11% and 18% of the total investment costs (Muller-Steinhagen, 2008; Caldes, 2009). The storage system costs can vary substantially according to its capacity and can lie between 8% and 20% accordingly (Muller-Steinhagen, 2008; Renac, 2008; Caldes, 2009). The final main component is the power block and is said to lie between 13% and 20% of total investment costs (Muller-Steinhagen, 2008; Renac, 2008; Caldes, 2009). These values can be graphically by a rough pie chart figured below:

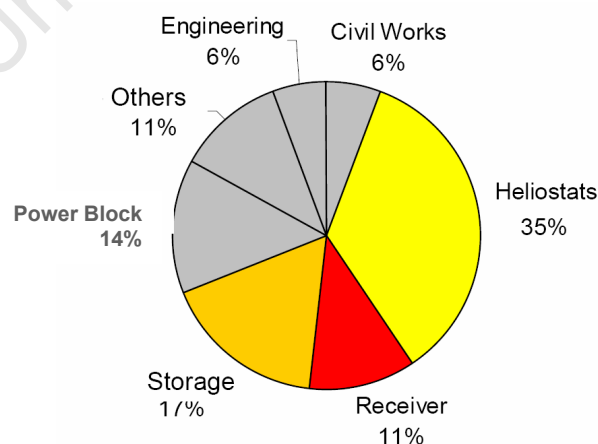


Figure 6.2: Approximate Investment costs of the various subsystems of a central receiver system
Source: (Muller-Steinhagen, 2008)

6.2.1 Heliostat Field

The heliostat field can be further divided up into the heliostats, consisting of reflector material, actuator mechanism, structure and foundation, the piping system, cables and spare parts. The percentage investment cost of these systems is shown below:

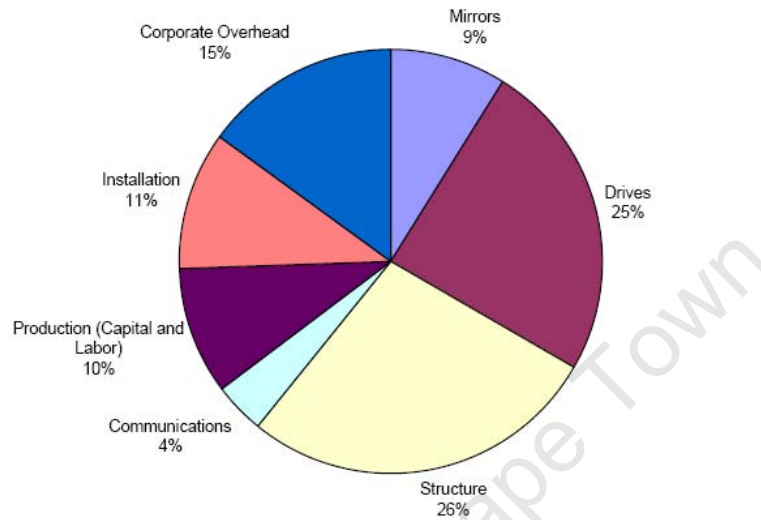


Figure 6.3: Approximate Investment costs of the various subsystems of a heliostat system. Source: (Sargent and Lundy, 2003)

The heliostats are able to direct incoming, direct solar radiation, by using two axes, onto the central receiver tower. The movements are controlled by a centrally programmed algorithm. The heliostat system is a critical component in the central receiver system and any slight error in design or manufacture will be replicated approximately 6000 times for an 8 hour storage system (Eskom, 2006). Therefore it is imperative that the design of the system is flawless whilst still being the most cost effective option as it represents the biggest investment of the plant. Due to this fact it is the recommendation of this dissertation that the first prototype central receiver plants should import tried and tested designs to avoid prototype failures, large financial losses and complete plant collapse. Once existing designs have been established and tested in the South African conditions improvements should be made in terms of cost, performance and optimization for large scale manufacture



Figure 6.4: Pictures of 80m², Sunlab heliostats indicating their scale. Optimum size is 148m² (Source: Kern, 2005)

The mirror and mirror assembly is a very simple structure and can easily be built locally with local materials. Much research has been documented on different reflective surfaces which include silvered glass mirrors, silvered polymer films, aluminized polymers and anodized sheet aluminum with additional protective polymer coating (Fend, 2003). The usual limiting factors are wind damage and corrosion (Fend, 2003). Flabeg thick glass, silver mirrors showed promising durability and corrosion resistance along with Naugatuck silvered thin glass (Fend, 2003). Further research and testing will need to be done to determine the best option for South African conditions, however none of the technologies exceed the South African materials and manufacturing resources.

The following table indicates the near term options which have been proven and the longer term options which may exhibit improved properties such as higher reflectance, improved durability and lower materials and manufacturing costs.

Table 6.2: Reflector material options for the near term and longer term utilization (Kennedy, 2003)

	Material						
	Thick Glass Mirror	Thin Glass Mirror	Commercial laminate	Aluminized reflector	Super thin glass	Front surface mirror	All polymeric
Present	X	X	X	X			
Future					X	X	X

An actuator mechanism design, developed by Sener of Spain, appears to have the qualities of performance, reliability, cost effectiveness and smart design and it is

recommended by this study that this design be further analyzed for prototype plant use (Sener, 2006). See figure 6.5 below and the design and testing study (Sener, 2006):



Figure 6.5: Pictures of the Sener actuator design. Source: (Sener, 2006)

The total cost of a single heliostat systems varies from source to source, however an assessment compiled in by Sargent and Lundy places the cost of a single 148m² at approximately R170 000 per unit, which includes all materials and installation costs. This study also estimates the capital equipment, tooling costs and engineering design which itself is estimated at \$259 000 or R2.072 million at R8 = \$1 exchange rate. The cost of heliostats is predicted to decline as economies of scale are rolled out as represented by the graph below:

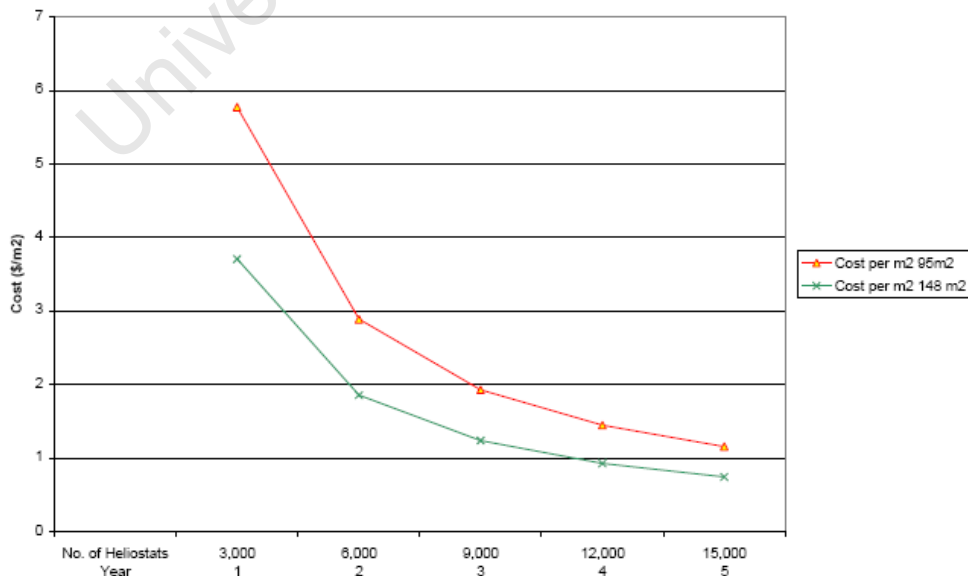


Figure 6.6: Heliostat capital and equipment cost reductions with economies of scale Source: (Sargent and Lundy, 2003)

6.2.2 Receiver and Tower

The central receiver is another critical plant component in the plant and is situated on top of a tower constructed of concrete or steel for smaller designs. For a 100MW plant, the towers height is approximately 190m with the foundation diameter at 45m and 4.5m deep (Van Heerden, 2009). The tower diameter tapers inwards as height increases, it starts at 24m in diameter and 0.75m thick walls and decreases to 17m diameter and 0.3m thick walls (Van Heerden, 2009). The receiver itself is approximately 15m in diameter, 20m tall and has 2m wide panels and is essentially a heat exchanger which absorbs the concentrated solar radiation and transfers in to the working fluid (Van Heerden, 2009; Eskom, 2006).



Figure 6.6: Close up of the receiver on Solar 2 and a graphic design model of Eskom plant. Source: (Eskom, 2006; Van Heerden, 2009)

The material composition of the receiver is of high importance as it should be thermally stable above 600°C, have a thermal absorbance of greater than 0.96 and thermal emittance below 0.07 at 600°C (Kennedy, 2003). Both the Eskom concept and Solar Tres have chosen a high nickel alloy, Inconel 625LCF but there is much research and development in the receiver material (Van Heerden, 2009). Sargent and Lundy's study estimates a receiver's capital cost lie between R232 an R272 Million (2003).

6.2.3 Storage System

As stated in previous chapters, the storage element of CSP plants is critical to achieve the flexibility of utility grade electricity generation. The six hour minimum storage, being reviewed by the REFIT, may not be a sufficient quantity if South Africa chooses to have a very large dependence on CSP power production. At least thirteen hours of storage may be needed to allow the supply of solar radiation to meet the main demands (DLR, 2003). The molten salt technology is the most mature of the storage technologies for the central receiver concept where the molten salt is used both as a heat transfer fluid and storage medium. The working fluid is a salt mixture of 60:40 ratio of Sodium Nitrate (NaNO_3) and Potassium Nitrate (KNO_3). Molten salt is used for a number of reasons including: High specific heat relative to cost, environmentally benign, low vapour pressure and non flammable or explosive (Dracker, 2008). The cold salt is pumped up the central tower at approximate 290°C and flows through the central receiver where it is heated to approximately 565°C after which it is stored for use when required (Eskom 2006). The traditional layout is by using two separate, insulated tanks to hold the molten salt. One tank stores the salt at around 290°C , called the cold tank and the other at around 565°C which is called the hot tank.

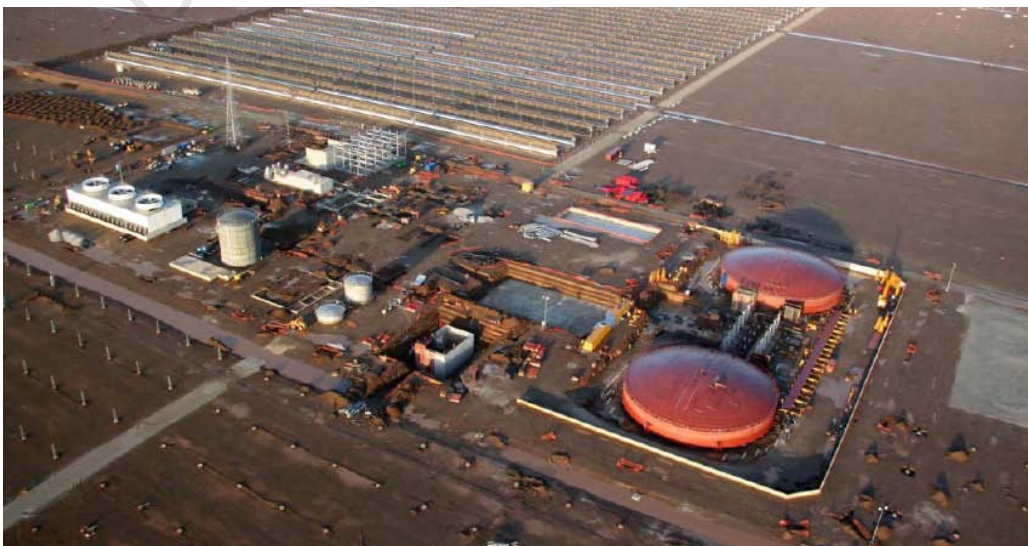


Figure 6.7: Two tank molten salt storage system in a trough plant. Source: (DLR, 2008)

The hot salt tank is constructed of either TP321H or TP347H stainless steels and the cold salt tank is constructed of standard high Carbon Steel (Van Heerden, 2009). The insulating material used is mineral wool, ASTM C612-93 of Type 4 (Van Heerden, 2009). The general layout and approximate size is shown by the schematic below:

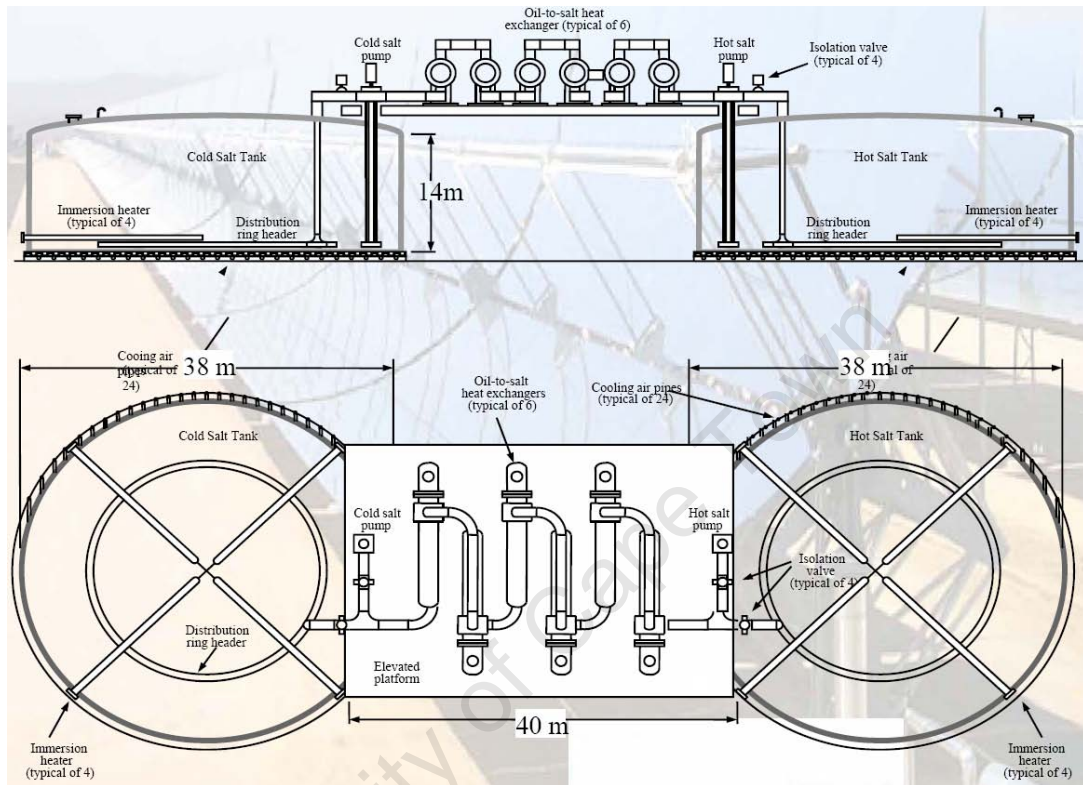


Figure 6.8: Two tank molten salt storage system schematic showing approximate sizes and heat exchangers. Source: (Dracker, 2008)

The progress ratio or learning curve development for molten salt storage is said to lie at approximately 92% and overall costs are approximately €50/kWh of R550/kWh (€1 = R11) (Trieb, 2009). For a full breakdown of the storage component costs, refer back to section 5.3.2.2 on page 100.

6.2.4 Power Block

The power block is what converts the thermal energy absorbed by the receiver, into electrical energy that can be transported by the national grid. The thermodynamic cycle, commonly used for this conversion is the Rankine Steam cycle. The live steam pressure lies around 125 bar and 550°C and the reheat steam pressure is said to lie around 30bar at 550°C (Van Heerden, 2009). The schematic for the power block conversion process is shown by the figure below:

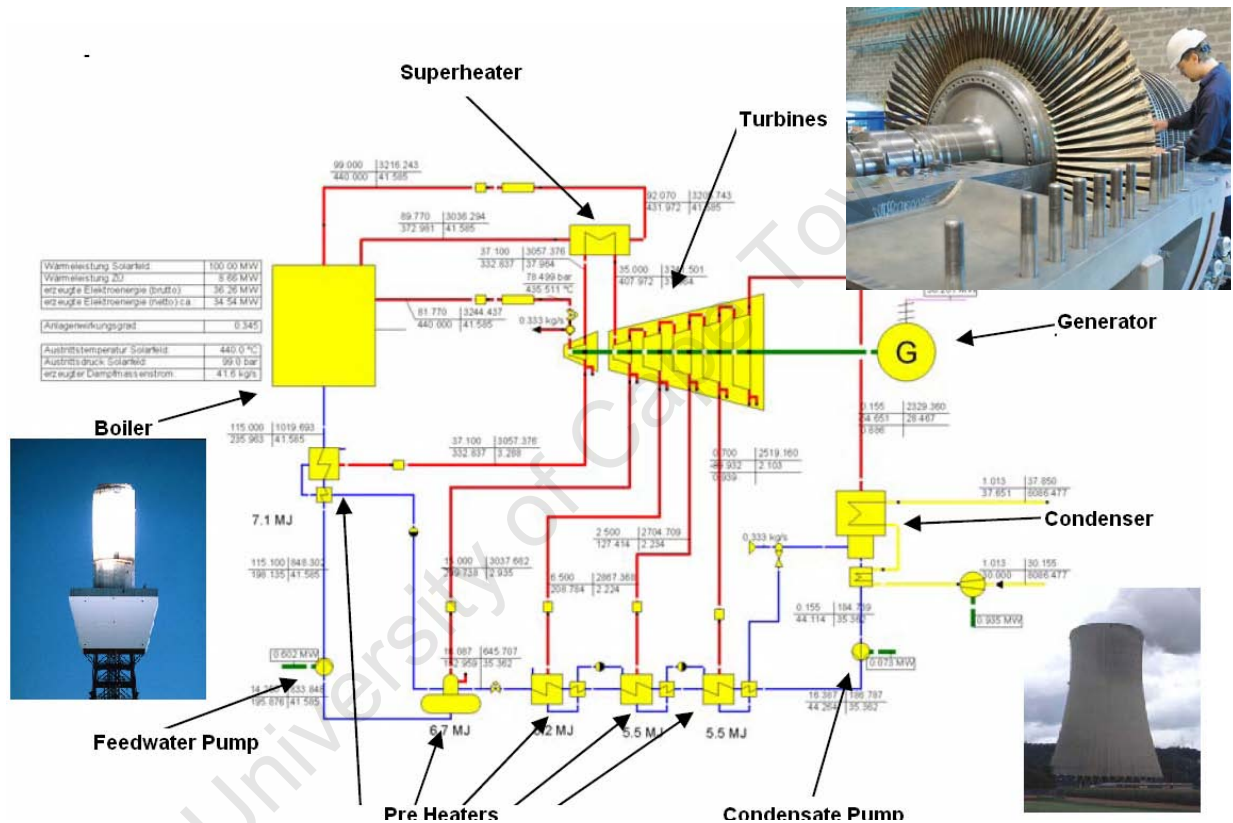


Figure 6.9: Schematic layout of the power block conversion process, showing the critical elements (Source: Renac, 2008)

The main components are the boiler, superheater, turbines, generator, condenser, various pre heaters and the feedwater and condensate pumps. A 100MW CSP plant could utilize a 100MW Reheat steam turbine in a combined High Pressure + Intermediate Pressure and double flow Low Pressure turbine configuration or a Tandem-Compound Turbine (Van Heerden, 2009). This HP + IP + dual LP type turbines layout is similar to the schematic in figure 6.10:

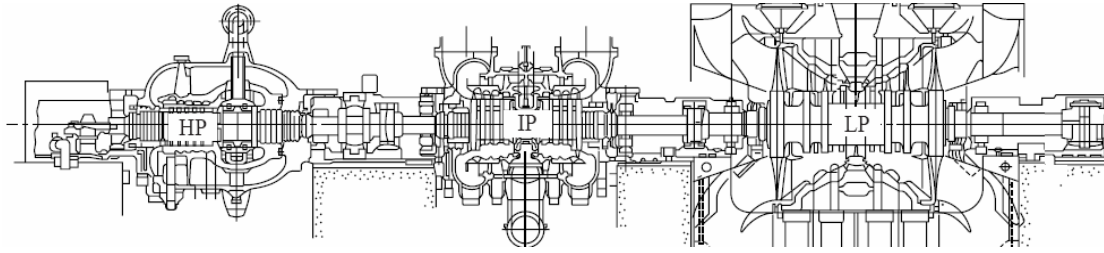


Figure 6.10: Schematic layout of HP + dual IP + Dual LP turbine configuration. Source: (MEC4036 UCT Power plant course notes, 2008)

The technology required in the power block is well established and many manufactures exist internationally and locally. Progress ration is said to lie at around 98% and costs are approximately €1200/kW or R13 200/kW (€1 = R11) (Trieb, 2009). Siemens have designed a steam turbine, the SST 700, which has specific advantages for solar thermal power generation. Its benefits include: compact design, easy installation and maintenance, wide application range including reheat configurations, high reliability and efficiency, short start up time and is a proven solution for solar thermal power plants (Siemens, 2008).

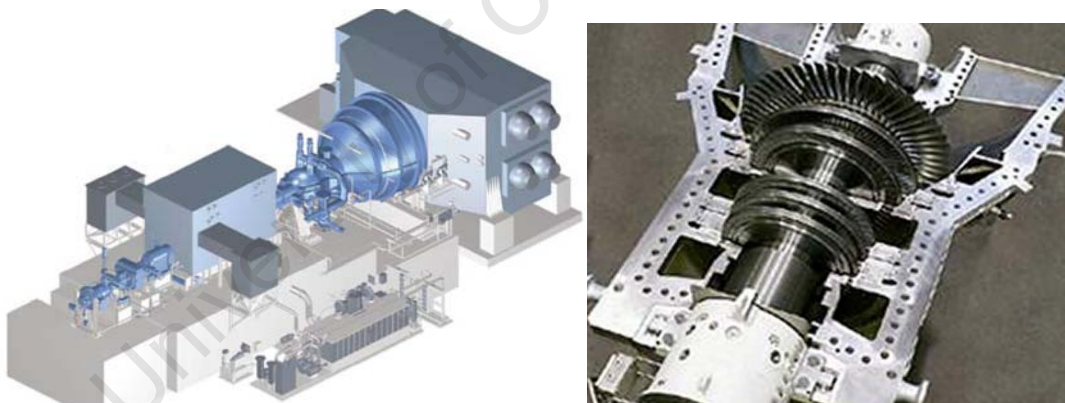


Figure 6.11: 3-D Schematic of the SST-700 dual casing, reheat solution. Source: (Siemens, 2008)

Technical Data:

- Power output: up to 175 MW
- Inlet steam pressure: up to 165 bar
- Inlet steam temperature: up to 585 °C
- Bleed: up to 7; up to 120 bar
- Reheat temperature up to 415 °C
- Rotational speed: 3,000 - 13,200 rpm

Exhaust steam conditions:

- Back pressure: up to 40 bar
- Condensing: up to 0.6 bar
- District heating: up to 3 bar
- Exhaust area: 1.7 - 11m²

Controlled extraction:

- Pressure: up to 40 bar
- Temperature: up to 415 °C

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The high investment costs of a CSP plant need to be justified by a highly efficient turbine that guarantees economic returns. The SST 700 from Siemens has been developed alongside CSP companies and has been fine tuned to optimise the solar steam cycle (Siemens, 2008). According to Green Energy News turbine generators need to be ordered approximately three years in advance due to a lengthy production process.

As stated before, to reduce research and development costs, the design of the most mature and promising plants and components, internationally, should be acquired for initial CSP start-up. Once this technology transfer has taken place the components of CSP plants must be established and fully tested under in the South African environment. Following this learning stage, further research, development and optimization in both performance and cost can take place and South Africa can further build the required infrastructure.

Some of the most promising international manufacturers and companies of the constituent components of a CSP plant are illustrated by the table below

Table 6.3: Index of CSP components and the most experienced manufacturers. Source: (Renac, 2008)

Mounting Structures	Mirror Providers	Receiver Providers	HTF Providers	Molten Salt Providers	Turbine Providers
> Abengoa* > Flagsol* > Grupo Sener* > Solargenix* > Solel Solar Sys.* > Sky Fuel Inc. (ReflecTech reflective foil***)	> Flabeg Hold. GmbH* > Rioglass Solar** – for Abengoa only > 3M*** > Alanod*** > Glasstech Inc.** > Guardian Ind.** > HERO-Glas** > Naugatuck Glass** > ReflecTech** > Saint-Gobain**	> Schott AG* > Solel* > Archimede Solar Energy srl. – for molten salt receiver*** > HIMIN – no reference***	> Dow Chemicals* > Solutia* > Lanxess – unknown so far	> Bertrams HEATEC AG* > Durrferit* > Haifa Chemicals* > SQM* - producer of salt > BASF** > Pratt&Witney Rocketdyne (PWR)	> GE Oil & Gas* > Siemens* > Bharat Heavy Electrical Ltd. - India > Ormat Tech. Inc.** > Pratt&Witney Rocketdyne* (PWR)
* with experience and reference in CSP ** probably o.k. if company can provide *** technology not yet proven					

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

The following table has been drawn up to summarise the 4 main component costs of a single 100MW central receiver plant with thirteen hours of storage. Additionally the costs for the capacities of 1GW, 10GW and 30GW have been estimated, based on these numbers and their constituent transmission capital costs. Note the approximated R758 billion total cost for 30GW CSP capacity falls in the same scale as Eskom's current capital build plan of 16.3GW for R342 billion coming from mainly new coal fired power plants (Eskom, 2008)

Table 6.4: Table summarizing the ranging capacity costs of the core components

	Heliostat			Receiver			Storage		
	Cost _(ea)	Amount	Total (million)	Cost (million)	Amount	Total million	Cost (per 13MWh)	Amount	Total (million)
100MW	R170 000	8000	R1360	R 252	1	R252	R7150 000	100	R715
1 GW	R170 000	80 000	R13 600	R 252	10	R2520	R7150 000	1 000	R7 150
10 GW	R170 000	800 000	R136 000	R 252	100	R25 200	R7150 000	10 000	R71 500
30 GW	R170 000	2 400 000	R408 000	R 252	300	R75 600	R7150 000	30 000	R214 500
	Power Block			Transmission				Complete Total Cost (billion)	
	Cost (million)	Amount	Total (million)	Capacity	Distance	Total (million)			
100MW	13,2	1	R13	275kV	20	R40		R 2. 380	
1 GW	13,2	10	R132	765kV	370	R1 930		R 25. 332	
10 GW	13,2	100	R1 320	800HVDC	850	R23 000		R 257. 020	
30 GW	13,2	300	R3 960	800HVDC	850	R56 100		R 758. 160	

6.3 RAW MATERIAL ESTIMATES

From the plant breakdown in the previous section, estimates can be made as to the amount of raw materials required for a 100MW CSP plant. The major materials in the CSP value chain are silica, iron and steel, concrete, plastic (or polyvinyl chloride), brass, copper, aluminium, and molten salt (Gereffi, 2008). The following diagram indicates the various materials and components that go into the finished CSP plant:

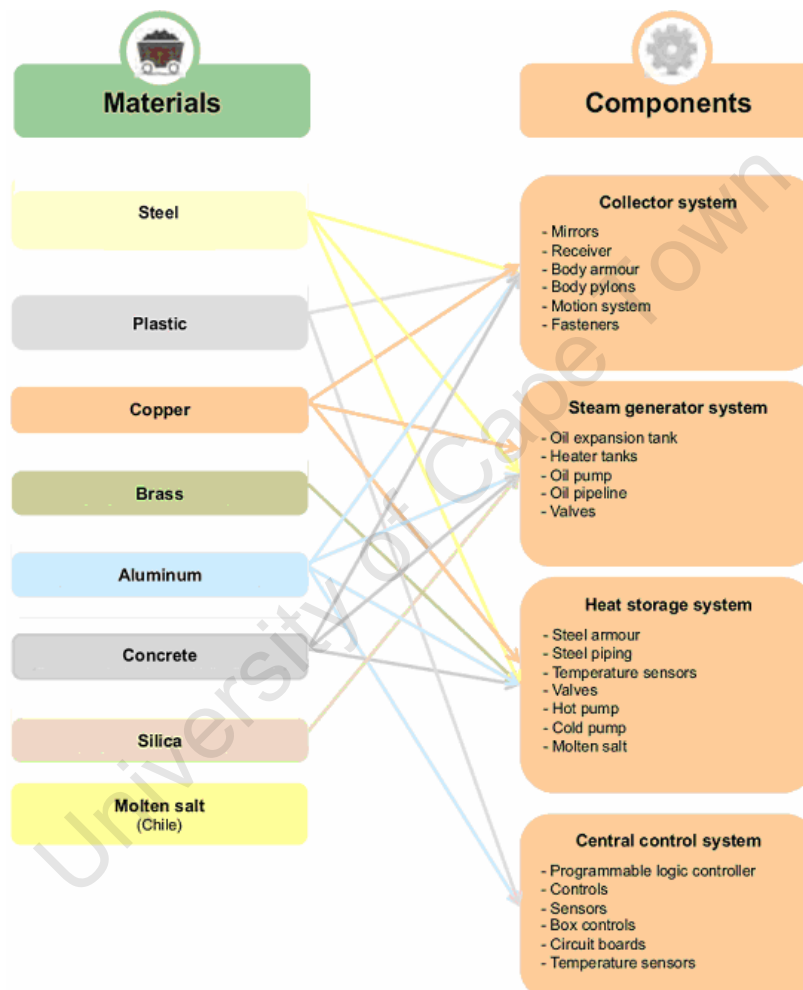


Figure 6.12: CSP materials and their constituent components. Source: (Gereffi, 2008)

In addition to the components listed above, CSP plants require other elements that are not outlined in this estimation as they represent standard technologies for electricity generation. The standard components include the boiler systems, turbines, steam generators, condensers and the dry cooling parts and towers (Gereffi, 2008).

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The components need to be included in the manufacturing and construction needs of any CSP plant.

A rough estimate of the major material capacities needed was made by Muller – Steinhagen (2008). This paper said a 100MW plant with thermal storage would require approximately:

- ✓ 25 000 Tons of steel
- ✓ 12 000 Tons of glass
- ✓ 30 000 Tons of molten salt
- ✓ 20 000 m³ of concrete

Up scaling these numbers to the capacities of 1, 10 and 30 GW allows an estimate if South Africa can handle the raw material requirements or if it will need to rely on imports.

Table 6.5: Table summarizing the raw material estimates for the various CSP capacities

	Steel (tons)	Glass(tons)	Molten Salt (tons)	Concrete (m³)
100MW Plant	25 000	12 000	30 000	20 000
1 GW CSP	250 000	120 000	300 000	200 000
10 GW CSP	2 500 000	1 200 000	3 000 000	2 000 000
30 GW CSP	7 500 000	3 600 000	9 000 000	6 000 000

Concrete is typically made up of 1 part cement 2 parts dry sand, 3 parts dry stone, 1/2 part water base on weight not volume (Wikipedia, 2009) . 1m³ of concrete weighs approximately 2 tons (Wikipedia, 2009) thus 1GW of CSP 66 667 tons of cement, likewise for 10GW needs 666 667 tons and 30GW needs 2 000 000 tons of cement.

South Africa is endowed with large mineral and raw material reserves, however the construction and refurbishment of stadiums and roads for 2010 have spiked the consumption of concrete and steel in 2008 and 2009 (DOT, 2007) therefore values

from 2007 will be used. The countries consumption of primary Carbon Steel fluctuates between 4 and 4.5 million tons annually and the ports of Richards Bay and Durban exported approximately 300 000 tons and 1.3 million tons of steel in 2006/2007 (DOT, 2007). Concrete capacity is being expanded in South Africa by 3.3 million tons per annum raising the total South African industrial capacity to around 16.5 million tons per year (DOT, 2007). This is said to be sufficient to satisfy growth until 2012, after which major infrastructure projects from 2010 would have been completed.

The production and export quantities of the various raw material and alloys required in a CSP plant were extracted from the DME's statistics tables and are shown below:

Table 6.6: Table summarizing production and exportation numbers of the various materials for 2007

Material	Production (Tons)	Export (Tons)	year
Aluminum	914 000	597 000	2007
Iron Ore	42 083 000	29 725 000	2007
Ferro Alloys	4 778 000	3 861 000	2007
Chromium Alloys	3 561 000	2 972 000	2007
Shale's for Cement	500 000	0	2007
Salt	411 000	0	2007
Silica	3 352 000	800	2007
Silver	69 800	76 900	2007
Copper	117 100	37 300	2007

To achieve the goals set out by the LTMS study of 27% renewables by 2050, ten new CSP plants of 100MW each would need to be built each year (SBT, 2007). This number fluctuates higher in certain scenarios but for the purpose of this estimation, 1GW per year is chosen as the bench mark.

At this rate, the 30GW CSP capacity would be reached by around 2040 See graph below:

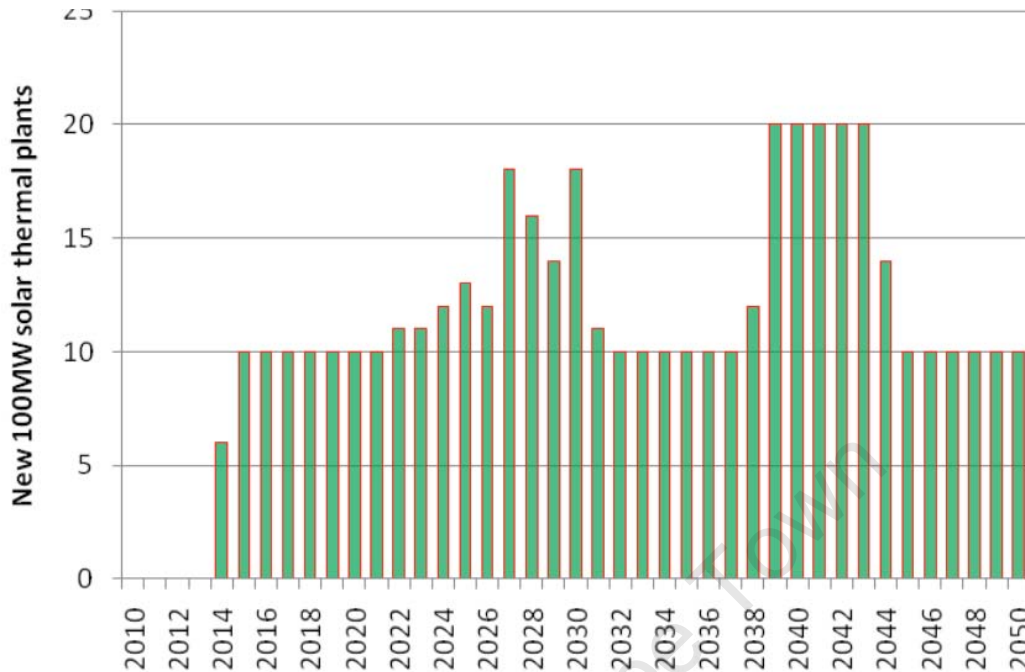


Figure 6.13: Long Term Mitigation Scenario's 27% renewables by 2050 CSP build plan. Source: (Marquard, 2009)

1GW of CSP capacity a year requires approximately 250 000 tons of steel, a fifth of what South Africa exports year. 120 000 tons of glass silica of which South Africa produces almost 30 times as much. Molten salt for CSP has a different composition to standard sea salt, sodium chloride, and information about the availability and quantities are hard to find. This fact leads to the conservative choice of importing 300 000 tons from Chile per year who is said to be a large supplier (Gereffi, 2008). The final main raw material is concrete of which there will be surplus after 2010 infrastructure is completed. Approximately 66 700 tons of cement will be needed per annum of which South Africa produces over 7 times the amount. From these results, it is evident that the major raw material requirements, other than molten salt, of a CSP industry can be satisfied by local resources.

6.4 MANUFACTURING REQUIREMENTS

The following section aims to investigate the requirements in terms of manufacturing and factories that CSP plants would require and where the most optimum placement of these factories would be in terms of existing infrastructure and transport costs.

In terms of transport of CSP components and materials, South Africa's road infrastructure for the Upington, Northern Cape region, is fairly well established when compared to other CSP sites around the world which are usually located in remote deserts (Taggart, 2008). An estimation for transport requirements is a 100MW plant would require approximately 4 000, 20 ton trucks or 2 000 railway trailers (Muller-Steinhagen, 2008). The following map shows the available National roads and accessible railway lines which connect all major manufacturing ports and cities in South Africa:



Figure 6.13: Map of South African national roads and railways connected to the Upington, Northern Cape region.

Source: (SA Transport, 2004)

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The construction of a CSP plant requires some common materials such as steel, glass and concrete, and non patented components can easily be outsourced to a wide variety of local manufacturers. The traditional approach is to have two assembly sites, one which produces easily transportable components which could be located anywhere in the country or world, and two, an on site location where the larger components are assembled to minimize transport costs (Stoddard, 2006). According to the IEA, CSP production capacity can be easily and rapidly up scaled to several hundred megawatts per year using existing industrial technologies (IEA, 2008).

South Africa has a well developed metals industry which has vast natural resources and supportive infrastructure and represents around a third of all the countries manufacturing activities (South Africa info, 2008). The industry manufactures primary iron and steel products from smelting to semi finishing stages which can easily handle a large portion of basic CSP component design. Additionally South Africa has a large amount of experience in conventional power station manufacture which has some major similarities to CSP stations in the power block component of the plant. In particular, engineering companies based in Woodmead Johannesburg, have major experience in design, manufacture and installation of wet natural draught cooling towers, indirect natural draught cooling towers and direct dry cooled systems (with air-cooled condensers) of particular interest to CSP (DB thermal, 2008).



This coal fired plant is one of the largest indirect dry cooling systems in the World. The Kendal Power station was manufactured by a South African company. This power station comprises 6 x 686 MW units, and operates with the largest indirect dry cooling system in service world wide. The plant has 6 Cooling Towers, each 165m high with a throat diameter of 102m.

Figure 6.14: Kendal, dry cooled coal fired Power Station. Source: (DB thermal, 2009)

Another large manufacturing industry in South Africa is its automotive industry accounting for around 10% of the country's exports, 7.5% of the gross domestic product (GDP) and employs around 36 000 people (South Africa info, 2008). The industry, which is mainly located in the Eastern Cape and Gauteng, has a number of competitive advantages including low cost ability on short and long volume runs, competitive tooling costs and a very high degree of flexibility in its manufacture of products (South Africa info, 2008). Recently however, the global economic downturn has negatively impacted this industry as both domestic and international demand for cars and components has declined. See the graph below representing the last 15 years of the automotive industry market's growth and decline:

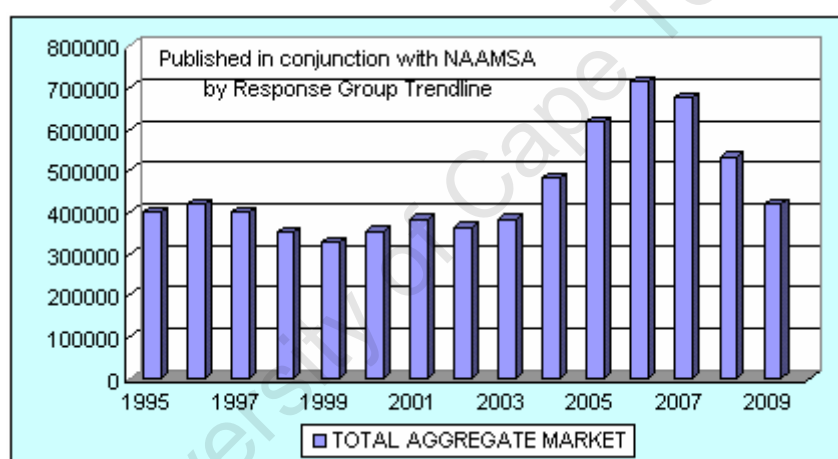


Figure 6.16: Total market of vehicle sales, both local and export for 1995 to 2009. Source: (Naamsa, 2009)

This loss of demand has lead to large retrenchment numbers and job losses in most sectors. At the end of 2008, 34 963 people were employed but by the end of the first quarter of 2009, aggregate industry employment had declined by 2 571 jobs to 32 392 (Naamsa, 2009). Matching the demand of 1GW of CSP capacity a year, as stated before, would not only re-employ those who lost their jobs in the first quarter but employ some 5 900, over double the amount that did so.

According to some energy and business experts' inputs during a CSP workshop, the South African automotive industry is quite capable of refitting and retooling their

workshops to build parts for CSP plants (ERC, 2009). The large automotive industry could yield itself in supplying various components such as glass, reflective coatings, drive trains, support and mounting structures, control systems etc (ERC, 2009). This option can allow a revitalization of a currently crippled industry and all that is needed is the demand for the product and certainty that the demand will remain. A future case study was compiled by the Infinia Corporation of the U.S where solar manufacturing can replace lost auto jobs (Gereffi, 2008). The company developed a concentrating dish system, not that dissimilar from heliostats, which can be “stamped out on a production line like a Chevy and installed like a “Maytag”. The unit can be manufactured on an existing automotive factory production line, packed, shipped and installed by a basic, semi-skilled construction crew (Gereffi, 2008). As much as 10 units can be manufactured on a retooled line of which there is some 4 million vehicle/year capacity not being used (Gereffi, 2008). This means around 40 million CSP units or 120 000MW of capacity can be built a year on their excess capacity .

The South African industry has a major potential to drive CSP development and become a major the supplier to Southern African and Africa due to its high flexibility and low retooling and operating costs.

6.5 SKILL AND LABOUR REQUIREMENTS

The following sections aims to analyze what the employment requirements of a CSP infrastructure are, which includes employments numbers, positions and skill or training level. The few international studies directed in this area, vary substantially in terms of location and predicted employment numbers and therefore the numbers stated in the following section can only serve as an average benchmark.

As mentioned before, job creation can be specified in three ways:

Direct jobs - Jobs which result directly from the CSP project, which includes the entire production cycle from energy production, component manufacture to waste management.

Indirect jobs - Jobs that arise in addition to the direct jobs stated above, which include services and inputs to the planning, manufacturing, operation and decommissioning of the CSP plant

Induced jobs - Jobs which are generated through the increased cash flow in the broader society which arise from the salaries of those employed in direct and indirect jobs mentioned above.

The direct jobs that could be associated with a CSP infrastructure include:

- ✓ Temporary Engineering, Procurement and Construction
- ✓ Permanent Operations, Maintenance, Engineering and Administrative

The Indirect jobs that could be generated through a CSP infrastructure include:

- ✓ Manufacturing
- ✓ Hospitality and Services
- ✓ Infrastructure
- ✓ Additional Commerce

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The NREL of the U.S estimates that roughly 455 construction jobs are created for every 100MW in CSP capacity (Stoddard, 2006). The U.S. firm, Black and Veatch, estimates that around 4000 direct and indirect jobs could be created for every 100MW CSP capacity, over eight times the amount created from fossil fueled stations of the same capacity (Stoddard, 2006). Once construction is completed, the operations of the plant require permanent jobs in the areas of administration, operation, maintenance, service contracting, water maintenance, spare parts and equipment and solar field parts replenishment (Gereffi, 2008). A 100MW CSP plant is said to generate 94 permanent jobs in operations and management, almost 10 times the amount of 100MW of coal generation (Gereffi, 2008).

Another estimate by Muller Steinhagen (2008) said that a 100MW plant in Spain with 9hr storage requires 400 million Euro investment and creates 1000 jobs during construction and 100 jobs in 25 years of operation. (2008)

A more conservative estimate by Sargent and Lundy (2006) found the staffing required for a Central Receiver of 100MW capacity, with 13 hours storage, should have the following requirements:

<u>Position:</u>	<u>#:</u>	<u>Skill Level:</u>
Administrative:	7	Non skilled/Semi Skilled
Plant Operations:	11	Semi Skilled/Skilled
Power Plant Maintenance:	7	Semi Skilled/Skilled
Solar Field maintenance and Wash Crew:	21	Non/Semi/skilled
<u>Total:</u>	<u>46</u>	

An increase in plant size would not affect the administrative, plant operations and power plant maintenance staffing numbers however field maintenance and wash crew numbers would increase at a rate of 0.03 per 1 000km² of solar field area (Sargent and Lundy, 2006).

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Up scaling S & L numbers, to the benchmark scenarios used through this thesis of 1GW, 10GW and 30GW, yields the following numbers for direct, on site, job creation:

1GW CSP capacity yields 460 permanent, direct, on site jobs

10GW CSP capacity yields 4 600 permanent, direct, on site jobs

30GW CSP capacity yields 13 800 permanent, direct, on site jobs

These figures are not the complete direct job estimates as the Temporary Engineering, Procurement and Construction jobs have not been included. The following table summarizes the various international estimates:

Table 6.7: Table summarizing the international estimates for direct, indirect and total job creation

	NREL	Black & Veach	Gerrefi	Muller Steinhagen		
	Direct	Total	Direct	Direct	Indirect	Total
100MW Plant	455	4 000	94	100	1 000	1 100
1 GW CSP	4 550	40 000	940	1 000	10 000	11 000
10 GW CSP	45 500	400 000	9 400	10 000	100 000	110 000
30 GW CSP	136 500	1 200 000	28 200	30 000	300 000	330 000

The only South African study that investigated the potential contribution of renewables to job creation was published by Agama energy (2003). This study estimated employment potential for solar thermal (10% of target), solar photovoltaic (0.5% of target), wind (50% of target), biomass (30% of target) and landfill (5% of target) with remaining coming from biogas, domestic solar water heaters and biofuels. The results of this study are shown by the table below:

Table 6.8: Summary of direct and indirect jobs from renewable energy sources in 2020, note the estimated numbers for approximately 1.4GW of Solar Thermal. Source: (Agama, 2003)

Technology	% of target	Direct Jobs	Indirect Jobs	Total Jobs	% of total jobs
Solar Thermal	10%	8 288	24864	33 152	23%
Solar PV	0.50%	2 475	7 425	9 900	7%
Wind	50%	22 400	67 100	89 600	62%
Biomass	30%	1 308	3 924	5 232	4%
Landfill	5%	1 902	5 706	7 608	5%
Total	96%	36 373	109 019	145 492	100%

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

Solar thermal has been modelled here to contribute around 1.4GW capacity to the total electricity generation mix by 2020. The total direct jobs created out of this scenario for CSP is 8 244 which relates to approximately 5.9 jobs per MW or 590 direct jobs per 100MW. These values translate to 17.7 indirect jobs per MW or 1770 jobs per 100MW. These direct jobs can further be divided up into manufacturing, installation and operations and management shown by the table below:

Table 6.9: CSP's employment potential data direct jobs/MW and /GWh (Source: Agama, 2003)

	Fuel		Manufacturing		Installation		Operations & management		Other		Total	
RET	/MW	/GWh	/MW	/GWh	/MW	/GWh	/MW	/GWh	/MW	/GWh	/MW	/GWh
Solar Thermal	0	0	1.7	3	4	7	0.2	0.4	0	0	5.9	10.4
100MW	0		170		400		20		0		590	
1GW	0		1700		4000		200		0		5 900	
10GW	0		17 000		40 000		2 000		0		59 000	
30GW	0		51 000		120 000		6 000		0		177 000	

These results show the South African study being the most conservative with only 6 000 jobs being created for 30GW, in operations and management compared 13 800 in Sargent and Lundy case. Additionally when compared to the Black and Veatch estimates of around 4000 direct and indirect jobs could be created for every 100MW CSP capacity compared to just 2 360 direct and indirect jobs for 100MW CSP capacity in the South African study. The DLR study gave a figure of 1 000 direct jobs during construction and 100 jobs during operation for 100MW plant, this again is higher than the 590 of South African study and 20 during operations.

Information, regarding a detailed breakdown of the actual employment figures, in the various sectors, was very hard to find. The only accessible paper with exact employment sector data was Caldes (2009). The paper was restricted to plant sizes of 50MW as this was the Spanish renewable feed-in limit for CSP.

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Table 6.10: Spanish employment estimates for direct and indirect job creation in exact sectors for 50MW CSP plant in Spain. Source: (Caldes, 2008)

New sector code	Sector name		
1	Agricultural products, livestock, hunting, forestry and fishing	13	Electronic devices, radio, precision, TV and communication equipments
2	Fuels and extractive activities	14	Motor vehicles and trailers
3	Carbon, refinery products and nuclear fuel	15	Furniture, other manufactured products and material recovering
4	Electricity, gas and water production and distribution services	16	Construction: building and civil engineering
5	Foodstuffs, drinks, textiles, clothes and footwear	17	Hotel industry, commerce and vehicle and motorcycle repairing, and fuel selling to small consumers
6	Wood, paper, cardboard, edition products	18	Transport services
7	Chemical products, plastics and rubber	19	Telecommunication services, financial services, insurance and auxiliary services to financial mediation
8	Cement, lime, plaster, glass and other no-mineral products	20	Building services, machinery renting, computing and R&D
9	Metallurgical products	21	Other business and service activities (health and social work, recreational activities, etc.)
10	Metal products, except machinery and equipments	22	Other no market personal services and public administration services
11	Machinery and equipments		
12	Office equipment, computing devices and electronic material		

Sector	National demand		
	Direct	Indirect	Total
1	1	5	7
2	0	70	70
3	0	35	35
4	184	62	246
5	0	12	12
6	0	38	38
7	30	61	91
8	108	34	142
9	26	78	104
10	109	55	163
11	197	41	238
12	34	32	66
13	19	11	30
14	0	6	6
15	0	14	14
16	119	55	174
17	0	52	52
18	3	65	68
19	372	91	463
20	35	43	78
21	132	96	228
22	0	5	5
Total	1369	960	2330

The following results are for a 50MW CSP plant in Spain

- Electricity, Gas and Water production and distribution services

- Chemical products, plastic and rubber

- Cement, Lime, plaster, glass and other non mineral products

- Metallurgical products

- Metal products, except machinery and equipment

- Machinery and Equipment

- Construction: Building and Civil Engineering

- Telecommunication, financials, insurance

- Building services, machinery renting, computing and R&D

- Other business and service

This total relates fairly well to the Black and Veatch estimate of 4000 direct and indirect jobs for 100MW

6.6 CONCLUSION

In summary, the key findings are highlighted and re-emphasized. South Africa's high unemployment rate of around 23% is increasing in response to the global economic downturn. CSP offers an opportunity to establish a new employment structure which spans multiple sectors while, at the same time, addressing climate change concerns. Job creation would occur through all skill levels, from highly qualified personnel, to semi-skilled even to unskilled and across the sectors of manufacturing, distribution, research and development and management. The employment estimations do vary from source to source but even the most pessimistic paper still makes a strong case, making CSP a compelling case.

In the breakdown of the plant, a couple of highly specialized key components are required, however none are beyond the ability of the South African manufacturing industry. It is the recommendation of this paper that the design of these critical components should, in the very least, be subject of a detailed study with input by international experts in the CSP field, whose experience could offer some security to the performance of the plants. Scaling up the manufacturing, installations and capacities of CSP plants, to the numbers discussed, would require a national commitment and plan from all sectors involved (Winkler, 2009a).

The raw material requirements of the large capacities estimated in this dissertation, did not appear to be an issue as South Africa is endowed with large mineral deposits of which exporting is a common occurrence. The distribution of decentralized manufactured products to the Northern Cape region did not appear to hold any barriers, as is the case for many CSP sites around the world, as the national road and railway infrastructure connects all the point sources concerned. The power generation, manufacturing industry is already well established in South Africa and is

believed by some to be a world leader. The crippling national automotive industry was highlighted as having flexibility and retooling capability to shift direction and focus on CSP component manufacture thereby minimizing job loss and revitalizing one of South Africa's major workhorses.

Finally the labor force required to be developed alongside the infrastructure is said to span multiple sectors and requires skill levels from highly specialized, right down to non skilled personal. The estimate by Caldes (2009) represented the best source for employment estimates, stating some very negative employment figures for fossil fuels infrastructure. It is therefore the findings and recommendations of this dissertation that in terms of employment, materials, manufacturing and skills, the CSP industry in South Africa will offer multiple solutions to the multiple problems of generation capacity, climate change mitigation and unemployment.

8 CONCLUSIONS

The aim of this dissertation was to answer two core questions which were highlighted as possible barriers to the large scale roll out of CSP in South Africa.

- I. **What are the geographical and electrical infrastructure requirements for large scale, intermittent renewable energy, and its timely diffusion into the South African grid?**
- II. **What are the logistical and skills requirements for creating a local design, manufacturing, operations and maintenance industry?**

To answer these two core questions a two pronged methodology was chosen where an extensive literature review was undertaken along with various semiformal interviews and communication dialogs. From these methods, information was gathered and assessed along with some simple modeling and linear approximations which yielded the following results:

Based on a literature review and a quantitative analysis, this dissertation examined the potential requirements for large scale deployment of concentrated solar power in South Africa based on a geographical, electrical, technological and logistical analysis. Where possible this dissertation has provided probable solutions and recommendations to overcome these barriers of which none appear to be overwhelmingly constraining. CSP's price is predicted to become competitive with base load fossil fuels power plants by 2020 – 2025 but this dissertation concludes, along with the scientific research, that this is too late to begin combating climate change and shifting our fossil based electricity supply structure to a more sustainable basis.

The geographical conditions of the Northern Cape region of South Africa are said to be one of the best in the world for the production of solar generated electricity. Land

is uninhabited and un-utilized and the solar radiation statistics have proven records of world leading figures. The issue of limited water resources has an all encompassing solution in the technology of dry cooling, which South Africa has world leading experience through its large dry cooled coal fired power plants of Kendal and Matimba. However, dry cooling has a cost of decreasing plant efficiency thus increases the levelized energy costs of CSP. This property needs to be factored into future CSP modeling scenarios.

One major infrastructural question that this thesis aimed to answer is the transmission grid required to distribute the vast electricity capacity generated from the large scale CSP plants. The national transmission grid, its capacity, current state and planned development was assessed along with recommendations where planning is inadequate or non existent. It was evident that initial start-up and pilot plants would require little additional infrastructure however the process of connecting to the national grid and the Power Purchase Agreements (PPA's) with Eskom were seen by many industry professionals, as a major barrier to CSP start-up. This dissertation concludes that this process be re-evaluated by government to become more transparent and user friendly to allow start-up CSP plants the security of demand, required by investments.

Minimal grid infrastructure was found to be needed for capacities of up to 500MW, if the additional 400KV planned lines are implemented. For around 1GW of CSP capacity, a 765KV HVAC line is recommended to extend from Upington to the Hydra substation, where the planned 765KV HVAC line to Cape Town, begins. For CSP capacities above 2GW it was found that the stability of the "backbone" of the national grid could be compromised thus additional, high capacity lines, would need be required to the key demand point sources. Cost and capacity analysis was performed on the HVAC and HVDC options and it became apparent that HVDC's properties

yielded it to be a superior choice in terms of capacity, losses, cost, land usage and appearance. What this analysis showed is that current grid planning will become rapidly insufficient if the large scale CSP capacity route, of at least 1GW CSP capacity per year, is taken.

Another major infrastructural challenge that constitutes both an opportunity and requirement to the large scale implementation of CSP was the technical issue of energy storage. It was evident that if South Africa were to rely on a large quantity of electricity to be generated from the intermittent source of solar energy, there needs to be a mechanism to match this intermittent source with the demand profile of the country. Various storage technologies were investigated, assessed and modelled against each other. This process drew out the options that were available for immediate to near term plants and which are suited to the South African conditions. Additionally the dissertation investigated where research on CSP is heading and which technologies are showing promise in terms of efficiency, cost and ease of use from which informed decisions can be made on possible “leap frog” technologies. Molten salt stood out as the obvious immediate choice due to its maturity. However volumetric air/gas, concrete, graphite and phase change materials are all showing promise in pilot plants around the world. Therefore there does not appear, as of yet, to be a “silver bullet” solution to storage. Out of a possible fourteen storage technologies this thesis was able to highlight roughly seven technologies for large scale CSP energy storage however, further observation and analysis is recommended to allow a fuller understanding of the implications and requirements of these advanced technologies.

The second major question this thesis aimed to answer was: what are the requirements to building a local design, manufacturing, operations and maintenance industry. One of the requirements in South African labour, which relates to this

question, is the potential to create jobs. South Africa's vast unemployment rate of around 25% is increasing in response to the global economic downturn. CSP offers an opportunity to establish a new employment structure which spans multiple sectors while, at the same time, addressing climate change concerns. Job creation will occur through all skill levels, from highly qualified personnel, to semi-skilled even to unskilled and across the sectors of manufacturing, distribution, research and development and management. The employment estimations do vary from source to source but even the most pessimistic paper still holds a strong case, making the option of CSP seem a compelling case.

In the breakdown of the plant, a couple of highly specialized key components are required, however none are beyond the ability of the South African manufacturing industry. It is the recommendation of this paper that the design of these critical components should, in the very least, been consulted over by the international community who are experts in the CSP field and whose experience could offer some security to the performance of the plants. Scaling up the manufacturing, installations and capacities of CSP plants, to the numbers discussed, would require a national commitment and plan from all sectors involved.

The raw material requirements of the large capacities estimated did not present a barrier as South Africa is endowed with large mineral deposits of which exporting is a common occurrence. The distribution of decentralized manufactured components to the Northern Cape region did not appear to hold any barriers, as is the case for many CSP sites around the world, as the national road and railway infrastructure connects all the point sources concerned. The power generation, manufacturing industry is already well established in South Africa and is believed by some to be a world leader. The crippling national automotive industry was highlighted as having flexibility and

retooling capability to shift direction and focus on CSP component manufacture thereby minimizing job loss and revitalizing one of South Africa's major workhorses.

Finally the labor force required to be developed alongside the infrastructure is said to span multiple sectors and requires skill levels from highly specialized, right down to non skilled personal. Caldes (2009) represented the best source for employment estimates, stating some very negative employment figures for fossil fuels infrastructure. It is therefore the findings of this dissertation that in terms of employment, materials, manufacturing and skills, the CSP industry in South Africa will offer multiple solutions to the multiple problems of generation capacity, climate change mitigation and unemployment.

It would be in South Africa's interest to encourage CSP technology, with the aim of building an industrial supply infrastructure on the model of China's success story in producing the industrial base for Wind Power. CSP can be the solution to address South Africa's future power demand, particularly around 2020-2025, when the majority of the country's coal fired generating capacity will have run its lifetime. CSP generated electricity, by some estimates, may already cheaper than electricity generated from nuclear, especially intermediate load-following nuclear, and if CSP is not cheaper today already, it will be in 10 years according to a conservative 2% learning factor. This calls into question the government's present long-term nuclear strategy, aimed at generating 25% of the capacity requirements in 2025.

Encouraging CSP would also contribute to South Africa's target of reversing its carbon emissions growth by 2020-2025 and international climate change financing can be encouraged in developing the CSP industry. Poverty alleviation should be seen as a major asset of the CSP path and South Africa has the potential to become a world leader in this new age of green, sustainable living.

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APPENDIX A

Renewable Energy Feed – In Tariff Guidelines

NATIONAL ENERGY REGULATOR OF SOUTH AFRICA

In the matter regarding

**RENEWABLE ENERGY FEED – IN TARIFF
GUIDELINES**

by

The Energy Regulator of South Africa (NERSA)

NATIONAL ENERGY REGULATOR OF SOUTH AFRICA

1. INTRODUCTION

RENEWABLE ENERGY FEED – IN TARIFF GUIDELINES

2.

the Energy Regulator of South Africa (NERSA)

DECISION

On 26th of October 2009, the EREG Committee, in its 11th meeting, considered the Renewable Energy Feed-in Tariff (REFIT) Guidelines. The Committee has decided to approve the REFIT Guidelines as presented to it.

1. The REFIT Guidelines are hereby approved. The REFIT Guidelines are attached as Appendix A to the Decision. The REFIT Guidelines are effective from 1 January 2010.

Table 1: REFIT Tariffs – 2009 (R/kWh)

Category	Sub-category	REFIT
Small Hydro	Small Hydro	1.25
Small Wind	Small Wind	0.94
Small Solar	Small Solar	0.90
Small Biomass	Small Biomass	2.10

2. The REFIT Guidelines are hereby approved. The REFIT Guidelines are attached as Appendix A to the Decision. The REFIT Guidelines are effective from 1 January 2010.

3. The REFIT Guidelines are hereby approved. The REFIT Guidelines are attached as Appendix A to the Decision. The REFIT Guidelines are effective from 20 January 2010.

4. The REFIT Guidelines are hereby approved. The REFIT Guidelines are attached as Appendix A to the Decision. The REFIT Guidelines are effective from 20 January 2010. The REFIT Guidelines are hereby approved. The REFIT Guidelines are attached as Appendix A to the Decision. The REFIT Guidelines are effective from 20 January 2010.

5. A REFIT Guidelines are hereby approved. The REFIT Guidelines are attached as Appendix A to the Decision. The REFIT Guidelines are effective from 20 January 2010.

- [illegible]

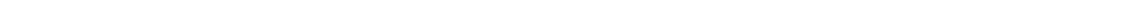
REASONS FOR DECISION

INTRODUCTION

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BACKGROUND

THE RENEWABLE ENERGY FEED IN TARIFF

- 13 

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E P

The diagram shows a large rectangle divided into two smaller rectangles. The top rectangle is labeled '10x5' and the bottom rectangle is labeled '5x5'. This illustrates the decomposition of a 10x10 grid into two 10x5 and 5x5 grids.

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OBJECTIONS AND INTERVENING PARTIES

23. **78** **p**

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[illegible]

26. Proposed Tariff Levels

- [illegible]

27. The Power Purchase Agreement Term Period

[illegible]

28. Future Tariffs Review

[illegible]

29. Reduction Rate

- [illegible]

30. Inclusion of carbon revenue from Clean Development Mechanism (CDM)

- I am not convinced that the results of the 2012 NEA are representative of the population of the United States. The results of the 2012 NEA are based on a sample of 3,000 people, which is not representative of the population of the United States.
- The results of the 2012 NEA are based on a sample of 3,000 people, which is not representative of the population of the United States. The results of the 2012 NEA are based on a sample of 3,000 people, which is not representative of the population of the United States.

31. Other REFIT Qualifying technologies

- 1990 年，美国科学家发现，在细胞核内，DNA 双链的其中一条链的碱基序列与 mRNA 的碱基序列完全相同，而另一条链的碱基序列则与 mRNA 的碱基序列互补。
- 1990 年，美国科学家发现，在细胞核内，DNA 双链的其中一条链的碱基序列与 mRNA 的碱基序列完全相同，而另一条链的碱基序列则与 mRNA 的碱基序列互补。

32. Appointment of Eskom as a Renewable Energy Purchasing Agency (REPA)

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- **E** **p** **E**
- **E** **pp** **p** **p**
- **EPA** **p**
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- **NEA** **EPA** **p**

33. Monitoring and Verification

The EPA is responsible for setting and enforcing the national standards for air quality. The EPA also provides technical assistance to states and localities to help them develop and implement their own air quality programs.

34. Licence Requirements

p -values are calculated from the test statistics by comparing them against the null distribution.

35. □□□□ □E□I□ □□□□□□□□□□ □□□□□ □□□□□□□□□□ □□□□□ □□□□□ N□□□□□
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36 A

- ### 37. Proposed Tariff Levels

- တစ်ခုတည်းသော μ ကို ခန့်မှန်းရာတွင် များမည်မျှသာ ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ များမည်မျှသာ ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ E ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ A ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ 2006 ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊
- တစ်ခုတည်းသော p ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ p ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ E ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ p ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊ E ခန့်မှန်းချက်များကို အသုံးပြုသော်လည်းကောင်း၊

Table 3: Market conditions, reference technology cost and performance assumptions

PARAMETER	UNITS	WIND	SMALL HYDRO	LANDFILL GAS METHANE	CONCENTRATED SOLAR PLANT (CSP), PARABOLIC TROUGH WITH STORAGE (6 hrs per day)
Pre-construction period (months)	months	2000	2600	2400	4700
Construction period (months)	months	5	2	2	2
Annual electricity production (MWh)	MWh	4.4	10.6	4.4	4.4
Annual electricity production (GWh)	GWh	3	3	3	3
Annual electricity production (TWh)	TWh	0	0	0	8
TOTAL INVESTMENT COST	\$/kW	2255	3020	2631	5545
Construction cost	2009\$/kW	24	39	116	66
Construction cost	2009\$/kW	0	0	0	0
Electricity production cost	\$/MWh	20	20	20	20
Annual electricity production	MWh	12	12	12	12
Pre-construction period	months	2	3	2	2
Construction period	months	5	2	2	2
Annual electricity production	MWh	10.6	0	1.5	0
Annual electricity production	GWh	0	0.00106	0	0
Annual electricity production	TWh	0	0	13500	0
Annual electricity production	MWh	27	50	80	40
Levelised cost of electricity production	\$/kWh	0.1247	0.0940	0.0896	0.2092
Electricity production cost	\$/MWh	10	10	10	10
Levelised cost of electricity production	R/kWh	1.247	0.940	0.896	2.092

38. The Power Purchase Agreement Term Period

- [illegible]

39. Future Tariffs Review

El **p** **p**

40. Reduction Rate

D
E

41. Inclusion of carbon revenues from CDM

[illegible]

42. Other REFIT Qualifying Technologies

[illegible]

43. Appointment of Eskom as a Renewable Energy Purchasing Agency (REPA)

- [illegible]

44. Monitoring and Verification

- EPA has proposed to regulate greenhouse gases from new cars and trucks. EPA estimates that NECA will save \$1 billion over the next 10 years.
- The American Petroleum Institute (API) has filed a lawsuit with the U.S. District Court in Washington, D.C., challenging EPA's authority to regulate greenhouse gases.

45. Licence Requirements

A) pp NE A p N P

46. Standard Power Purchase Agreement (PPA)

- [illegible]

APPENDIX A: RENEWABLE ENERGY FEED-IN TARIFF GUIDELINES

APPENDIX B

Summary of Key Tables

University of Cape Town

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

Table 1.1: Eskom planned mitigation case scenarios A and B. Source: (Eskom, 2008)

Technology	Reference Case	Scenario A	Scenario B
Efficiency	Load growth 4.4% per year to 2026; 2.5% (no efficiency) to 2050	Reduces expected growth in annual demand by estimated 0.23%	Reduces expected growth in annual demand by estimated 0.23%
Renewables	900 MW wind by 2026, 2GW by 2050	4.5GW wind plus 8.5GW solar by 2050	4.5GW wind plus 30GW solar by 2050
Nuclear	No new nuclear	40GW by 2050 (20GW by 2026)	30GW by 2050 (20GW by 2026)
Hydro imports	No new imports	17GW by 2050	17GW by 2050
Clean Coal	Supercritical (36%)	41% (2025); 45% (2030); 47% (2035)	41% (2025); 45% (2030); 47% (2035)
Capture & Storage	None	All new coal plant from 2035	All new coal plant from 2035

Table 5.1: International Solar Potential relative to Upington, South Africa. Source: (Eskom, 2006)

Location	Site Latitude	Annual DNI (kWh/m2)	Relative Solar Resource
South Africa			
Upington, North Cape	28°S	2 955	100%
United States			
Barstow, California	35°N	2 725	92%
Las Vegas, Nevada	36°N	2 573	87%
Albuquerque, New Mexico	35°N	2 443	83%
International			
Northern Mexico	26-30°N	2 835	96%
Wadi Rum, Jordan	30°N	2 500	85%
Ouarzazate, Morocco	31°N	2 364	80%
Crete	35°N	2 293	78%
Jodhpur, India	26°N	2 200	74%
Spain	34°N	2 100	71%

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

Table 5.2: Table of the suitable land area in the relevant provinces in South Africa and their associated energy generation potential. Source: (Fluri, 2009)

Province	NC	FS	WC	EC	Total
Suitable Land Area, km ²	14 288	708	294	44	15 334
Power Generation Potential, GW	510.3	25.3	10.5	1.6	547.6
Net Energy Generation, TWh/a	1 734.3	85.9	35.7	5.3	1 861.4

Table 5.3: Table of the water requirements for the relevant provinces (Source: Fluri, 2009)

Province	NC	FS	WC	EC	Total
Power Generation Potential, GW	510.3	25.3	10.5	1.6	547.6
Net Energy Generation, TWh/a	1 734.3	85.9	35.7	5.3	1 861.4
Water requirement (wet cooling), million m ³ /a	6 399.9	317.1	131.7	19.7	6 868.5
Water requirement (dry cooling), million m ³ /a	520.3	25.8	10.7	1.6	558.4

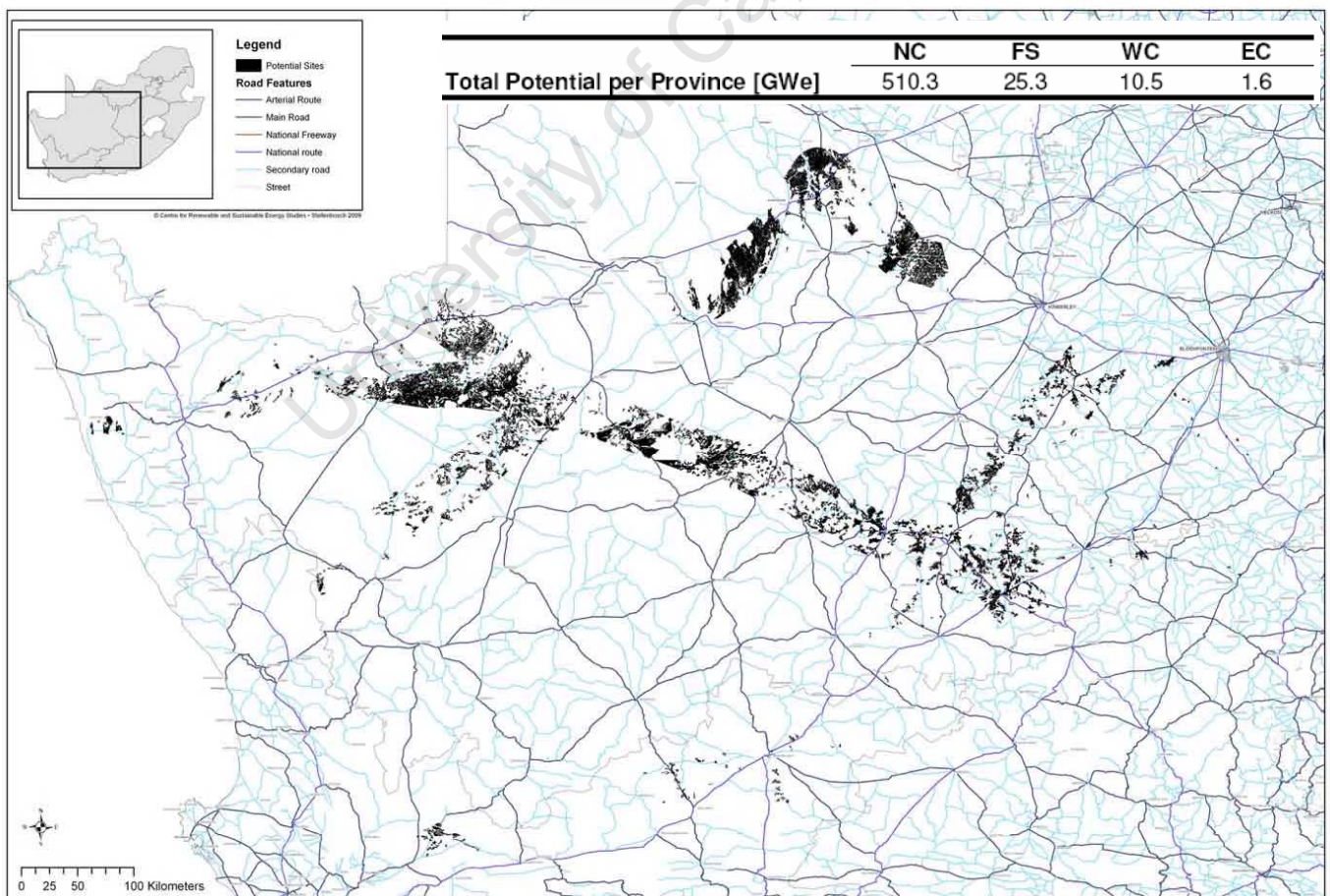


Figure 5.1.7: Map of South Africa, indicating areas which are suitable for the installation of large concentrating solar thermal power plants without significant changes to infrastructure (Source: Fluri, 2009)

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

Table 5.4: Table of the various line configuration capacities and sizes. Source: (Van der Merwe, 2009)

Line Capacities:			
Configuration Name	Transmission Line Size		
	275kV	400kV	765kV
Twin Zebra	0.9GW	1.3GW	-
Twin Dinosaur	1.2GW	1.8GW	3.4GW
Quad Zebra	1.6GW	2.3GW	4.3GW
Quad Dinosaur	-	3.6GW	6.8GW

Table 5.5: Table of the associated line costs in Million Rand's per kilometre (Van der Merwe, 2009)

Line Costs:	
Line Voltage	Cost / km (R millions)
275kV	R 1.7 million
400kV	R 2.6 million
765kV	R 6 million

Table 5.6: Tables indicating the associated costs with the various variables of HVAC (Source: Van de Merwe, 2009)

	Transformer Costs:		Transformer Bays	Busbars	Line Bays
Line Voltage	Transformer size and voltage	Cost (R)	Cost (R)	Cost (R)	Cost (R)
275 kV	160MVA	R 28 million	R 6 million	R 1.7 million	R 5 million
400 kV	315MVA	R 50 million	R13 million	R 2 million	R 11 million
765 kV	500MVA	R 55 million	R 25 million	R4 million	R 20 million

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

Table 5.7: Tables indicating the properties of the various HVDC projects around the world. Source: (DLR, 2006)

HVDC/country	Design	Start of operation	Power [MW]	Voltage $\pm$ [kV]	Length [km]	System
SACOI/Sardinia-Corsica-Italy	SC,O	1967	300	200	423	Bipole - multi-terminal
Cahora Bassa/ Mozambique-SouthAfrica	O	1977-79	1 930	533	1 420	Bipole - 2 lines
Inga-Shaba/ Congo	O	1982	560	500	1 700	2 x Monopole
Itaipu/ Brasilia	O	1984 - 87	6 300	600	800	Double Bipole
Québec-New England/ Canada-USA	O	1990 - 92	2 000	450	1 480	Bipole Multi terminal
BalticCable/ Swe-Ger	SC	1994	600	450	250	Monopole
SwedPol/ Sweden-Poland	SC	2000	600	450	260	Monopole, metallic return
Italy-Greece	UC,SC,O	2001	500	400	310	Monopole
Murraylink/Australia	UC, SC, O	2002	220	150	177	Bipole, HVDC light
NorNed/Nor-NL	SC	2007	700	450	580	2x Monopole

Table 5.8: Cost and performance variables of HVDC and HVAC options transmitting 5GW of power. Source: (DLR, 2006)

Parameter	Unit	HVAC		HVDC	
Operation Voltage	kV	750	1150	600	800
overhead line losses	%/1000 km	8%	6%	5%	2.50%
sea cable losses	%/100 km	60%	50%	0.33%	0.25%
terminal losses	%/ staion	0.20%	0.20%	0.70%	0.60%
overhead line cost	Billion R/1000 km	4.5 - 8.5	11.3	4.5 - 5.1	2.8 -3.4
sea cable cost	Billion R/1000 km	36.2	66.7	28.3	20.3
terminal cost	Billion R/station	0.9	0.9	2.9 – 4.0	2.9 – 4.0

Table 5.11: Summary table indicating the various requirements for immediate, large scale CSP storage and the performance of each storage technology

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

Technology	Key Requirements (5 = good, 1 = poor, 0 = fail, U = unknown)						
	Size	Duration	Geography	Maturity	Cost	Efficiency	Total (30)
Superconducting	3	0	5	3	1	5	Fail
Supercapcitors	0	3	5	3	2	5	Fail
Flywheel	1	0	5	4	1	5	Fail
Pumped Hydro	5	5	U	5	4	4	Unknown
Compressed Air	5	5	U	4	5	4	Unknown
Batteries (Lead, NiCd)	3	4	5	5	2	4	23
Fuel Cells	4	4	5	2	0	2	Fail
Flow Batteries	3	4	5	3	U	4	Unknown
Solar Fuels	3	5	3	1	U	1	Unknown
Molten Salt	5	5	5	3	5	3	26
Concrete	4	4	5	2	5	U	Unknown
Direct Steam	3	2	5	2	4	U	Unknown
Graphite	4	5	5	2	4	U	Unknown
Phase change	4	4	5	2	4	U	Unknown

Table 5.12: Summary table indicating the various requirements for future, large scale CSP storage and the performance of each storage technology

Technology	Key Requirements (5 = good, 1 = poor, 0 = fail, U = unknown)						
	Size	Duration	Geography	Maturity	Cost	Efficiency	Total (30)
Superconducting	3	0	5	5	1	5	Fail
Supercapcitors	0	3	5	5	2	5	Fail
Flywheel	1	0	5	5	1	5	Fail
Pumped Hydro	5	5	U	5	4	4	Unknown
Compressed Air	5	5	U	5	5	4	Unknown
Batteries (Lead, NiCd)	3	4	5	5	2	4	23
Fuel Cells	4	4	5	5	0	2	Fail
Flow Batteries	3	4	5	5	3	4	24
Solar Fuels	3	5	5	5	3	3	25
Molten Salt	5	5	5	5	5	3	28
Concrete	4	4	5	5	5	4	27
Direct Steam	3	2	5	5	4	4	23
Graphite	4	5	5	5	4	4	28
Phase change	4	4	5	5	4	4	26

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

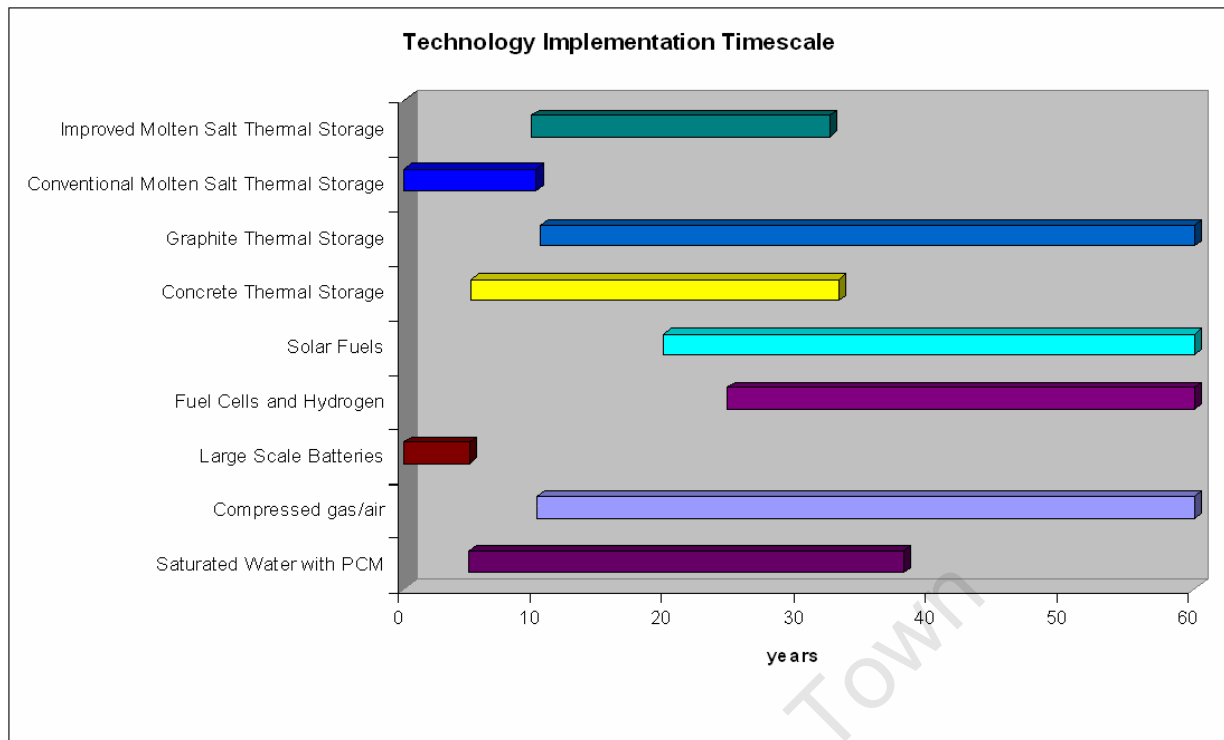


Figure 5.3.29: Graphic showing possible implementation timeline of the various storage technology options for large scale CSP in South Africa

Table 6.1: Approximate direct job creation of various energy technologies. Source: (Agama, 2003)

Conventional Energy Technologies	Direct jobs per MW capacity	Direct jobs per GWh generated	Renewable energy technologies	Direct jobs per MW capacity	Direct jobs per GWh generated
Coal (current)	1.7	0.3	Solar Thermal	5.9	10.4
Coal (future)	3	0.7	Solar PV	35.4	62
Nuclear	0.5	0.1	Wind	4.8	12.6
Nuclear PBMR	1.3	0.2	Biomass	1	5.6
Gas	1.2	0.1	Landfills	6	23

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

Table 6.4: Table summarizing the ranging capacity costs of the core components

	Heliostat			Receiver			Storage		
	Cost _(ea)	Amount	Total (million)	Cost (million)	Amount	Total million	Cost _(per 13MWh)	Amount	Total (million)
100MW	R170 000	8 000	R1 360	R 252	1	R252	R7 150 000	100	R715
1 GW	R170 000	80 000	R13 600	R 252	10	R2 520	R7 150 000	1 000	R7 150
10 GW	R170 000	800 000	R136 000	R 252	100	R25 200	R7 150 000	10 000	R71 500
30 GW	R170 000	2 400 000	R408 000	R 252	300	R75 600	R7 150 000	30 000	R214 500
	Power Block			Transmission				Complete Total Cost (billion)	
	Cost (million)	Amount	Total (million)	Capacity	Distance	Total (million)			
100MW	13,2	1	R13	275kV	20	R40		R 2. 380	
1 GW	13,2	10	R132	765kV	370	R1 930		R 25. 332	
10 GW	13,2	100	R1 320	800HVDC	850	R23 000		R 257. 020	
30 GW	13,2	300	R3 960	800HVDC	850	R56 100		R 758. 160	

Table 6.5: Table summarizing the raw material estimates for the various CSP capacities

	Steel (tons)	Glass(tons)	Molten Salt (tons)	Concrete (m³)
100MW Plant	25 000	12 000	30 000	20 000
1 GW CSP	250 000	120 000	300 000	200 000
10 GW CSP	2 500 000	1 200 000	3 000 000	2 000 000
30 GW CSP	7 500 000	3 600 000	9 000 000	6 000 000

Table 6.6: Table summarizing production and exportation numbers of the various materials for 2007

Material	Production (Tons)	Export (Tons)	year
Aluminum	914 000	597 000	2007
Iron Ore	42 083 000	29 725 000	2007
Ferro Alloys	4 778 000	3 861 000	2007
Chromium Alloys	3 561 000	2 972 000	2007
Shale's for Cement	500 000	0	2007
Salt	411 000	0	2007
Silica	3 352 000	800	2007
Silver	69 800	76 900	2007
Copper	117 100	37 300	2007

Table 6.7: Table summarizing the international estimates for direct, indirect and total job creation

REQUIREMENTS FOR LARGE SCALE CSP DEPLOYMENT IN SOUTH AFRICA

	NREL	Black & Veatch	Gerrefi	Muller Steinhagen		
	Direct	Total	Direct	Direct	Indirect	Total
100MW Plant	455	4 000	94	100	1 000	1 100
1 GW CSP	4 550	40 000	940	1 000	10 000	11 000
10 GW CSP	45 500	400 000	9 400	10 000	100 000	110 000
30 GW CSP	136 500	1 200 000	28 200	30 000	300 000	330 000

Table 6.8: Summary of direct and indirect jobs from renewable energy sources in 2020, note the estimated numbers for approximately 1.4GW of Solar Thermal. Source: (Agama, 2003)

Technology	% of target	Direct Jobs	Indirect Jobs	Total Jobs	% of total jobs
Solar Thermal	10%	8 288	24 864	33 152	23%
Solar PV	0.50%	2 475	7 425	9 900	7%
Wind	50%	22 400	67 100	89 600	62%
Biomass	30%	1 308	3 924	5 232	4%
Landfill	5%	1 902	5 706	7 608	5%
Total	96%	36 373	109 019	14 5492	100%

Table 6.9: CSP's employment potential data direct jobs/MW and /GWh (Source: Agama, 2003)

	Fuel		Manufacturing		Installation		Operations & management		Other		Total	
	/MW	/GWh	/MW	/GWh	/MW	/GWh	/MW	/GWh	/MW	/GWh	/MW	/GWh
RET												
Solar Thermal	0	0	1.7	3	4	7	0.2	0.4	0	0	5.9	10.4
100MW	0		170		400		20		0		590	
1GW	0		1700		4000		200		0		5 900	
10GW	0		17 000		40 000		2000		0		59 000	
30GW	0		51 000		120 000		6000		0		177 000	