STRATEGIC ASSESSMENT AND MAPPING OF OPPORTUNITIES FOR WATER DESALINATION AND WATER-USE OPTIMISATION OF CONCENTRATED SOLAR POWER GENERATION IN SOUTH AFRICA

Report to the
WATER RESEARCH COMMISSION

by

Malin Govender, Sam Leyde, Theo Fischer and Michael Weston
EScience Associates (Pty) Ltd

WRC Report No. 2382/1/16
ISBN 978-1-4312-0787-9

May 2016

Obtainable from
Water research Commission
Private Bag X03
Gezina, 0031

orders@wrc.org.za or download from www.wrc.org.za

DISCLAIMER

This report has been reviewed by the Water Research Commission (WRC) and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the WRC, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

EXECUTIVE SUMMARY

BACKGROUND

South Africa has a high solar resource potential for use in Concentrated Solar Power (CSP) plants and other Solar Thermal (ST) plants, but it has limited water resources. Most thermal power plants require steam to be cooled after it has passed through the turbines (steam condensing at back end of turbine increases the pressure differential and thus increases the power output). This can be done using dry-cooling, wet-cooling or a combination of the two technologies (hybrid-cooling). Wet-cooled plants use a large amount of water and thus, especially in water scarce regions, dry-cooling or hybrid-cooling are more desirable options. Wet-cooling technology using brackish or saline water is an alternative to freshwater evaporative cooling. With large amounts of inland brackish and saline groundwater in South Africa, this resource could be utilised more efficiently; seawater may also be used. In either case the post turbine condensing energy can be used to drive desalination processes.

Whatever the cooling regime, a CSP plant still requires water of a reasonable quality for the steam cycle and mirror washing. Depending on the quality of the water resource available, varying degrees of treatment, including desalination, are necessary and this treatment inevitably results in brine that needs to be disposed of.

RATIONALE

Renewable energy projects, including CSP, are being increasingly developed in South Africa while the country attempts to minimise its reliance on fossil fuel-based power production. Concentrated Solar Power plants use a thermal power generation process which requires a steam cycle; the steam is required to be condensed, and this requires cooling. Wet-cooling, dry-cooling, or hybrid-cooling technologies may be used. While wet-cooling is the most efficient technology, it requires large amounts of water. Concentrated Solar Power offers potential for combined power generation and desalination. Areas that have a high Direct Normal Irradiance (DNI) usually have limited or no water resources and therefore wet-cooled CSP plants may compete for scarce water resources unless alternatives of CSP, including optimally sited dry cooling, CSP saline water cooling and CSP desalination, are investigated. Concentrated Solar Power plants using air cooling reduce water consumption by 90% but when the ambient temperatures exceed 30-35°C, the plant efficiency is reduced and less electricity is produced. Sites need to be chosen that have a suitable combination of cost of energy and cost of water to maximise the energy cost efficiency of CSP plants while still minimising water consumption.

AIMS

The overall aim of this project was to undertake strategic assessment and mapping of opportunities for water desalination and water use optimisation of concentrated solar power generation in South Africa. A set of GIS maps has been produced for the scenarios identified as being of interest.

The following were the aims of the project:

1. Obtain hourly solar DNI from existing databases, as well as Weather Research and Forecasting (WRF) mesoscale model on 4 km^2 resolution for high solar resource potential

areas (water-constrained arid areas such as Northern Cape, North West and the Free State and other areas with DNI > 2300 kWh/m^2).
2. Verify WRF DNI model data against ground based DNI monitoring stations.
3. Obtain hourly atmospheric data (temperature, pressure, wind speed, etc.) from WRF mesoscale model on 4 km^2 resolution in order to develop weather files to model CSP performance.
4. Verify WRF model temperature and DNI data against South African Weather Service (SAWS) and Department of Science and Technology (DST) Solar Radiation Monitoring Stations and weather data from associated automatic weather stations.
5. Adapt the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) with configuration files for air cooling, hybrid cooling, saline water cooling, and desalination cost options to produce CSP water cooled cost model, CSP air cooled cost model, CSP Saline water cooled cost model, CSP desalination cost model that can be operated on the Geographic Information Systems (GIS) database of Solar DNI, weather data, and other determinants of CSP feasibility.
6. Develop a GIS database platform for modelling CSP energy cost efficiency and water use model and output water used / water desalinated and mapping CSP water cooling, dry cooling and desalination cost maps as well as the cost of electricity and cost of water produced.
7. Using the model, identify areas best suited to CSP power generation in each category (CSP water cooled, CSP air cooled, CSP Saline water cooled, CSP desalination) and map water use implications associated with each option.
8. Undertake a comparison of CSP cooling option scenarios (dry cooling, wet cooling using fresh water, wet cooling using saline water and hybrid cooling) so that water usage associated with each option may be compared.
9. Investigate the effect of CSP storage for the various cooling and desalination scenarios.

METHODOLOGY

A CSP cost of energy/cost of water model was developed to include a technical and financial component. The model was developed using the NREL SAM model as a backbone. Ambient weather data and DNI were modelled using WRF. The base case SAM model was initially set up for the wet/evaporative cooling option. Before running the model for the different scenarios, a verification of the system architecture and WRF forecasting for DNI was undertaken. The model was then scripted to run in batch mode, i.e. receive the ambient weather and DNI data for a grid cell, perform the SAM CSP simulation for the grid cell; write out the relevant parameters of interest, before moving to the next grid cell and repeating the operations.

The DNI input into the model was obtained through WRF modelling and verified against three months of observations of DNI data. The verification revealed over-prediction of the DNI on cloudy days to the extent that the WRF model was not capturing the frequency of cloudy days, resulting in an over-prediction of DNI and consequently power produced. Corrections were made when the WRF model misses clouds, or WRF overestimates clouds. This process corrected the initial overestimation in the WRF DNI and provided a more reliable spatial distribution of DNI.

The model outputs were then post-processed and interfaced with GIS mapping functions to produce maps reflecting the combined costs of output, i.e. cost of energy and cost of water for the different cooling options, water sources and desalination technologies considered. The scenarios that were modelled include wet, dry, and hybrid cooling, different cooling water supplies, and different desalination methods.

KEY FINDINGS

With the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) two-tier tariff regime for Round 4 CSP projects, all of the scenarios considered offer reasonable returns on investment. It would be economically feasible to operate CSP plants in South Africa under the two-tier tariff for all the scenarios that were modelled. Storage allows the plant to be optimised for part load operation which could see better Internal Rates of Return (IRRs) achieved than those predicted in the non-optimised scenarios.

Hybrid wet/dry cooling employing between 0 and 30% fresh water cooling during different hours of the day is the most attractive option in terms of IRR. Wet cooling using brackish or saline water with saline cooling towers is also attractive, with slight penalties for the additional cost of the cooling towers as well as brine disposal. These are nevertheless viable options as there is a significant amount of freshwater demand that is avoided and the IRR achieved is competitive with that of an air cooled plant.

Desalination costs are greatly decreased by co-locating the desalination plant at a CSP facility in order to exploit the CSP infrastructure. Reverse Osmosis (RO) plants appear to have a marginally better return than Multi-Effect Distillation (MED) plants, but MED is still very competitive. With increasing electricity prices and potential insecurity of supply, RO-based water production could face some challenges in future. The other important benefit of CSP coupled to MED or RO plants is derived from the amount of freshwater use avoided in the cooling as well as being produced as a saleable product. In terms of IRR, MED and RO plants coupled to a CSP plant can compete with air-cooled CSP plants. However, in terms of the cumulative effects of power produced, Freshwater Demand Avoided and IRR, the scenarios involving the MED and RO plants are the most attractive.

All the scenarios modelled included costs for brine disposal to an evaporation pond. For the MED and RO scenarios the cost of the brine disposal is shown to have a significant effect on the financial viability of the plant as is the well-field establishment and operation cost, however the results indicate that projects are still economically competitive under all the scenarios using an evaporation landfill as method of brine handling.

RECOMMENDATIONS

It is proposed to further investigate CSP coupled desalination and brine treatment in order to exploit existing CSP infrastructure to reduce costs relative to green-field implementations. It is recommended that the future research include a techno-economic assessment to determine sustainability, cost effectiveness and practicality of these opportunities.

The study can be expanded to assess the feasibility of pumping seawater inland for desalination at a CSP desalination plant. The costs of this could be somewhat offset against the high costs used in the model for well-field establishment and operation.

CSP plants combined with desalination are shown to be economically competitive. A plant of this nature would be in line with the policy laid out in the National Water Resources Strategy. Unlike desalination plants powered by PV or wind, A CSP desalination plant can provide both electricity and freshwater. Further allocation to CSP in the REIPPP would aide in the implementation of such plants.

ACKNOWLEDGEMENTS

The project team wishes to thank the following people for their contributions to the project.

Dr Jo Burgess	Water Research Commission
Mr Vikesh Rajpaul	Eskom
Mrs Dhelia Raman	Eskom
Dr Thomas Roos	Council for Scientific and Industrial Research
Dr Amos Madhlopa	University of Cape Town
Mr Michael Price	Sebenzana / Industrial Energy
Prof Thoko Majozi	University of the Witwatersrand

The project team would also like to thank the Water Research Commission for their support and funding of this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACC	Air-cooled condensers
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
EC	Evaporative crystallization
EFC	Eutectic Freeze Crystallization
FR	Fresnel Reflector
IRR	Internal Rate of Return
LCOE	Levelised cost of energy
MED	Multi Effect Distillation
MEH	Multi Effect Humidification
MSF	Multi-stage Flash Distillation
O&M	Operations and Maintenance
PT	Parabolic Trough
RO	Reverse Osmosis
SAM	System Advisor Model
SD	Solar Dish
SH	Superheated
ST	Solar Tower
VMEMD	Vapour Membrane Distillation
WCC	Water-cooled condensers
WRF	Weather Research and Forecasting

1 INTRODUCTION AND OBJECTIVES

1.1 Background

South Africa has a high resource potential for the use of Concentrated Solar Power (CSP) Plants, however, this is coupled with limited water resources. Concentrated Solar Power plants use light energy from the sun to generate heat which is used to power a Rankine steam cycle, thereby converting solar thermal energy into electricity. Most thermal power plants require the steam to be cooled after it has passed through the turbines, as steam condensing at the back end of turbine reduces the pressure differential and increases the power output. This cooling can be achieved using dry-cooling, wet-cooling or a combination of the two technologies (hybrid-cooling). Wet-cooled plants use 2270 to 3030 ℓ water/MWh generated (US Department of Energy, 2009) (US Department of Energy, 2009) and thus, especially in water scarce regions, dry-cooling or hybrid-cooling is a more desired option.

Although an air-cooled CSP plant typically uses 10% of the water that a wet-cooled plant uses, this method of cooling reduces the efficiency of the plant. An air cooled plant produces about 5% less electricity than an equivalent wet-cooled plant. When ambient air temperatures exceed 35°C air cooling of the post turbine condensing steam does not achieve the reduction comparable with wet cooling, and the plant is less efficient. Thus, the cost of the electricity produced in a dry-cooled plant is 7-9% more expensive than at a wet-cooled plant (US Department of Energy, 2009).

However, these figures are location specific, as the ambient air temperature at an air-cooled plant dictates the efficiency of that plant. The nature of the regions that receive a high amount of Direct Normal Irradiation (DNI) means that these areas have high daytime temperatures, and the higher these temperatures are, the less effective dry-cooling technology becomes. In order to optimise CSP efficiency, dry-cooled CSP plants need to be carefully sited so that they are located in areas with a high DNI but experience a limited number of days with temperatures exceeding 30°C. Optimal sites need to have a suitably high DNI, combined with low average daily temperature (to reduce efficiency losses). Further requirements are that the site needs to be located in a region with suitably flat land (CSP typically requiring a slope of less than 1%) and, ideally, within reasonable range of existing transmission infrastructure.

A study completed in the South-Western United States showed that for wet-cooled plants the ambient temperature had a negligible effect on the plant performance. However, with dry-cooling, once the ambient temperature exceeds 35°C the plant performance begins to drop and when temperatures exceed 38°C performance is reduced significantly (Carter & Campbell, 2009).

Another option to reduce water usage, without decreasing the plant performance and increasing the plant costs as much as with a dry-cooled plant, is to use hybrid cooling systems. Hybrid cooling can reduce the water usage of a plant by as much as 90%. A hybrid cooled plant utilising 10% of the water required at a wet-cooled plant can supply 97% of the performance of a fully wet-cooled plant. Alternatively, the plant can use 50% of the amount of water used for a wet-cooled plant, achieving 99% of the performance of a wet-cooled plant. There is a fine balance between efficiency and water consumption when designing a CSP plant.

The different technologies of CSP include Linear Fresnel, Parabolic troughs, Power tower and Dish/engine. All of the technologies have different water usage statistics for wet-cooled and dry-cooled plants, as well as a difference in performance efficiency for their associated cooling systems.

Wet-cooling technology using brackish or saline water is an alternative to freshwater evaporative cooling. Currently there a number of power plants in the United States of America that use saline/sea water cooling towers. The cost is higher than that associated with freshwater cooling towers due to a requirement for more expensive, corrosion resistant materials of construction, as well as the fact that for an equivalent cooling capacity a saltwater cooling tower is required to be slightly larger than a freshwater cooling tower. According to a study by the Californian Energy Commission, the costs associated with saltwater cooling towers are approximately 1.5 times higher than that of freshwater cooling towers (Maulbetsch & Di Filippo, 2010).

The resources of inland brackish and saline groundwater in South Africa could be utilised more efficiently, and seawater may be used on the coast. In either case the post turbine condensing energy can be used to drive desalination processes. This desalination process would work in the following way: water containing dissolved salts is sprayed on the outside surface of tubes laying in horizontal configuration with the post turbine steam flowing within the tubes. As the steam travels through the tubes it cools and condenses; meanwhile, the raw water sprayed on the outside is heated and begins to evaporate. The heavy brine condensate collects at the bottom, and the raw water which has now been heated to steam travels to the next stage, where the process is repeated until the saline water has been sufficiently purified. This process operates at less than 70°C to prevent scale formation. This process is called MED (multi-effect distillation) desalinisation. Typical industrial MED systems have up to 12 stages, in which low pressure steam extracted from cogeneration boilers is used in the first stage. The vapour generated in this first effect is used to evaporate the water/effluent in the second stage, and this continues until the temperature drops to 30-40°C. With such low temperature desalination processes, for every 1 MW of electricity that is generated through CSP thermal plant, some 3 MW of waste heat that is captured through steam condensation (at the back end of the turbine) may be used to drive desalination, resulting in a fresh water output of 3 m^3/h (thus delivering approximately 3 m^3/MWh).

Combined solar power and desalination plants apply the principle of co-generation to achieve the best possible technical and economic efficiency of solar energy conversion. They deliver two key products for economic development: power and water, both at a reasonable and sustainable cost. In terms of environmental impact, they produce much less pollution and greenhouse gas emissions than equivalent reverse osmosis (RO) desalination plants operated on electricity from fossil fuel fired power generation systems. Two existing thermal desalination technologies are available: MED and MSF (multi-stage flash distillation). In terms of primary energy and electricity consumption, MED is more efficient than MSF. Multi-effect distillation also has a lower cost. Moreover, the operating temperature of MED is lower than MSF, thus requiring steam at lower pressure if connected for combined generation to a steam cycle power plant.

Currently, RO plants have much lower primary energy consumption and significantly lower capital costs (although similar water production costs) than MED. Currently, RO technology is the preferred desalination technology in the market due to historical low electricity prices, low capital costs, and the ability to run the plant only when required (e.g. in times of drought, as opposed to MED that has to run continually to service capital costs).

However, where MED is coupled to a power plant, it replaces the cost of the condensation unit of the steam cycle and partially uses waste heat from power generation for the desalination process. In this case, not all the primary energy used is for the desalination process, but only the portion that is equivalent to a reduction of the amount of electricity generated in the plant when compared to conventional cooling at lower temperature, as well as, the direct power consumption of the MED process.

It must be noted that, currently, the majority of South Africa's salt is produced from inland brackish water deposits. Brackish water is pumped into salt pans and allowed to evaporate, leaving the salt behind. A review of the South African salt industry in 2001 showed that an estimated 261,000 tons of salt was produced from inland salt production in 2001 (Department of Minerals and Energy, 2001). The brackish water used for this process has a similar salt concentration to seawater (these deposits have a marine origin and groundwater has a salinity similar to that of seawater). Additionally, 9.9 billion litres of water would have been used in the production of that salt in 2001. With water cooling consumption of 3030 ℓ/MWh, CSP plants generating 3.26 million MWh could have been operated using this saline water as cooling water in 2001 (equal to 1 GW of CSP generation plant cooling water requirements). Not only could this be beneficial to the CSP industry but also to the salt industry, by making salt production more competitive (currently South Africa imports the majority of its salt as domestic producers struggle to compete with import prices). Using saline water in cooling towers can make local salt producers more competitive by covering pumping costs, accelerating evaporation and thus, increasing salt production rates.

Concentrated solar power plants may be hybridised with fossil fuel plants so that fossil fuels provide energy to generate steam for passing through turbines, thus enabling hybrid power plants to generate base load power without needing thermal storage systems. Should shale gas production take place through the hydraulic fracturing process, an opportunity exists for CSP power plants to be hybridised with shale gas as shale gas resources overlap significantly with high DNI solar resources. With shale gas production, water produced from hydraulic fracturing can be used for CSP cooling or may be desalinated by CSP waste heat. Water mixed with various chemicals is pumped into the ground during hydraulic fracturing, in many instances through strata that have a marine origin. It is estimated that 68-82% of this water is recovered and in certain instances more water may be liberated. This water must then be treated so as to remove the chemicals of which some may be harmful to the environment. Instead of the produced water being concentrated to brine and solid concentrates through evaporation, such produced saline water may be put to productive use in wet-cooled CSP plants, thereby leaving salts that could be recovered through differential crystallisation (United States Environmental Protection Agency, 2004).

South Africa's Integrated Resource Plan (IRP) envisages generation of an additional 56 500 MW by 2030, compared with current capacity of about 38 000 MW, most of which is currently produced by Eskom coal-fuelled power stations. Of the new capacity, 21 534 MW, or 38%, is scheduled to be generated through renewable energy technologies, with 1 200 MW allocated to CSP (Department of Energy (DoE), 2010). European Academies Science Advisory Council (November 2011) predicts grid price parity with fossil fuels between 2020 and 2030 in Europe, and sooner in places with high DNI. It may be expected that CSP will shortly compete with coal power and significant CSP generation capacity is expected to be added to South Africa's power generation capacity.

1.2 Rationale

Renewable energy projects, including CSP, are being increasingly developed while South Africa attempts to minimise its reliance on fossil fuel based power production. Concentrated Solar Power plants use a thermal power generation process which requires a steam cycle, the steam therefore is required to be condensed and this requires cooling. Cooling is done using wet-cooling, dry-cooling, or hybrid-cooling technologies. Whereas wet-cooling is the most efficient technology, it requires large amounts of water. Concentrated Solar Power offers potential for combined power generation and desalination. Areas that have a high DNI usually have limited or no water resources therefore wet-cooled CSP plants may come to compete for scarce water resources unless alternatives of CSP including optimally sited dry cooling, CSP saline water cooling and CSP desalination is investigated. Concentrated Solar Power plants using air cooling reduce water consumption by 90% but when the ambient temperatures are high (above 30-35°C) the plant efficiency is reduced thus less electricity is produced. In order to optimise the energy cost efficiency of CSP plants while still minimizing water consumption sites need to be chosen that have an optimal combination of cost of energy and cost of water.

1.3 Aims and Objectives

The following were the aims of the project:

1. Obtain hourly solar DNI from existing databases, as well as Weather Research and Forecasting (WRF) mesoscale model on 4 km^2 resolution for high solar resource potential areas (water constrained arid areas such as Northern Cape, North West and the Free State and other areas with DNI > 2300 kWh/m^2)
2. Verify WRF DNI model data against ground based DNI monitoring stations
3. Obtain hourly atmospheric data (temperature, pressure, wind speed, etc.) from WRF mesoscale model on 4 km^2 resolution in order to develop weather files to model CSP performance
4. Verify WRF model temperature and DNI data against South African Weather Service (SAWS) and Department of Science and Technology (DST) Solar Radiation Monitoring Stations and weather data from associated automatic weather stations
5. Adapt the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) with configuration files for air cooling, hybrid cooling, saline water cooling, and desalination cost options to produce CSP water cooled cost model, CSP air cooled cost model, CSP Saline water cooled cost model, CSP desalination cost model that can be operated on the Geographic Information Systems (GIS) database of Solar DNI, weather data and other determinants of CSP feasibility
6. Develop a GIS database platform for modelling CSP energy cost efficiency and water use model and output water used/ water desalinated and mapping CSP water cooling, dry cooling and desalination cost maps as well as the cost of electricity and cost of water produced
7. Using the model, identify areas best suited to CSP power generation in each category (CSP water cooled, CSP air cooled, CSP Saline water cooled, CSP desalination) and map water use implications associated with each option may be compared
8. Undertake a comparison of CSP cooling option scenarios (dry cooling, wet cooling using fresh water, wet cooling using saline water and hybrid cooling) so that water usage associated with each option may be compared
9. Investigate the effect of CSP storage for the various cooling and desalination scenarios

The results of this study are intended to guide the Southern Africa Solar Thermal and Electricity Association in promoting development in the most suitable areas, to guide CSP developers bidding in the Renewable Energy Independent Power Producer Procurement Programme (REIPPP) programme to develop sites in areas most optimally suited to do so, and for Environmental Impact Assessment (EIA) reviewers including the Department of Environmental Affairs (DEA) and the Department of Water and Sanitation (DWS) in the review of CSP applications.

2 LITERATURE REVIEW

2.1 Overview of Concentrated Solar Power technologies

Concentrated solar power plants use light energy from the sun to generate heat, in order to convert solar thermal energy into electricity. A field of large mirrors is used to reflect light to a receiver element thereby concentrating the solar radiation intensity and producing heat. This heat can then be used in a Rankine steam cycle to power steam turbines, or stored in a number of ways such as the melting of salts or other phase-changing materials in order to deliver the heat to the power cycle at times of insufficient solar radiation. Concentrated solar power plants can range from 5 MW to several 100 MW of capacity (Trieb & Moser, 2009).

The different CSP technologies; Parabolic Trough (PT), Fresnel Reflector (FR), Solar Tower (ST) and Solar Dish (SD) are explained below.

Parabolic Trough

The PT is the most commonly utilised CSP technology, accounting for 90% of current commercially installed CSP capacity. Parabolic mirrors concentrate the sun's rays onto a focal line or receiver that contains a heat transfer fluid such as oil or molten salts. The linear receiver is designed to absorb most of the heat energy focused onto it, and to withstand the high temperature developed internally. Typical receivers for this purpose are made of steel tubing with a black coating, surrounded by a protective glass cover, with the space between the two evacuated to reduce heat loss. The heat collecting fluid which is pumped through the linear receiver tube is typically synthetic oil, similar to engine oil, capable of operating at high temperature. During operation temperatures are likely to reach between 300°C and 400°C. After circulating through the receivers, the oil is passed through a heat exchanger where the heat it contains is extracted to raise steam in a separate sealed system. The generated steam is used to drive a steam turbine generator to produce electricity. Typical steam conditions reached at the turbine inlet are 370-395°C at 100 bar. The spent steam from the turbine is condensed in a condenser and returned to the heat exchanger via condensate and feed water pumps to be transformed back into steam. Condenser cooling is typically provided by mechanical draft wet cooling towers, although, dry cooling is also an alternative option in areas isolated from water sources. The heat collecting fluid is then cycled back through the solar collector field to collect more heat.

The solar field is modular in nature and is composed of many parallel rows of solar collectors aligned with their long axes oriented north to south and mounted on supports that allow them to track the sun from east to west across the sky.

Most PT CSP plants in operation have capacities of between 14-80 MWe with efficiencies of 14-16% and maximum operating temperatures of 390°C (ETSAP and IRENA, 2013).

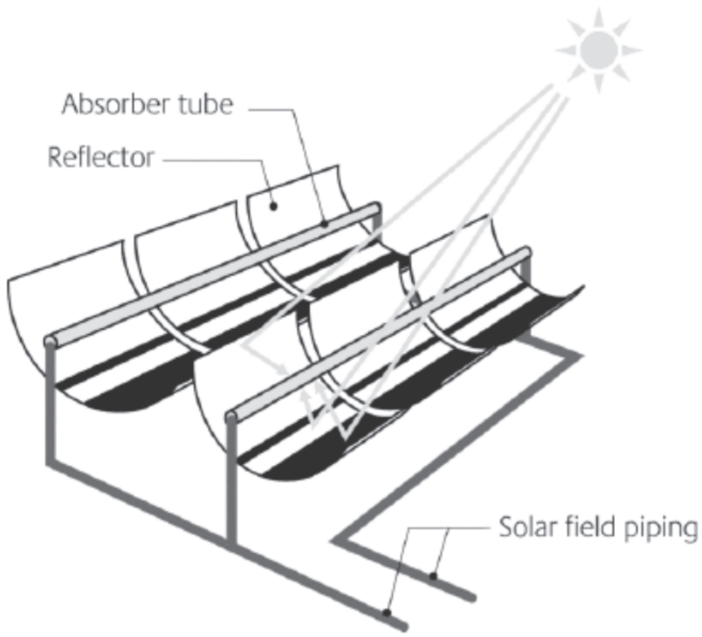


Figure 2-1: Parabolic Trough System (Poullikkas et al., 2013)

Fresnel Reflector

Fresnel Reflector (FR) plants are similar to PT plants but they use a series of flat mirrors placed either side of a stationary central focal line or pipe (receiver). These mirrors track the sunlight and are arranged in order to reflect the sun’s rays onto the focal line. These mirrors also track the sun’s path along a single axis. The mirrors are capable of concentrating the sun’s energy to approximately 30 times its normal intensity. Typical steam conditions that can be generated by this technology at the steam turbine inlet of a Fresnel CSP plant are 270°C at 55 bar. Optical efficiency of a typical linear Fresnel reflector system can reach 70%, and it is, however, still inferior to that of a parabolic trough system which is in the range of 75-80% (Mills, 2009).

The ground-based mirrors and solar collectors of FR plants are less costly than those of PT plants. These reflectors make use of the Fresnel lens effect, which allows for a concentrating mirror with a large aperture and short focal length while simultaneously reducing the volume of material required for the reflector. This greatly reduces the system’s cost since curved glass parabolic reflectors are typically very expensive. It should be noted, however, that in recent years thin-film nanotechnology has significantly reduced the cost of the parabolic mirrors used in PT plants.

The FR is the most recent CSP technology with only a few plants in operation (1.4 MW in Spain, 5 MW in Australia and a new 30 MW power plant, the Puerto Errado 2, in Spain, which started operation in September 2012). Further FR plants are currently under construction (e.g. Kogan Creek, Australia 44 MW, 2013) or consideration (ETSAP and IRENA, 2013).

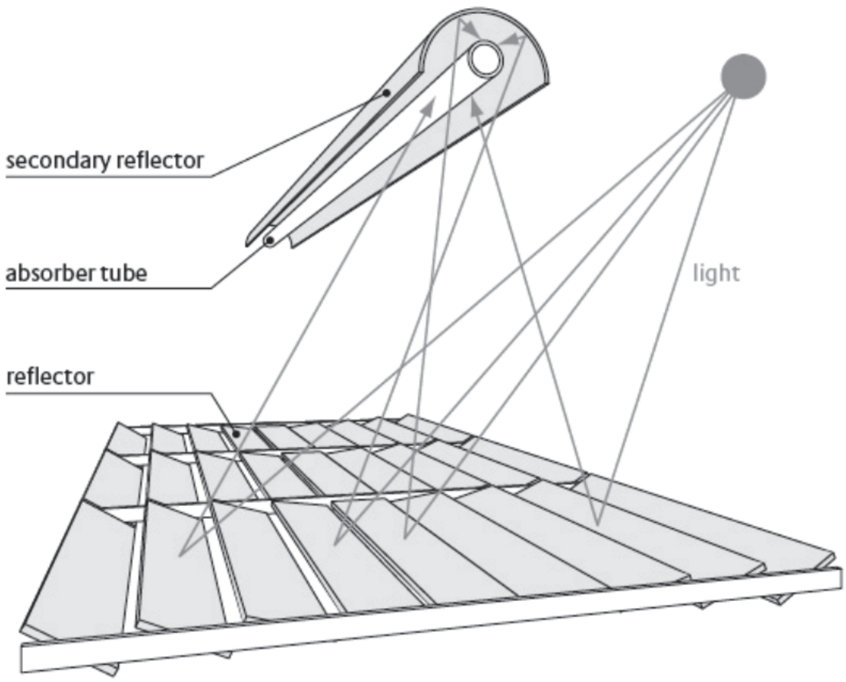


Figure 2-2: Principle of operation of linear Fresnel reflector solar system (Poullikkas et al., 2013)

Solar Tower

Solar Tower (ST) plants use a series of computer operated mirrors or heliostats that track the sun's path on two axes in order to reflect the sun's rays onto a single receiver placed on top of a tower in the centre of the field of heliostats. These plants are best suited for large utility-scale applications in the 30 MW to 400 MW range. The primary heat transfer fluid which is heated at this central receiver can be water-steam, molten salts or oil. The use of water eliminates the need for a heat exchanger between the primary heat transfer fluid and the steam cycle, but this makes heat storage more difficult. Current ST plants can achieve steam conditions at the steam turbine inlet of 250°C at 40 bar. Also, a recent ST, the Sierra Sun Tower in California, United States of America, can achieve input steam conditions to the power generation block of 440°C at 60 bar (Poullikkas et al., 2013). The advantage that ST technology has over the parabolic trough design is that thermal energy, at theoretically higher temperatures, can be converted to electricity more efficiently and can be stored for later use more cheaply. Furthermore, with STs, there is less need to flatten the ground area. In principle, a ST can be built on a hillside. Mirrors can be flat and plumbing is concentrated in the tower. However, each mirror must have its own dual axis control, while in the PT design one axis can be shared for a large array of mirrors.

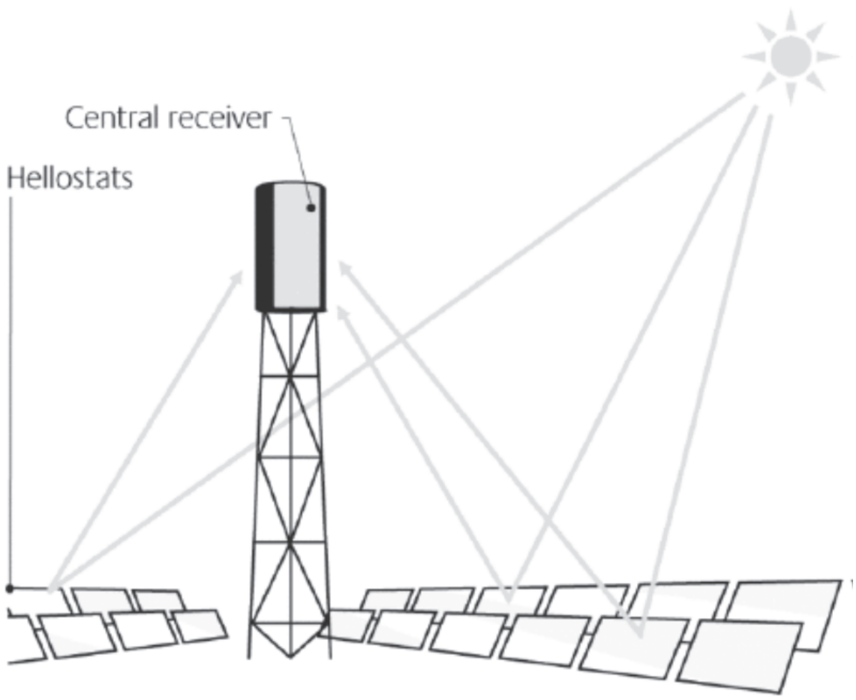


Figure 2-3: Principle of operation of ST system (Poullikkas et al., 2013)

Solar Dish

A Solar Dish (SD) is a reflective parabolic dish that reflects the sun's rays onto a central receiver at the focal point of the dish. The receivers are either Stirling engines or micro turbines. There is currently no significant commercial project making use of the SD system.

Advantages of SD systems are that they are highly efficient (up to 30%) and modular. SD systems also do not require cooling systems for the exhaust heat which makes them suitable for water-constrained areas. SD technology is still under demonstration and electricity generation costs are still high. Several SD prototypes have successfully operated over the last ten years with capacities ranging from 10-100 kW including Big Dish, at Australian National University. The Big Dish technology uses an ammonia-based thermo-chemical storage system. Thermal storage systems for SD are still under development. Multi-megawatt SD projects up to 100 MW are under consideration in Australia and the United States (ETSAP and IRENA, 2013).

2.2 Thermal storage

Thermal storage can be integrated into a CSP plant in order to generate electricity during times of low or absent solar radiation, such as cloudy days or during the night. Using molten salts for the storage of heat is the primary system used in today's PT plants. Molten salts can store energy for long periods of time whilst only suffering insignificant losses. This molten salt thermal storage system typically uses a mixture of sodium and potassium nitrates which melts at about 220°C. In operation, the salt is stored in a tank maintained at about 300°C. Molten salt is taken from this tank and passed through the high temperature receiver where it absorbs heat provided by the solar field mirrors, and is then returned to a high temperature storage tank at a temperature of around 550°C (Poullikkas et al., 2013). In most cases the solar energy being collected by the solar field during the day is greater than the energy required to produce steam to power the turbine. Therefore, the thermal storage system can be heated whilst the plant is producing electricity at full capacity.

Electricity is then generated during times of insufficient solar radiation by passing the molten salt through a heat exchanger, where the heat it contains is transferred to water, generating superheated steam to drive a conventional Rankine cycle steam turbine-generator system. The cooled molten salt is then returned to the cold storage tank. Thermal energy storage in a CSP plant allows electricity to be dispatched to the grid when demand for power is the highest, thus increasing the monetary value of the electricity. Whilst thermal storage will increase the cost of a CSP plant it allows for better economic utilisation of the plant equipment.

2.3 CSP Plant Cooling

Concentrated Solar Power plants, like the majority of global electricity generation plants, use Rankine cycle steam turbine generators to produce electricity. The Rankine cycle requires cooling to condense exhaust steam from the low pressure turbine. The cooling system is therefore considered an integral part of the power generation process and it can have a major influence on the overall plant performance. When the steam condenses, the rapid decrease in vapour-to-liquid specific volume creates a vacuum at the turbine outlet that increases power generation efficiency. The condensing of the steam takes place in either an air-cooled condenser (ACC) or a water-cooled condenser (WCC). For all the CSP plant technologies discussed here, water availability can be a significant issue in the arid regions best suited for the installation of CSP plants. Cooling towers account for approximately 90% of water consumption of the operational CSP plants. Water consumption is nominally the same as it would be for any Rankine cycle power plant with water-cooled condensers, which produces the same level of electric generation.

There is a growing and competing demand for water for domestic, agricultural and industrial use. In addition to this, the issue of water scarcity has brought an increased interest in the use of air as a cooling medium in place of water for electricity generation plants. Air cooled condensers can be used to significantly reduce plant water consumption, however, their use can result in a reduction in overall power plant efficiency.

Water-cooled condensers (WCC)

Having a high unit heat capacity, water has been the traditional heat transfer medium of choice. Water-cooled condensers use water to absorb heat via indirect contact with steam in a condenser. Water cooling for power plants is accomplished by using two types of condenser systems: Direct (once-through) wet cooling systems, and Indirect (recirculating) wet cooling systems.

<u>Direct (once-through) wet cooling systems</u>

In a direct system the cooling water is discharged into the receiving environment after a single use. Ideally none of the discharge finds its way back to the intake, at least not until its temperature has returned to near-ambient. This is the least complex, generally most thermally efficient and often cheapest option, with the additional advantage of being visually unobtrusive (Turnpenny et al., 2010). Although it does not consume any water in the cooling process, it does increase the temperature of, and hence the evaporation rate from, the body of water. This cooling system is mostly limited in application to plants adjacent to the sea. Environmental restrictions on the use of lake or river water prevent the use of this method due to the potential environmental consequences of thermal pollution, as well as the potential mortality of aquatic life due to impingement where the fish are trapped against the intake structure and entrainment (Poullikkas et al., 2013).

Indirect (recirculating) wet cooling systems

Indirect (recirculating) wet cooling systems are an economical and high performing power plant cooling technique. The waste heat energy dissipated from the power plant is rejected to the air via evaporation of the cooling water, most often by wet towers. The cooling water is sprayed in the tower and upwards air flow past the falling droplets is induced. Air contact with the water is thereby maximised. A wet tower is not only cheaper to construct than a dry system, but it also provides lower re-cool temperatures and requires less maintenance. The degree of cooling depends upon the wet bulb temperature of the air (T_{wb}). A low T_{wb} indicates cool air, low humidity; the lower the T_{wb} the greater the scope for evaporation and evaporative cooling. Towers can function even when the inlet air is at its wet bulb temperature since the air entering the tower is warmed (through sensible heat) by contact with the water, thereby raising its temperature so that the air is no longer saturated. The minimum re-cool temperature would be the wet bulb temperature of the air entering the tower (100% wet bulb performance). In practice this can never be realised and even at low wet bulb temperatures 65-70% performance is acceptable (Turnpenny et al., 2010).

The cooling towers utilised are either induced draught or forced draught cooling towers, and in some cases a hybrid of the two. Induced draught cooling towers are usually a lot taller than forced draught, and operate like a chimney. There is no way to control the air flow through induced draught towers and this often results in overcooling. Forced draught towers use fans to push the air past the cooling water. The air flow can be controlled in order to ensure consistent cooling, but the fans increase the running costs. The water treatment chemicals and minerals contained in the water being evaporated become concentrated over time, which requires a portion of the cooling water to be drained to remove particles and salts. This discharge or “blow-down” is a potential source of environmental contamination due to the high concentrations of salts, however, correct waste-water management can limit the potential for this contamination.

A typical CSP parabolic trough plant with a recirculating evaporative cooling system uses water at a rate of 2955-3030 ℓ/MWh, of which 98% is used for evaporation, boiler blow-down and water makeup and 2% for mirror washing, compared to 1890-2840 ℓ/MWh for a CSP solar power plant.

Air-cooled condensers (ACC)

Air-cooled condenser (ACC) systems designed for the electricity utility industry evolved into a configuration that recognised the special needs of condensing a large volume of low pressure vapour, as well as the removal of non-condensable gases. The ACC technology that meets these needs, while it has some disadvantages, has been able to provide a solution to some design problems. In addition ACC systems make it possible to build power plants in locations without abundant water system resources, often the case for locations suitable for a CSP plant. Air-cooled condensers reduce the efficiency of the plant, thereby reducing electricity production, as well as increasing the capital costs. They consist of direct ACC systems and indirect ACC systems.

Direct ACC systems

In direct ACC systems, the saturated steam from the steam turbine is passed through an array of A-framed fin tube bundles, which are externally cooled by ambient air. Although there are two options for circulating the ambient air for condensate cooling, either by the use of fans known as mechanical draft, or by the use of a hyperbolic tower known as natural draft, all the existing direct

ACC systems use solely the mechanical draft option. Natural draft direct ACC would need not only significantly higher investment cost than the mechanical draft one, but would result in operational problems such as fluctuation of steam turbine backpressure, high wind sensitivity and reduced availability.

Currently, the principal difference between the commercial direct ACC designs lies in the detailed design of the heat exchanger and its finned tubes. There are basically two types of heat exchangers: single-row, and multi-row. The single-row design is inherently more suitable in extreme freezing ambient conditions. There are, also, three tube shapes available in the market: round, oval, and flat. Oval and flat tubes perform better than round ones under almost all operating conditions. The fin shape varies between suppliers. Some fins are less susceptible to fouling and are mechanically more resistant in transient conditions. The best quality fins have a strong bond to the bare tube, which guarantees a useful life expectancy comparable to that of the power plant. The final important design factor is the material selected for the finned tubes. Aluminium fins brazed on flat bare tubes coated with aluminium, or oval galvanised finned tubes bundles, are generally recognised as the two most reliable technologies for use in power plants (Poullikkas et al., 2013).

Indirect ACC systems

In indirect ACC systems the steam is condensed by spraying water directly into the exhaust flow of the steam turbine in a ratio of about 50:1, creating a large volume of warm water, some of which is pumped back to the boiler (as the working fluid) and the rest of which is pumped to bundles of tubes arrayed at the base of a hyperbolic cooling tower. The warm water circulating around the base of the tower and the cooler air at the top of the tower, combined with the tower's hyperbolic shape, stimulate a powerful updraft that draws ambient air over the tube bundles, thereby convectively cooling the water before it is returned to the condenser. In case of the indirect ACC systems, either mechanical or natural draft can be used for providing the required cooling air flow. With increasing cooling capacity, the natural draft becomes more attractive by avoiding high fan power requirements, as well as sharply reducing maintenance costs by minimising the amount of moving parts in the system. Additionally, the increasing capacity makes the supporting structure of the mechanical draft tower more expensive, by requiring higher elevation for adequate air access to the heat exchangers, or at least in the cases where these heat exchangers are arranged horizontally.

Hybrid wet/dry systems

The use of hybrid cooling systems is in order to achieve one of two aims; either plume abatement or to reduce water requirements. Plume abatement is the reduction of the water plume being emitted by a wet cooling tower to reduce its visual impact or to avoid ice deposition on nearby roads. This is usually not an issue for CSP plants, as they are usually located in dry and remote areas. The reduction in water consumption is the aspect of greater importance for CSP plants. Concentrated Solar Power plants utilising hybrid cooling systems use less water than plants with WCC systems, and have enhanced performance in warm weather when compared to plants using exclusively ACC systems.

Hybrid systems consist of WCC and ACC units either running in parallel or operated in series, where a WCC is used to cool the air prior to it flowing through the ACC. Parallel cooling systems consist of a primary (usually the ACC) and a secondary system. Where the ACC is the primary cooling system it is utilised for the majority of the time. However, on hot days, when the ACC becomes inefficient, a portion of the steam is routed through a separate WCC system. By reducing the load on the ACC on hotter days, the dry unit can bring the condensing steam temperature closer to the design condenser temperature. A hybrid system uses a fraction of the water that traditional WCC system would use, and the turbine performance can be maintained at, or close to, design conditions. Such a system would have a small WCC system cooling tower and would typically have a smaller ACC than a plant integrated with only an ACC system. Although it is more expensive than a plant integrated with only a WCC system, it would be less expensive than a plant integrated with only an ACC system (Poullikkas et al., 2013).

Comparison of water consumption by cooling system

Table 2-1: Comparison of water consumption by cooling system (Poullikkas et al., 2013)

Technology	Water consumption (ℓ/MWh)		
	Direct dry cooling ACC system	Circulating evaporative WCC system	Hybrid ACC/WCC system
CSP parabolic trough plant	303	3030	378-1703
CSP solar power plant	340	1890-2840	340-945
CSP Fresnel plant	n/a	3785	n/a

<u>CSP plant performance as a function of cooling technology</u>

The use of ACC systems over the traditional WCC in CSP plants results in a reduction in the plant's efficiency, the extent of which is dependent on the CSP technology utilised, as well as the ambient conditions of the site. The reason for the efficiency reduction lies primarily on the inherent underperformance of ACC technologies in high temperatures and, secondly, on the additional auxiliary power requirements introduced by the ACC technology condenser (e.g. fans). Essentially, for ACC systems, sensible heat transfer is the only form of heat rejection and therefore, their performance relies heavily on the dry bulb temperature (or the temperature of the ambient air). The typical condensing steam temperature in the ACC is always higher than the ambient air temperature in order to provide for adequate heat exchange and cooling. Therefore, on hot days and during midday, when the ambient temperatures are usually at their maximum, high condensate temperatures are being developed in the ACC, which translates to increased condenser pressure. This increased condenser pressure, in turn, causes the steam turbine backpressure to increase and the turbine to become less efficient. It has been reported that a CSP plant may begin to experience efficiency losses, due to direct ACC underperformance, at ambient temperatures above 32°C, while significant efficiency losses at ambient temperatures above 37.7°C. These losses could reach 5% and above (Poullikkas, et al., 2013). The extent of the performance decrease depends on the design of the condenser. However, some of the hot hours of the day may occur during late afternoon when the DNI is decreasing, and thus the plant may run at partial load. This means that the performance penalty from the high ambient temperature, might be reduced by the performance gain of the ACC system running at partial load. For this reason, the integration of thermal storage technologies in a CSP plant with ACC cooling technology. in order to shift the steam cooling loads to times with lower ambient temperatures, could be highly beneficial in reducing efficiency penalisation.

The amount of efficiency reduction of a CSP plant employing an ACC technology over evaporative WCC technology is heavily influenced by the type of CSP technology of the plant. Generally, the efficiency of the steam cycle is a function of the difference between the steam turbine's inlet steam temperature and the steam rejection (output) temperature. As explained above, ACC technologies exhibit high condensing temperatures on hot days, and this tends to reduce the efficiency of the cycle, as it increases the turbine backpressure and the steam rejection temperature. However, the efficiency of CSP plants using CSP technologies that can theoretically deliver higher steam inlet temperatures, such as the solar tower technology, are less affected by increases in steam rejection temperatures. Therefore, the overall efficiency of solar tower CSP plants was less affected by the integration of an ACC system than that of parabolic trough or Fresnel CSP plants, which operate with lower steam inlet temperatures. Table 2-2 compares efficiency reduction by each cooling system.

Table 2-2: Comparison of efficiency reduction by cooling system (Poullikkas et al., 2013)

Technology	Efficiency reduction (%)		
	Direct dry cooling ACC system	Circulating evaporative WCC system	Hybrid ACC/WCC system
CSP parabolic trough plant	4.5-5	Base case	1-4
CSP solar power plant	1-3	Base case	1-3
CSP Fresnel plant	n/a	Base case	n/a

Saline water cooling

Saltwater cooling towers have been used since the 1970's in power generation facilities in order to reduce the consumption of fresh water. The salts however, present a number of engineering challenges, such as salt deposition, packing blockage, corrosion, rising salt concentrations, salt emissions, as well as the difference in thermodynamic properties when compared to freshwater (Leinhard et al., 2010).

The challenge of corrosion can be addressed by the use of appropriate construction materials and equipment. Ferrous metals must be avoided, and in cases where metal is required stainless steel should be utilised. All of these materials, of course, add to the capital cost of the cooling system.

As a rule, cooling tower vendors recommend degrading the tower performance by approximately 1% for every 10 000 mg/ℓ of salts in the cooling water. In practice, most engineering contractors specify a 0.55-1.1°C margin on the wet bulb temperature to account for salts in the cooling water (Leinhard et al., 2010).

<u>Thermal Performance</u>

The following comparative properties of saltwater versus freshwater are the properties that most strongly affect the performance of cooling towers using saltwater (Leinhard et al., 2010):

- The vapour pressure of seawater is less than that of freshwater, which reduces the potential for water evaporation.
- The specific heat of seawater is less than that of freshwater, which reduces the amount of sensible heat that can be transferred at the same temperature difference.
- The density of saltwater is higher than that of freshwater due to the salt content. This increases the mass flow rate of seawater for the same volumetric flow rate and consequently increases the pumping power required.

Design considerations

The use of saline water in cooling towers requires careful materials selection in the design of the cooling tower. For the tower ponds and other structures to be constructed with reinforced concrete, a proportion of the cement should be replaced with pulverised coal ash or furnace slag. This reduces the chloride diffusion. The metal rebar can be epoxy coated to avoid corrosion. Medium-density polyethylene (MDPE) and glass reinforced plastic (GRP) pipes and sections are preferable to coated steel. The use of these, in some cases, less readily available materials increases the cost of saline water cooling towers when compared to fresh water cooling towers.

2.4 CSP Costs

The costs of CSP electricity include investment costs and operation and maintenance costs (O&M). The investment costs often account for 80% of the electricity cost, and the O&M the remaining 20%. The present day CSP market is dominated by PT technology, and due to this, the majority of the information regarding CSP costs refers to PT plants.

Concentrated solar power capital costs

Concentrated solar power plants with thermal energy storage generally have higher investment costs, but allow higher capacity factors and potentially lower levelised cost of energy (LCOE) (particularly for molten salt solar towers), while also having the ability to shift generation to when the sun does not shine, and/or the ability to maximise generation at peak demand times when electricity is more expensive (Table 2-3).

Table 2-3: Capital costs and key characteristics of PT and ST plants (IRENA, 2013)

	Source	Heat transfer fluid	Solar multiple	Storage (hours)	Capacity factor (%)	Cost (2011 USD/kW)
Parabolic Trough	(Turchi et al., 2010)	Synthetic oil	1.3	0	26	4 700
	(Hinkley et al., 2011)	Synthetic oil	1.3	0	23	7 300
	(Turchi et al., 2010)	Synthetic oil	2	6	41	8 170
	(Turchi, 2010)	Synthetic oil	2	6.3	47-48	9 140 to 10 020
	(Hinkley et al., 2011)	Synthetic oil	2	6	43	7 900
	(Fichtner, 2010)	Molten salt	2.8	4.5	50	7 535
Solar Tower	(Ernest and Young, 2011)	Molten salt		7.5		7 430
	(Turchi et al., 2010)	Molten salt	1.8	6	43	6 430
	(Kolb et al., 2011)	Molten salt	2.1	9	48	7 580
	(Hinkley et al., 2011)	Molten salt	1.8	6	41	7 620
	(Fichtner, 2010)	Molten salt	2	9	54	7 880

Concentrated solar power plant capital costs as a function of cooling technology

The capital costs of direct ACC technology have been reported to be 2.5 to 3 times as much as those for the evaporative WCC (Poullikkas et al., 2013). Hybrid WCC/ACC technology capital costs would lie between the two technology costs, depending on the capacity of the WCC part of the cooling system. Since the capital costs of the direct ACC technology are mostly composed of material costs (dependent on commodity prices), a reduction of capital costs seems unlikely at this time. Despite the higher capital costs, the direct ACC technology offers much lower operation and maintenance costs since it avoids dealing with water, water treatment, water freezing issues and the discharge of waste water. However, the operating and maintenance costs are minimal from an economic feasibility point of view, compared to the capital costs.

The higher capital costs of the ACC technologies mean that the overall capital costs of a CSP plant, with such technology, was higher than a similar CSP plant with the evaporative WCC technology.

Table 2-4: Comparison of capital cost increase by cooling system (Poullikkas et al., 2013)

Technology	Capital cost increase (%)		
	Direct dry cooling ACC system	**Circulating evaporative WCC system**	**Hybrid ACC/WCC system**
CSP parabolic trough plant	4-5	Base case	2-3
CSP solar power plant	4-5	Base case	2-3
CSP Fresnel plant	n/a	Base case	n/a

Concentrated solar power plant electricity unit costs as a function of cooling technology

In order to estimate the electricity unit cost in the case of a CSP plant with ACC technologies, the specific effect of ACC technologies on the plant's water usage, efficiency and capital cost should be investigated.

The above sections show that, overall, the substitution of evaporative WCC with ACC technologies provides advantages in terms of significantly reduced water usage, but disadvantages in terms of reduced plant efficiency and increased capital cost. The net effect of these factors appears to result in a net increase in the overall plant electricity unit cost, when ACC technologies are used in place of the evaporative WCC technology for cooling purposes. Table 2-5 shows the estimated CSP plant electricity unit cost increase depending on the type of CSP technology, and the type of cooling technology, employed by the plant.

Table 2-5: Comparison of electricity unit cost increase by cooling system (Poullikkas et al., 2013)

Technology	Electricity unit cost increase (%)		
	Direct dry cooling ACC system	**Circulating evaporative WCC system**	**Hybrid ACC/WCC system**
CSP parabolic trough plant	2-9	Base case	Up to 8
CSP solar power plant	2-5	Base case	Up to 5
CSP Fresnel plant	n/a	Base case	n/a

2.5 Desalination technologies

Desalinated water can be produced from saline water by two main processes, evaporation and size exclusion. The driving energy for both processes can be either electrical power or thermal energy. The different available desalination technologies include: Multi Stage Flash desalination (MSF), Multi Effect Distillation (MED) and Reverse Osmosis (RO), as well as, new developments such as Multi Effect Humidification (MEH) and Vapour Membrane Distillation (VMEMD).

Thermal desalination plants use heat sources as the driving force. These heat sources can be hot water or steam from a turbine. Therefore, thermal desalination can be combined for co-generation with power plants. Electrical power is only necessary for parasitical internal demands such as pumps.

Evaporation Processes

Multi Stage Flash desalination (MSF)

A multi stage flash (MSF) desalination plant consists of several serial stages of chambers/vessels. The upper parts are condensers. Each stage is operated at about 2-5°C lower temperature than the previous one. The number of flash stages can vary from 10 to 30. The saline water is heated step-by-step in the condenser tubes. In the last step saline water is heated by hot water or steam from an external source in the brine heater. The hot saline water is then flashed into the first chamber and partly evaporated. The generated steam is condensed and collected to be used as the distillate.

Multi stage flash plants are extremely robust and have a high reliability with long running periods between cleaning (6-24 months). They can treat very saline raw water and still produce good distillate quality (typically 1-10 mg/ℓ TDS). Inside the condenser tubes there is only single phase heat transfer and no degassing inside heat exchangers which in turn reduces scaling. However, MSF plants are expensive, needing large specific heat transfer surfaces. Furthermore, the electrical energy consumption is high (3-4 kWh/t) compared to other thermal systems. The MSF desalination technology has been employed in industry for more than 40 years (Trieb et al., 2010).

Multi Effect Distillation (MED)

A multi effect distillation (MED) plant consists of several stages of evaporators under vacuum. Saline water is distributed on the outer surface of the tubes and partly evaporated. The driving heat of the first evaporator is hot water or low pressure steam from an external source with a maximum temperature of 70°C. All other evaporators use the evaporated water vapour of the previous stage as a heat source. This steam condenses and can be used as process or drinking water.

Like the MSF, MED plants can treat very saline raw water and produce good distillate quality. They are also highly reliable with long running periods between cleaning (6-24 months). MEDs are less expensive than MSF since they need a much smaller heat transfer surface. Furthermore, no sophisticated equipment is required. MED's have a better thermal efficiency and very low electrical consumption (0.5-0.6 kWh/t) (Trieb et al., 2010) compared to MSF's. The heat transfer in MED is with dual phase flow, thus degassing occurs during evaporation. However, the tube surface can only be cleaned chemically. The maximum steam temperature is limited to 70°C due to scaling (Trieb et al., 2010).

Mechanical Vapour Compression (MVC)

A mechanical vapour compression (MVC) unit is essentially a MED unit. Like with a MED process, saline water is sprayed on the tube surface. The evaporated water was compressed in a mechanical compressor. The compressed steam is condensed and exchanging heat again with the saline water. MVC plants are driven by electrical power. The advantage of a MED with mechanical vapour compressor is, it does not need steam and is very robust like all MED. But the compressors are expensive, though compressors with higher compression ratio are now available. A MED-MVC requires large heat transfer surface in order to achieve low power consumption. Large pre-heaters have to be installed to maintain evaporation at roughly 55-65°C (Trieb et al., 2010).

Solar Stills

A rather simple technology is the solar still, using the solar energy directly. A glass roof covers a basin of saline water. Water evaporates under the influence of solar radiation. The dark inner surface of the pond enhances the evaporation. The water is then condensed underneath the glass surface, which is cooled by the ambient air. The condensate is recovered on both sides of the construction. These stills are used for small scale applications, the daily production being limited to about 5 ℓ/m^2. Solar stills do not require any auxiliary power, nor any control, and can be erected with a minimum of materials of construction. Feed flow can be kept very low as solar stills operate up to high salt concentrations including crystallisation. This technology is also known as “solar distillation”.

Multi Effect Humidification (MEH)

Multi effect humidification is based upon the principle of solar stills (Müller-Holst 2002). An isolated chamber consists of an evaporator section and a condenser section. Hot saline water is distributed on top of the evaporator section, which is constructed with parallel plates. Part of the water evaporates while flowing downward and cooling down. At the same time air flows up through natural convection and becomes more humid through absorbing the water vapour. Cold saline water flows from bottom to top in the condenser section, exchanging heat with the down flowing air. Water condenses on the heat exchanger surface and is collected at the bottom. Brine is collected at the bottom of the evaporator section. The saline water is further heated to 85°C by an external heat source like hot water or steam (Trieb et al., 2010).

Facts about the MEH system and its advantages:

- Low temperature heat of 85°C is used for evaporation.
- Absence of moving parts within the distillation chamber ensure low maintenance demand
- Sophisticated geometrical design allows easy maintenance and optimum performance at the same time.
- No pre-treatment of raw water is needed. The process is insensitive to high salt contents.
- Modular set-up, available sizes comprise units with 1000, 5000 and 10000 ℓ /d capacity.

Membrane Processes

The purpose of membranes is the separation of phase (liquid/vapour) or molecules and ions. For phase change membranes the driving force is heat. Evaporation occurs in the membrane because of vapour pressure difference on either side of the membrane, and thus dividing the liquid from the vapour. The other separation process is diffusion. Only Molecules or ions which are small enough can pass through the pores of a membrane. The driving force is a difference of chemical potential, which can be either pressure or electrical voltage. Electro-dialysis (ED) separates the ions from water by using direct current across the membrane which an ion conductor. The membrane selectively lets pass the ions leaving distilled water behind. The membrane in the RO acts like a filter, letting the water molecules through the membrane and leaving the ions of the brine behind. Electric pumps generate the necessary high pressure up to 70 bar for saline water desalination in RO while a differential voltage is applied across an ED membrane.

Electro Dialysis

The cathode and anode envelope a block of membranes. Two different kinds of membranes alternate – one selective for anions, the other for cations. Saline water is distributed into the channels between the membranes. The salt in the water then ionises when the electrical field is applied. In every second channel the water is enriched with salt while the other channel is depleted of salt. The two streams, distillate and brine, are collected at the bottom of the cell. Electro-dialysis processes are used for brackish water desalination only. Newest plants have output rates over 20 000 m^3/d (Trieb et al., 2010).

Reverse Osmosis

Since their introduction in the late 1950s, RO, nanofiltration, ultrafiltration and microfiltration have been increasingly used in the field of water treatment. Improved performance, reliability and lower operating cost over the years have made membranes the preferred technology for desalination of saline water, brackish water and waste water. In the last decade RO desalination has gone through a significant transformation. Currently most of the implemented saline water desalination plants use RO technology. Systems of 300 000 m^3/day and larger, have been built, and are in operation in many parts of the world. Desalinated water costs decreased from 2.0 \$/m^3 to 0.5 \$/m^3 (Trieb et al., 2010) and world-wide capacity is continuously increasing.

Osmosis is a physical process, which takes place when two solutions of different salt concentrations are separated by a semi permeable membrane. Under normal conditions water will pass from the solution whose salt concentration is higher until the hydrostatic pressure difference between the two is equalised. The pressure difference between distilled water and any saline solution, when the flow of water in both directions is identical, is equal to the osmotic pressure of the solution. The application of an external pressure on the concentrated solution, which is larger than the osmotic pressure will cause water flow from the concentrated solution to the dilute solution through the membrane, this process is called reverse osmosis. The osmotic pressure is proportional to the salt concentration.

Vapour Membrane Distillation (VMEMD)

Membrane distillation two chambers are divided by a micro-porous, hydrophobic membrane. One chamber contains the saline water. The other chamber contains water vapour. If heat is applied to the water side, a pressure difference occurs between the two chambers, with the lower pressure being on the water vapour side, water vapour then permeates though the membrane.

A newly developed technique, Vapour Membrane Distillation (VMWMD), combines the distillation via membrane with a MED process. In this new technique, preheated saline water enters into the channel of stage 1, which is enclosed on one side by a condensing non-permeable membrane and on the other side by a hydrophobic but permeable membrane. The condensing membrane of the first stage is heated by hot water or steam. Thus, heat is transferred to the saline water. The pressure of the second stage is lower than in the first stage. Water evaporates through the membrane into the second chamber. This vapour condenses again at the condensing membrane of the second stage, transferring heat to the saline water chamber. The thermal and electrical power consumption is the same as for MEDs. Capacities of up to 10 000 m^3/d and more can be achieved with serial and parallel arrays of modules (Trieb et al., 2010).

2.6 Integration of CSP and Desalination Technology

Suitable desalination technologies

In terms of primary energy and electricity consumptions, MED is more efficient than MSF, and MED has a lower capital cost. The operating temperature of MED is lower than that of MSF thus, it can utilise steam at a lower pressure, if combined with a steam cycle power generation plant. Reverse osmosis desalination has lower primary energy consumption than that of MED, however, if MED is combined with a power generation plant it replaces the cost of the condensation unit of the steam cycle and partially uses waste heat for the desalination process. Therefore not all the primary energy required must be accounted for by the desalination.

Energy consumption by desalination was assumed to be at the lower end of the range provided in Table 2-6 where less saline water was to be used, and at the upper end where the more saline water was to be used.

For this study the MED and RO processes were considered as suitable technologies for thermal and for mechanical desalination processes, respectively.

Table 2-6: Characteristics of the two desalination technologies considered (Trieb et al., 2010)

Desalination Process	MED	RO
Technology status	Commercial	Commercial
Heat consumption (kJ/kg)	145-390	-
Electricity consumption (kWh/m³)*	0.6-1.3 *	2.5-7.0
Plant cost ($/m³/d)**	900-1700	900-1500
Production unit capacity (m³/d)	< 36000	< 20000
Conversion (freshwater/saline water)	23-33%	20-50%
Max. top brine temperature (°C)	55-70	45 (max)
Reliability	Very high	Moderate
Maintenance (cleaning per year)	1-2	Several times
Pre-treatment of water	Simple	Demanding
Operation requirements	Simple	Demanding
Product water quality (mg/ℓ)	<10	200-500

*Power consumption does not include power losses for cooling in conventional power plant required for RO, and does not include power losses induced by cogeneration due to increasing outlet temperature at the turbine in case of MED.
**Plant cost increases with decreasing feedwater quality and energy efficiency.

Suitable CSP technologies

Due to the fact that most CSP technologies utilise a Rankine cycle for the generation of power. In principle, all CSP technologies can be used for the generation of electricity and heat, and are therefore suited to be combined with mechanical as well as with thermal desalination systems.

2.7 Policy Alignment: National Water Resources Strategy 2.

The following is taken from the National Water Resources Strategy 2 (Gazetted 16th August 2013) (Nkondo et al., 2012).

"Whilst South Africa benefited from a surplus of water available in 2000, the time has now come where a mix of water resources is required to reconcile supply and demand. Towards this end, Reconciliation Strategies have been developed to assess water balance against future needs. These strategies will inform our future water resource planning, management and investment and key issues include:

- *greater focus on WCWDM – every drop counts and we cannot afford to waste any more water, anywhere*
- *increased value and utilisation of ground water*
- *re-use of waste water at the coast as well as in inland systems*
- *opportunity for more dams (though limited) and transfer schemes (and where the opportunity exists, it is at great cost)*
- *desalination:*
  - *Small scale seawater desalination already being used in certain areas*
  - *Treated mine water desalination becoming more important*
  - *Desalination of seawater on a large scale*
- *catchment rehabilitation, clearing of invasive alien plants and*
- *rainwater harvesting is growing in importance*
- *making more water available in the future, but at sharply rising costs.*

South Africa has to prioritise, considering the mix of options available to supply the huge water demands for equitable allocation for development and economic growth. The country will thus consider other potential sources, which include water re-use, desalination, groundwater utilisation, water conservation and water demand management measures, rain water harvesting, recovering water from acid mine drainage, and the import of water intensive goods."

"4.4.1 Groundwater development and management
The DWA will implement the National Ground Water Strategy, thereby promoting the use of groundwater on a larger scale. The focus is on supplying water mainly for household use in remote rural areas, where levels of water services are often unacceptable, as well as in other situations where groundwater can contribute to the reliability of supply for domestic and other uses."

"4.4.11 Water re-use
The DWA has developed a National Strategy for Water Reuse, which provides a considered approach to the implementation of water reuse projects. The National Strategy for Water Reuse is a sub-component of, and is consistent with the NWRS2 (see Annexure D).
The intention of the National Strategy for Water Re-use is to better inform decision-making surrounding this valuable resource through the development of guidelines for the implementation of water reuse projects."

"12.4.1 National Water Investment Framework.
National Water Investment Framework: The water sector, led by the DWA in partnership with relevant sector stakeholders, both public and private, will develop, finalise and maintain the investment framework. The water sector investment framework will incorporate the costs of the total sector value chain, infrastructure development and sustainable water management, including:

- *water resource protection*
- *water reallocation*
- *financial support to water-based rural livelihoods and food security for all*

- *development of appropriate water and sanitation infrastructure*
- *re-use and other alternative sources of water (including mine-water drainage and desalination of sea and inland water)*
- *water conservation and water demand management*
- *refurbishment and upgrading of wastewater treatment plants to prevent pollution of water resources*
- *reducing the backlog in the maintenance of water infrastructure*
- *institutional re-alignment*
- *capacity building*
- *the water management programmes included in this Strategy."*

From Page 150:
"Most Northern Cape towns and mining enterprises within the Orange River WMA are dependent on groundwater. There are problems with the natural quality of the water, especially with high salinity, but new desalination technologies make the use of this groundwater much more feasible and small-scale desalination plants can make this water acceptable for use.
The National Desalination Strategy is a sub-component of, and is consistent with the NWRS2 (see Annexure C). The DWA will work with the Department of Energy (DOE), the Department of Public Enterprises (DPE) and Eskom to ensure the integration of medium- and long-term planning for the development of energy and water resources. Particular attention will be given to the potential for the desalination of seawater for supplying coastal towns and cities where there are sufficient sources of electricity for this purpose."

From Page 174
"National Desalination Strategy
The main applications of desalination in the South African context are likely to be:
- *Development of brackish surface water or saline effluents as a water resource*
- *Development of brackish groundwater as a water resource*
- *Development of seawater as a water resource*

Desalination is already taking place in South Africa (albeit at a small scale) and planning for future major desalination facilities is already underway. The reclamation and re-use of effluents after some form of treatment, which may include desalination, is becoming financially attractive compared to other conventional water resources development options.

Some desalination projects are now linked to the development of renewable energy resources to offset the carbon footprint of energy intensive plants. Globally, the more affordable renewable energy sources include wind and biomass with solar, tidal and wave energy sources more expensive to develop. South Africa has potential to develop a wide range of renewable energy resources. The sustainability of desalination projects can be advanced if such projects are implemented in a carbon neutral manner. This can be achieved by developing desalination projects in parallel with nuclear energy and renewable energy projects. This approach will also contribute towards a better mix of energy resources in South Africa."

3.1.4 The linkages between energy and water

Desalination technologies[5] are all relatively energy intensive as reflected below:

Desalination technology	Unit energy consumption (kWh/m^3 water)
Distillation, using multiple effect distillation technology	12-18
Distillation/evaporation using mechanical vapour compression technology	11-16
Membrane desalination of seawater (with energy recovery)	4-8
Membrane desalination of brackish water	2-4
Conventional water treatment	0.2 – 0.3
Conventional sewage treatment	0.6 – 1.0

"4.2 Integrating energy and water planning

There are strong relationships between the choice of future electricity generation options, the implications for the location water requirements and the potential and cost-effectiveness of desalination. National government, through the National Planning Commission (NPC), and together with DWA, the Department of Energy (DOE), the Department of Public Enterprises (DPE) and Eskom, will ensure strong integration of the medium and long term energy and water planning. Particular attention will be paid to the potential for desalination of seawater for coastal cities in relation to a possible expansion of nuclear power generation, vis-a-vis other power generation alternatives and their implications for water planning."

"4.6 Financing desalination projects

Water infrastructure in South Africa is mainly funded by a combination of loans raised on the basis of user charges (water tariffs) and government grants (primarily through the municipal infrastructure grants and regional bulk infrastructure grants). At present there is little private equity and investment in water infrastructure.

Desalination projects, especially large scale projects, lend themselves to loan financing due to the secure nature of the revenue streams that can be generated from the sale of desalinated water. In an environment where government grants and borrowing capability are constrained, the option of using privately raised loan finance (that is, project finance) for the development of large-scale desalination facilities will be explored. Typically this can be achieved through design-build-operate type contracts (or variations of this type of contract) with the private sector."

"4.12 Developing guidelines
The Department will develop further guidelines for the implementation of desalination projects as necessary and appropriate. These guidelines will address relevant topics, such as:

- *Selection of appropriate technology and equipment*
- *Capital and capital replacement costs*
- *Operations and maintenance costs*
- *Management, operations and maintenance staffing and resources requirements*
- *Financing of projects*
- *Tariff development and implementation*
- *Public and consumer communications and outreach programmes"*

The following is from http://www.gov.za/about-SA/water-affairs

"Desalination strategy
The department has developed a supporting desalination strategy, which also includes desalination as a technology for treating water other than seawater for water reuse. Desalination of seawater could potentially provide an unlimited resource of fresh water.
It has become more attractive since the NWRS-1 because of improved technologies, decreasing costs and increasing water scarcity.
However, the rising cost of energy may be a deterrent. Like other infrastructure projects with potential environmental impacts, the planning for a desalination plant will have to undergo an environmental impact assessment in compliance with NEMA of 1998.
The department will ensure that desalination is considered as an option for meeting future water requirements, in particular in coastal cities where there is sufficient electricity for desalination.
The target is not only to implement desalination in several locations in South Africa, but also to become an international knowledge centre in this particular field."

3 METHODOLOGY

3.1 Concentrated solar power cost of energy/cost of water model

A CSP cost of energy/cost of water model was developed to include a technical and financial component (Figure 3-1). The model was developed using NREL's SAM model as a backbone. Ambient weather data and DNI were modelled using WRF. The base case SAM model was initially setup for the wet/evaporative cooling option. Before running the model for the different scenarios, a verification of the system architecture and WRF forecasting for DNI was undertaken. This is described in Chapter 4 of this report. The model was then scripted to run in batch mode, i.e. receive the ambient weather and DNI data for a grid cell, perform the SAM CSP simulation for the grid cell; write out the relevant parameters of interest as shown in Table 3-1; before moving to the next grid cell and repeating the operations.

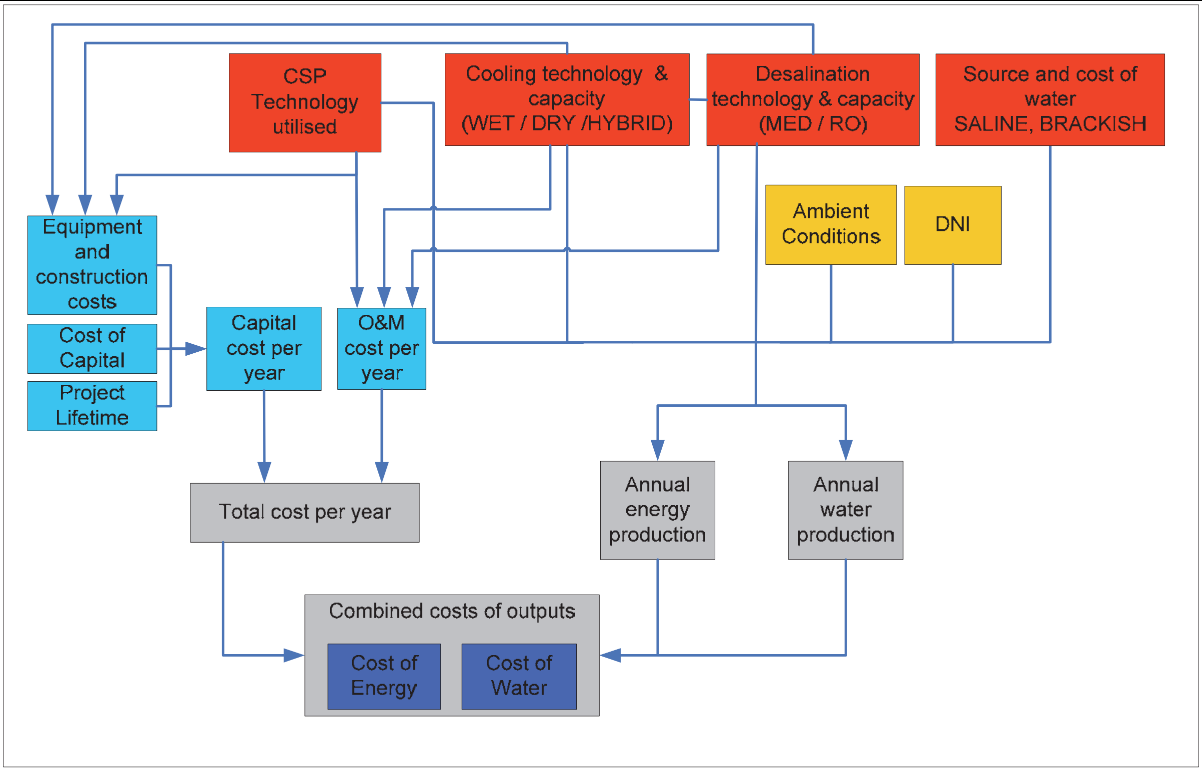


Figure 3-1: Flow diagram of modelling methodology illustrating the contributions to the modelled scenarios.

Table 3-1: SAM Output

Annual Energy	267 543 088 kWh
PPA Price	16.50 c/kWh
LCOE Nominal	20.21 c/kWh
LCOE Real	16.33 c/kWh
Internal Rate of Return (%)	25.66%
Minimum DSCR	1.47
Net Present Value ($)	$102 537 656
Calculated PPA Escalation (%)	1%
Calculated Debt Fraction (%)	50%
Capacity Factor	30.6%
Gross to Net Conversion Factor	0.93
Annual Water Usage	1 010 686 m^3
Total Land Area	898.08 acres

The model outputs were then post-processed and interfaced with GIS mapping functions to produce maps reflecting the combined costs of output, i.e. cost of energy and cost of water for the different cooling options, water sources and desalination technologies considered. Thermal storage was considered for this analysis but for the purposes of this strategic investigation a fixed storage capacity (6 hours) was specified.

3.2 Scenarios modelled

The scenarios modelled (Table 3-2) were designed to include multiple permutations of cooling method, water supply, and presence / absence of desalination. The base case (or reference) against which alternatives were compared was a PT with wet cooling, using fresh groundwater and without integrated desalination.

The scenarios that included desalination (MED and RO) assumed that the water supply was saline. Therefore if brackish or freshwater is to be used, the costs of doing so will be lower than the costs predicted by the model.

Scenarios 1 through 7 do not include any storage. This is not a realistic scenario for CSP plants with integrated desalination, but was used for comparative purposes, to determine the impact of storage in all cases 8 through 14.

Table 3-2: Scenarios modelled

Scenario	CSP Technology	Cooling Method	Cooling Water Supply	Storage	Desalination
BASE CASE	Parabolic trough	Wet cooled	Fresh groundwater	0 hrs	
2	Parabolic trough	Wet cooled	Brackish groundwater	0 hrs	
3	Parabolic trough	Wet cooled	Saline water	0 hrs	
4	Parabolic trough	Air cooled	(None)	0 hrs	
5	Parabolic trough	Hybrid cooled	Fresh groundwater	0 hrs	
6	Parabolic trough	Wet cooled	Saline water	0 hrs	MED
7	Parabolic trough	Wet cooled	Saline water	0 hrs	RO
8	Parabolic trough	Wet cooled	Fresh groundwater	6 hrs	
9	Parabolic trough	Wet cooled	Brackish groundwater	6 hrs	
10	Parabolic trough	Wet cooled	Saline water	6 hrs	
11	Parabolic trough	Air cooled	(None)	6 hrs	
12	Parabolic trough	Hybrid cooled	Fresh groundwater	6 hrs	
13	Parabolic trough	Wet cooled	Saline water	6 hrs	MED
14	Parabolic trough	Wet cooled	Saline water	6 hrs	RO

Figure 3-2 to Figure 3-15 give diagrammatic representations of each of the scenarios. The demineralisation plant is in each case is an RO plant with polishing

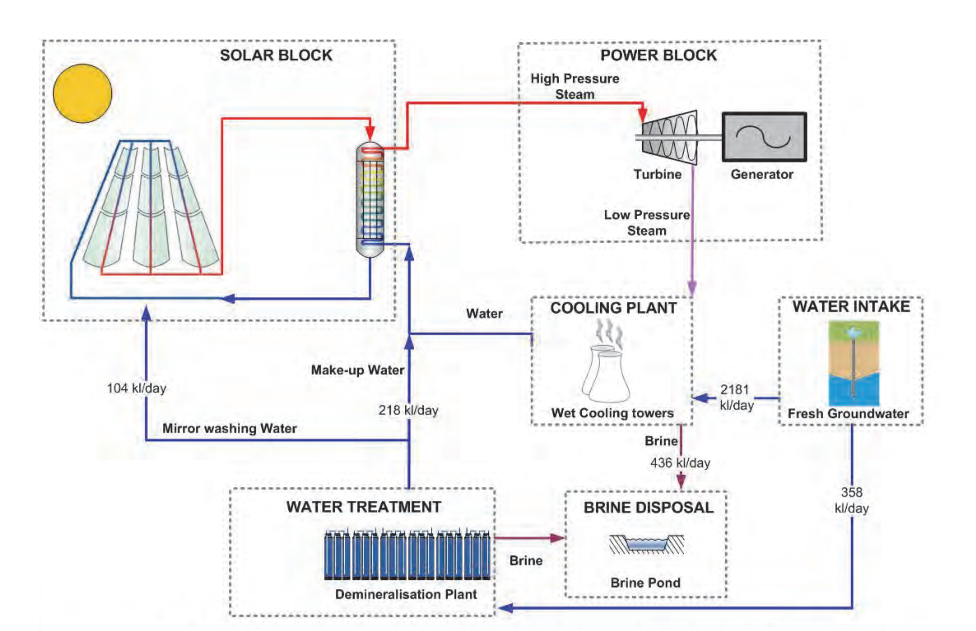


Figure 3-2: Scenario 1: Wet Cooled / Fresh Groundwater / No Storage

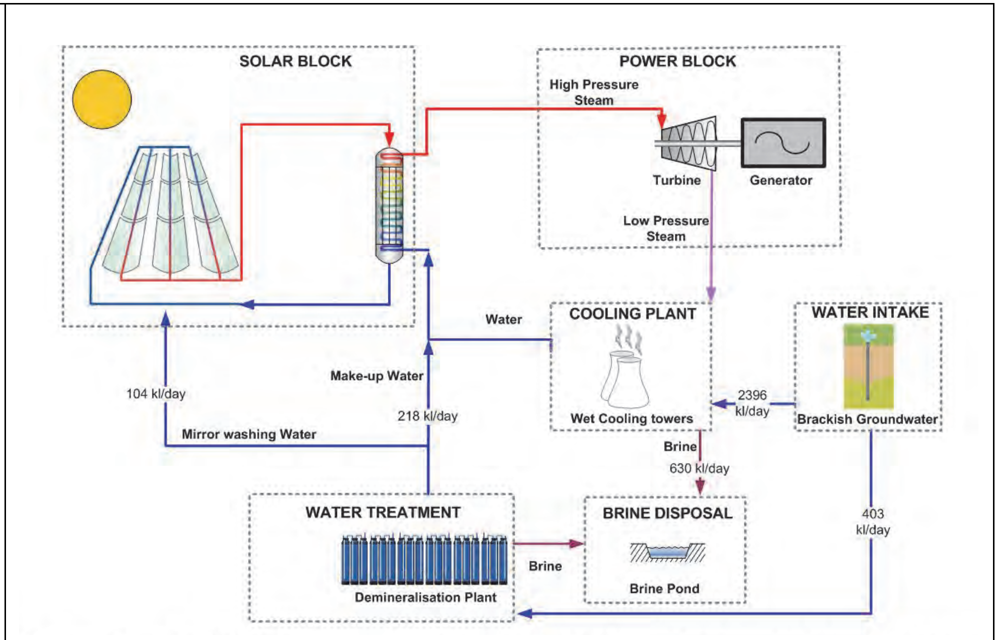


Figure 3-3: Scenario 2: Wet Cooled / Brackish Groundwater / No Storage

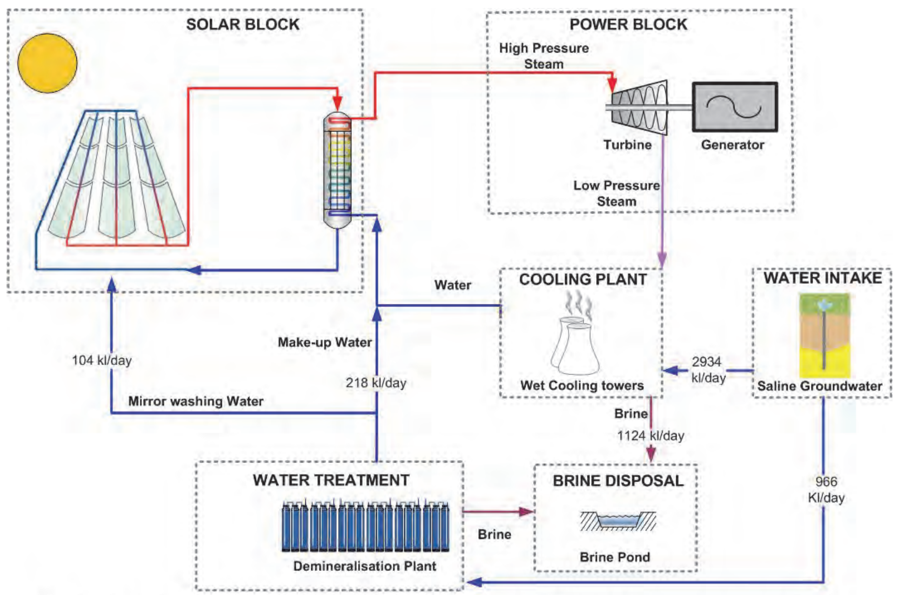


Figure 3-4: Scenario 3: Wet Cooled / Saline Water / No Storage

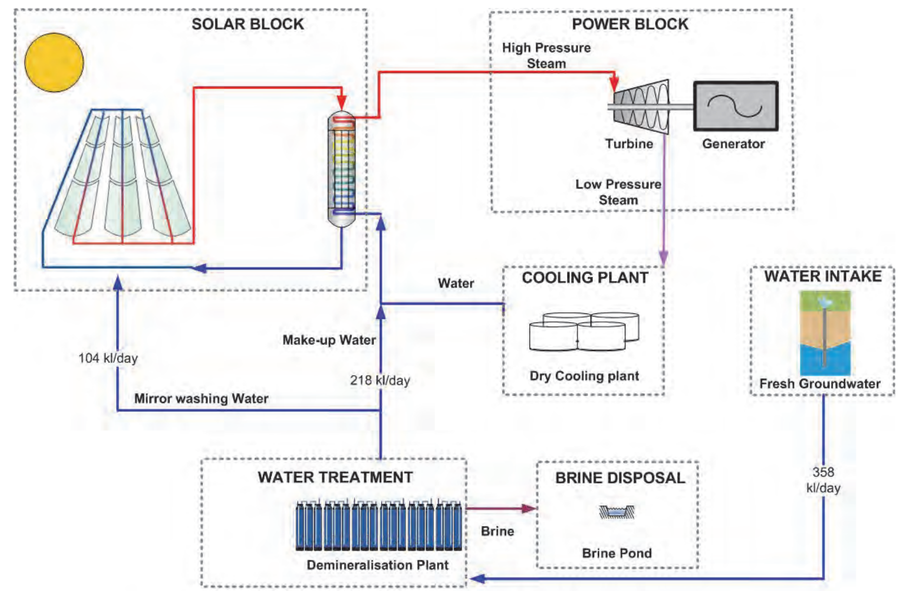


Figure 3-5: Scenario 4: Air Cooled / No Storage

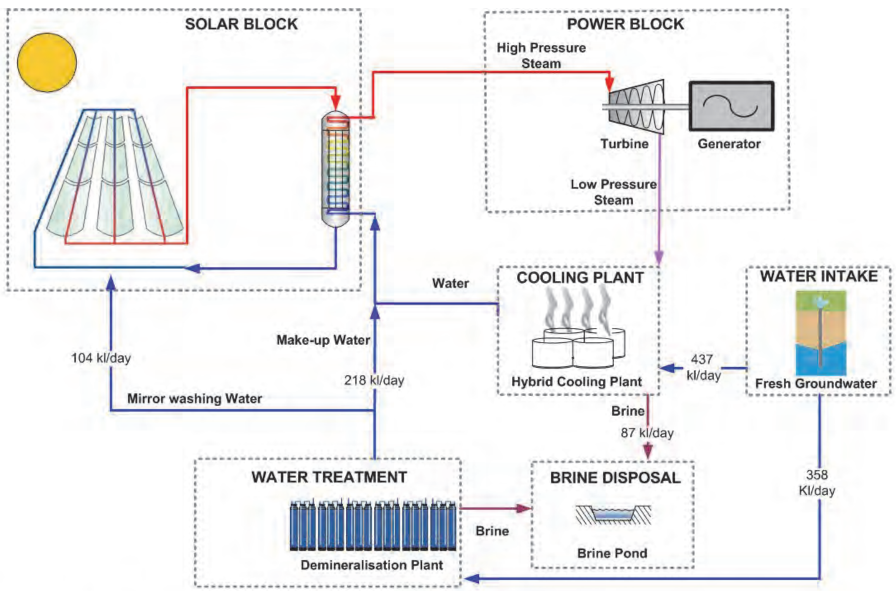


Figure 3-6: Scenario 5: Hybrid Cooled / Fresh Groundwater / No Storage

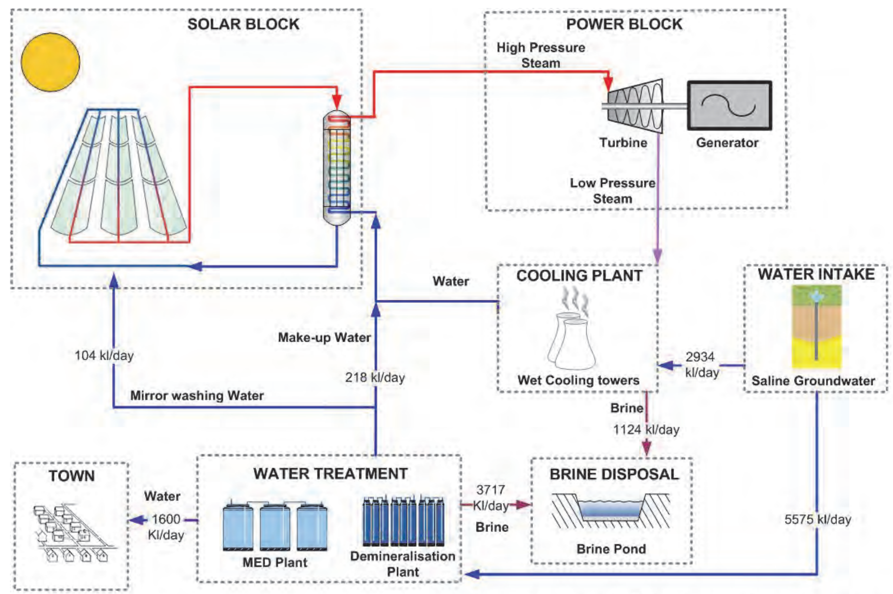


Figure 3-7: Scenario 6: Wet Cooled / Saline Water / MED / No Storage

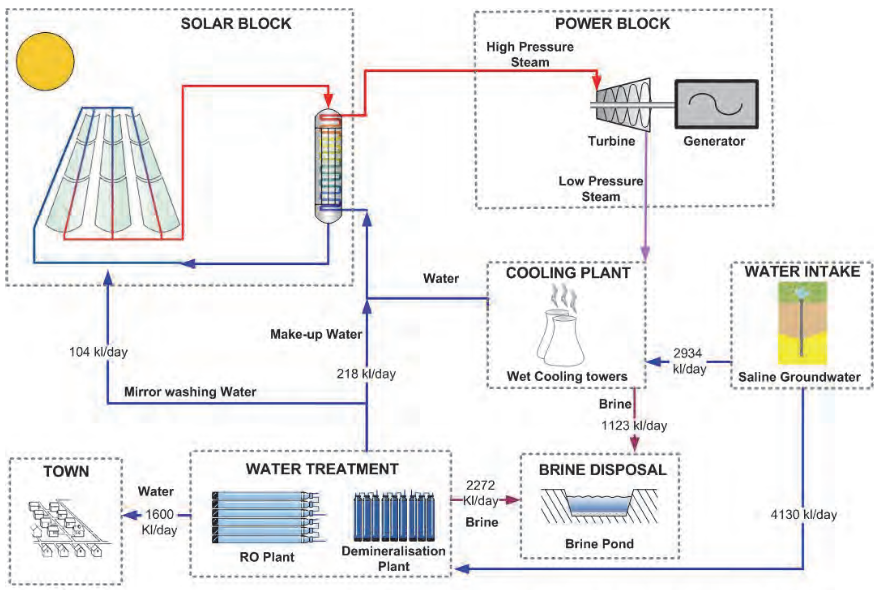


Figure 3-8: Scenario 7: Wet Cooled / Saline Water / RO / No Storage

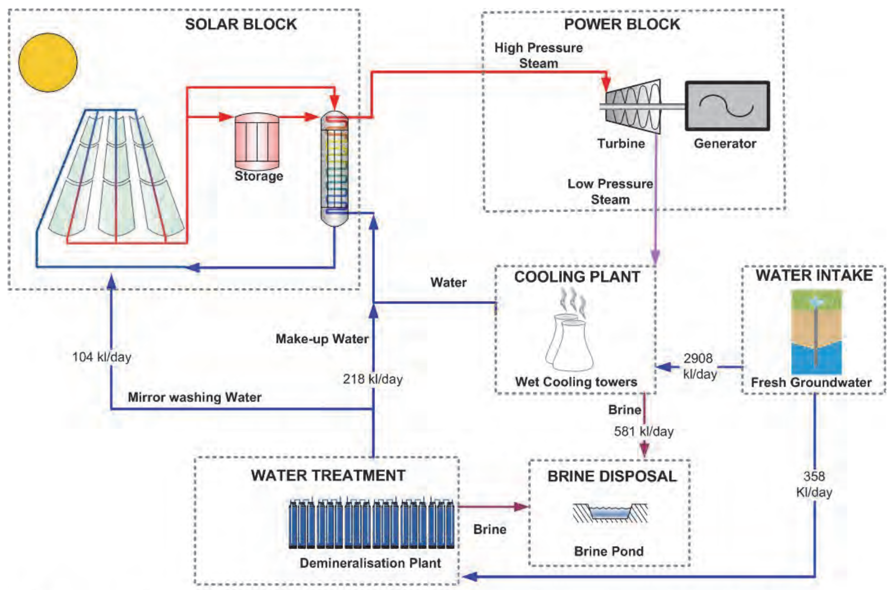


Figure 3-9: Scenario 8: Wet Cooled / Fresh Groundwater / Storage

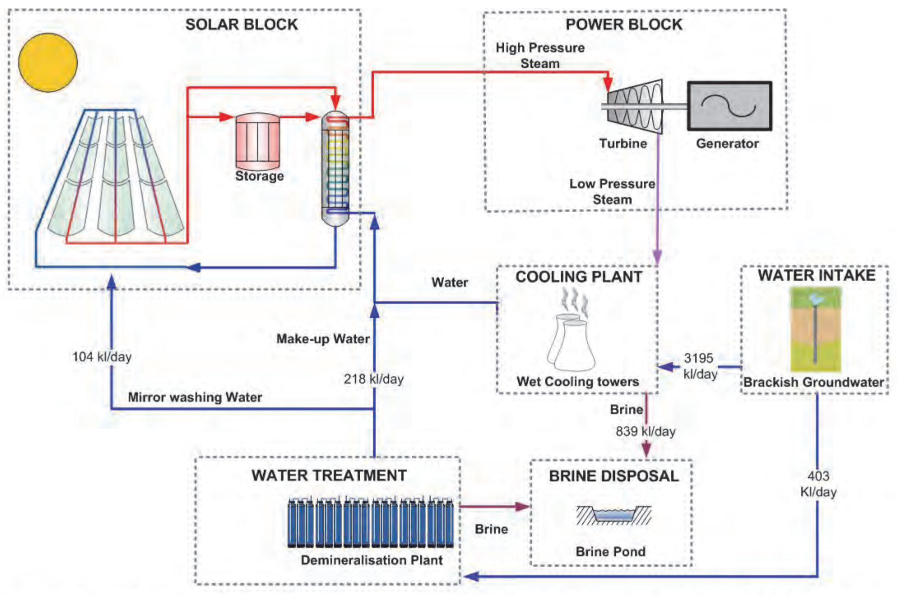


Figure 3-10: Scenario 9: Wet Cooled / Brackish Groundwater / Storage

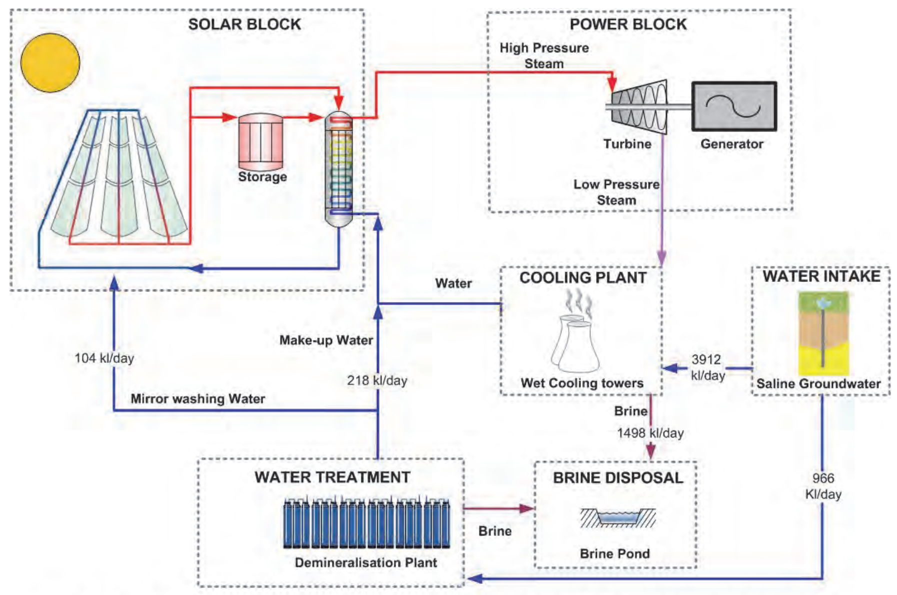


Figure 3-11: Scenario 10: Wet Cooled / Saline Water / Storage

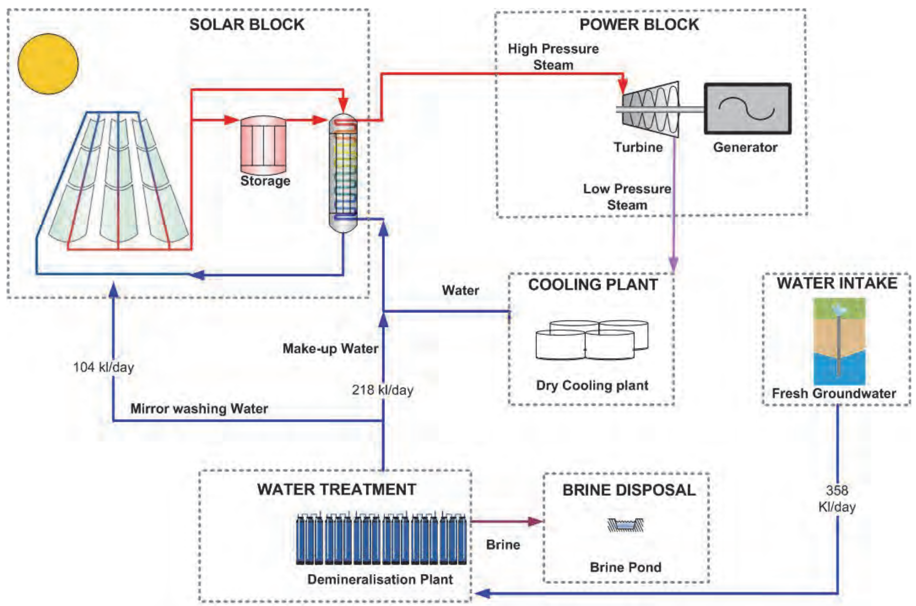


Figure 3-12: Scenario 11: Air Cooled / Storage

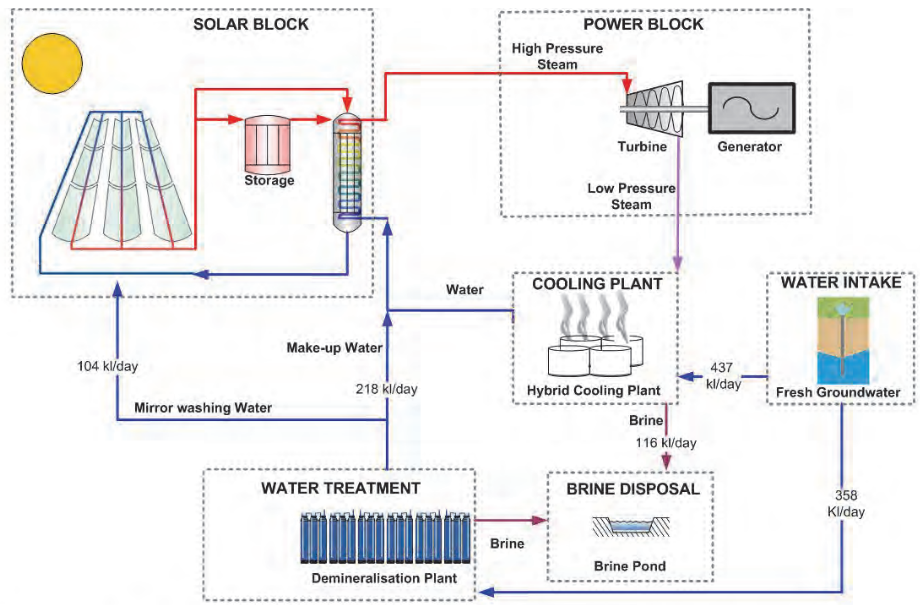


Figure 3-13: Scenario 12: Hybrid Cooled / Fresh Groundwater / Storage

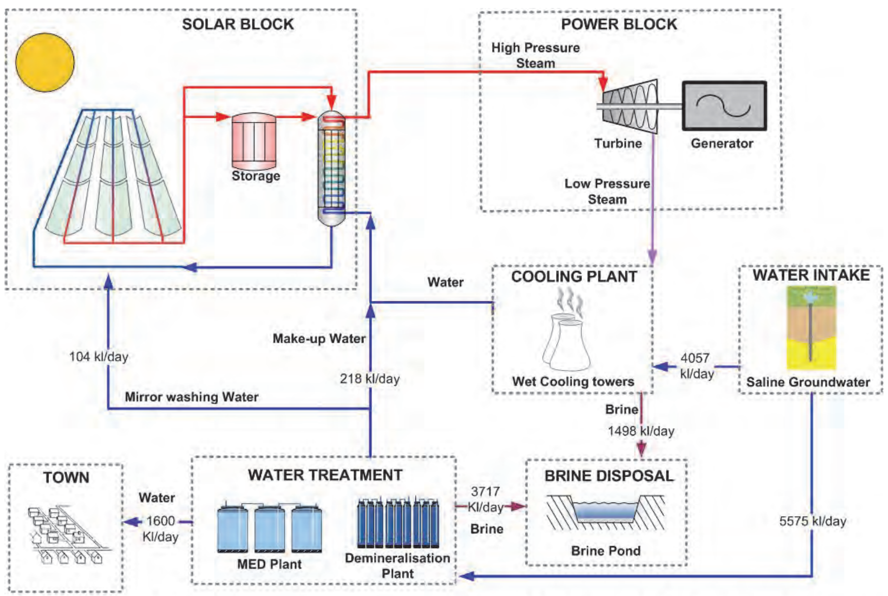


Figure 3-14: Scenario 13: Wet Cooled / Saline Water / MED / Storage

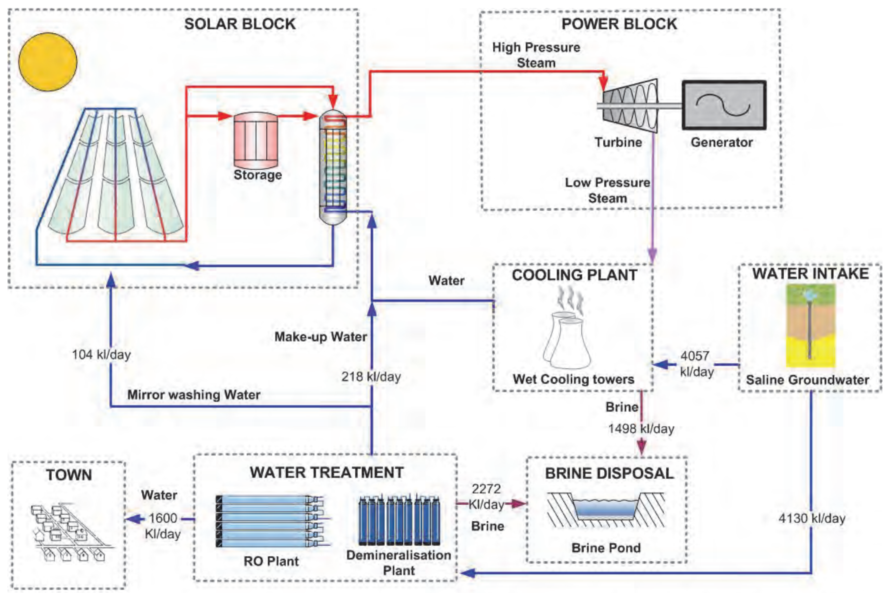


Figure 3-15: Scenario 14: Wet Cooled / Saline Water / RO / Storage

3.3 Model Assumptions

Technology and Costs

The model was run for a 100 MW parabolic trough CSP plant for the scenarios shown in Table 3-2. The wet-cooled parabolic trough plant with no thermal storage was used as the base case scenario. The default capital and O&M costs from SAM (Figure 3-16) were used as there was good agreement with the literature review. For the other scenarios, adjustments were made to capital and O&M costs as well as performance parameters. Figure 3-16 shows the costs for the base case scenario. For each scenario other than the base case adjustments were made to the capital cost by adjusting the cell titled “Total Installed Cost”, and to the operations and maintenance costs

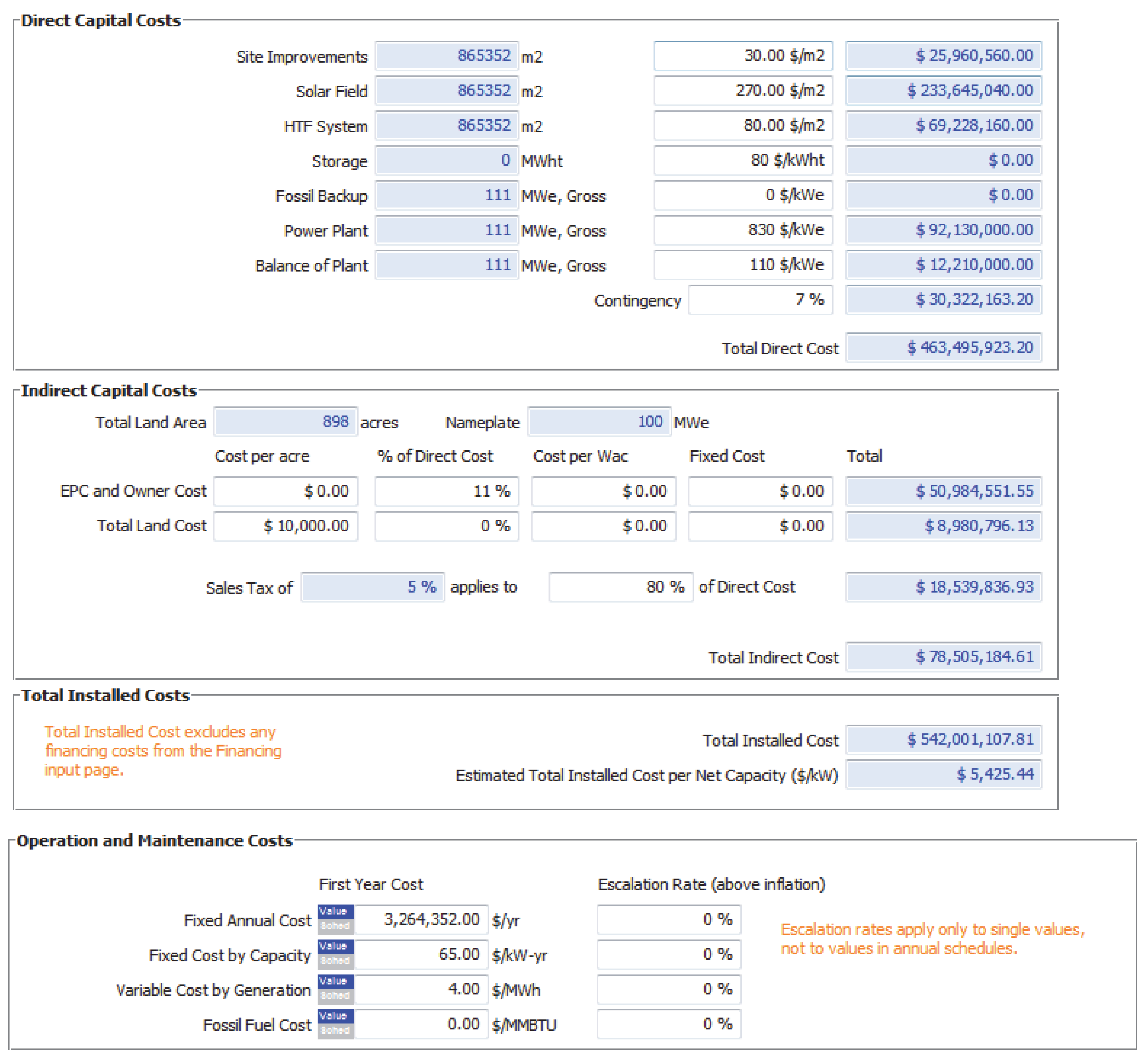


Figure 3-16: Base Case Scenario – SAM Capital and O&M costs

For the brackish and saline water scenarios (2, 3, 6, 7, 9, 10, 13 and 14), brackish water was considered to have a salinity level of 10 000 mg/ℓ and saline water a level of 30 000 mg/ℓ. For the scenarios involving saline cooling towers (2, 3, 6, 7, 9, 10, 13 and 14), a 50% increase in cooling tower costs from the base case due to the requirement to use more costly, corrosion resistant construction materials and build a somewhat larger tower due to the decrease in efficiency of 1% per 10 000 mg/ℓ was factored into the model. (Maulbetsch & Di Filippo, 2010)

The cycles of concentration was assumed to be 5 for the fresh water cooling towers, 3.5 for brackish water cooling towers and 2 for saline cooling towers. (Maulbetsch & Di Filippo, 2010)

In the hybrid cooling scenarios (5 and 9), 20% wet cooling was employed between 13h00-14h00 and between 17h00-18h00. Between 14h00-17h00, 30% wet cooling was employed in the SAM model. At all other times in the day, the plant was air-cooled. These times were guided by the time of day that experiences highest ambient temperatures and arrived at through conducting an optimisation process with manual SAM runs for Upington for the year 2014.

For the MED scenarios (6 and 13), the MED plant was sized to produce 1 600 kℓ/day for a medium to large sized town. With the free basic water right being 25 ℓ per person per day this amounts to the provision of water to meet the constitutional rights to water of 64 000 people. The capital and O&M costs of the MED plant as well as parasitic electrical power use were incorporated into SAM. It was assumed that the MED plant was operational for 30% of the day in scenario 6 and 40% of the day in scenario 13. This is in line with the respective capacity factors of the non-storage and storage scenarios. The water source was considered to be saline and the fresh water recovery rate assumed to be 33%. The income from sale of water was incorporated into the SAM model. Two water selling prices were considered: R7.55/kℓ (Bulk water supply tariff) and R22.50/kℓ (Typical cost of potable water produced through an RO plant).

For the RO scenarios (7 and 14), the RO plant was also sized to produce 1 600 kℓ/day. The capital and O&M costs of the RO plant as well as parasitic electrical power use were incorporated into SAM. For the purposes of comparison with the MED plant, it was assumed that the RO plant was only operational during the times of CSP power production. The water source was considered to be saline and the fresh water recovery rate assumed to be 45% for a TDS of 30 000 mg/ℓ. The income from sale of water was incorporated into the SAM model. Two water selling prices were considered: R7.55/kℓ and R22.50/kℓ.

The model considered the costs of water extraction where R39.12/kℓ was allowed for well-field capital and O&M costs (Murray et al., 2012).

The cost of brine disposal was also considered. It was assumed that brine disposal was to an evaporation pond designed with 25 years life. The evaporation landfill was considered as having 5 cells with the first cell being built in year 1 and subsequent cells every 5 years. The first year capital cost was added to the SAM CSP power plant capital cost and the balance of the cost as well as the cost of salt removal at R300/ton was captured as annualised O&M in SAM.

The model uses the TOU tariff structure introduced during Round 3 of the REIPPPP. The new tariff structure for CSP is determined as follows: 1 650 ZAR/MWh for off peak generation 04h00 to 16h29, 21h30 to 22h29 and a multiplier of 2.7 for generating during peak hours – 16h30 to 21h29 pm. The tariff for the night time – 22h00 to 04h59 is 0.00 ZAR/MWh. We did not undertake a sensitivity analysis on the tariffs, but they do not significantly influence capex or opex. A change to tariff structure would affect revenue. The tariffs used here are the DoE tariffs prevailing at the time of writing.

Capital and O&M costs graphs for Non-Storage Scenarios

Figure 3-17 shows the capital costs for the non-storage scenarios. It must be noted that scenarios 4 and 5 do include evaporation ponds however the costs are comparatively small and as such are not visible on the chart. It must also be noted that freshwater production only occurs in scenarios 6 and 7.

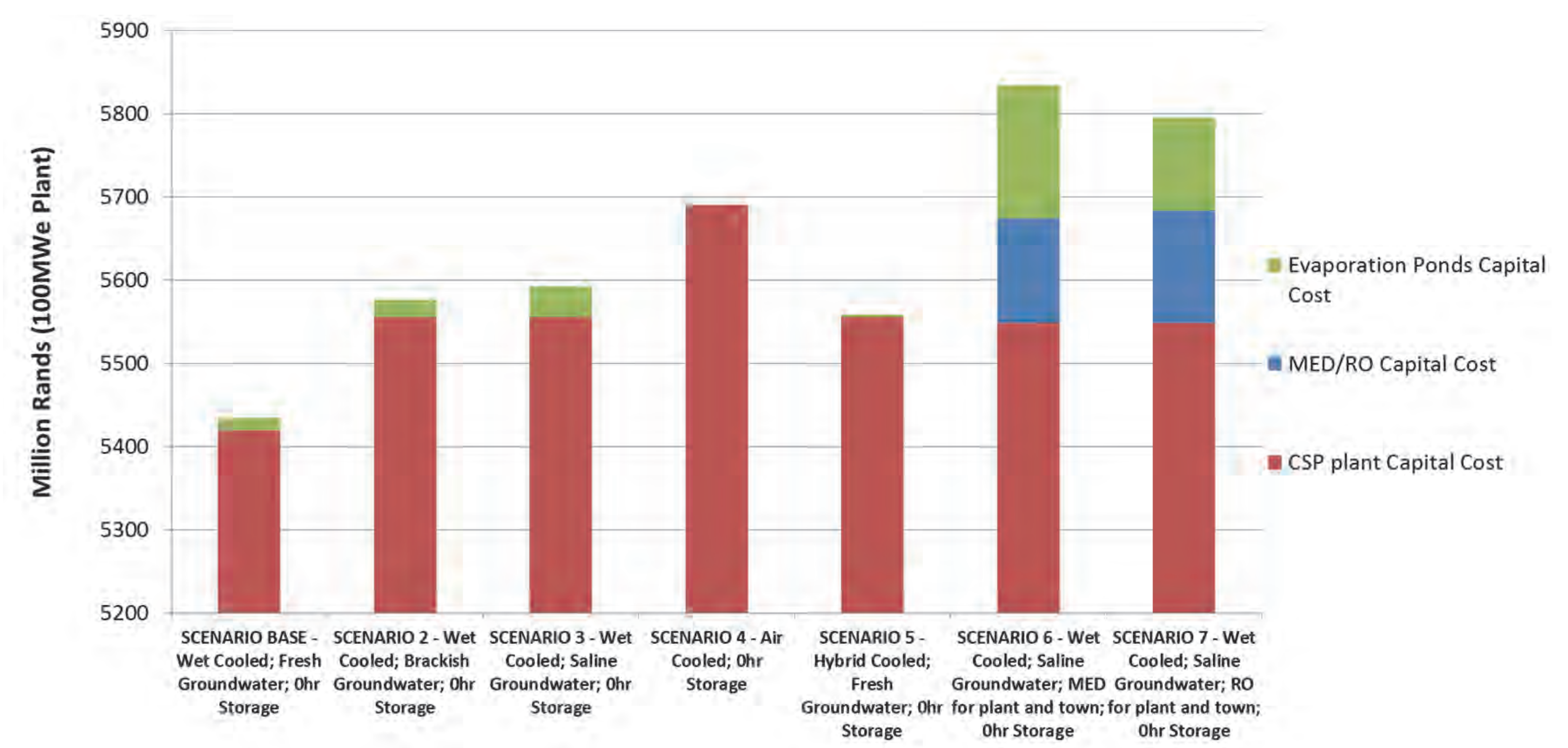


Figure 3-17: Capital costs graph for Non-Storage Scenarios

Figure 3-18 shows the O&M costs for the non-storage scenarios. It must be noted that scenarios 4 and 5 do include evaporation ponds however the costs are comparatively small and as such are not visible on the chart. It must also be noted that freshwater production only occurs in scenarios 6 and 7.

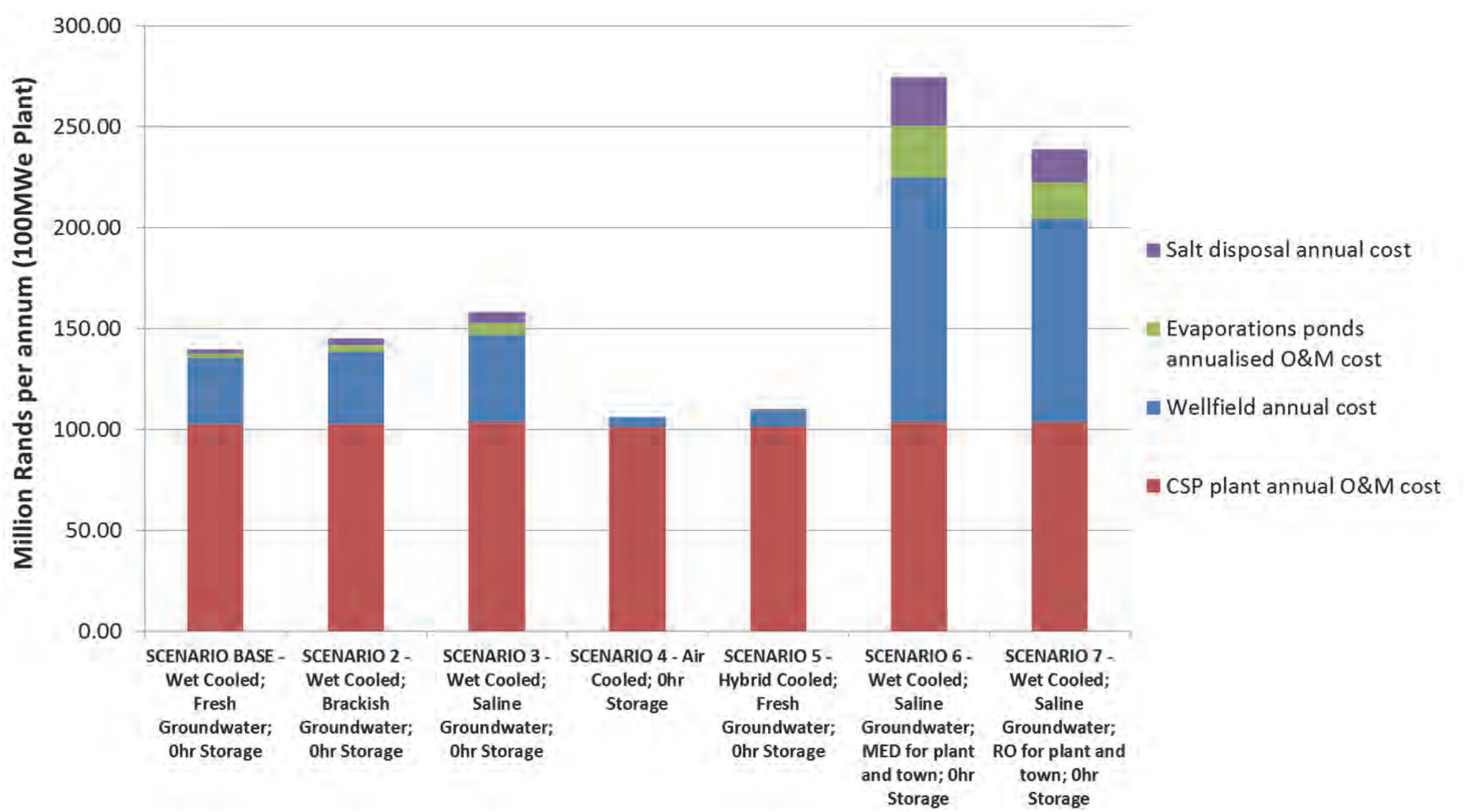


Figure 3-18: O&M costs graph for Non-Storage Scenarios

Capital and O&M costs graphs for Storage Scenarios

Figure 3-19 shows the capital costs for the storage scenarios. It must be noted that scenarios 11 and 12 do include evaporation ponds however the costs are comparatively small and as such are not visible on the chart. It must also be noted that freshwater production only occurs in scenarios 13 and 14.

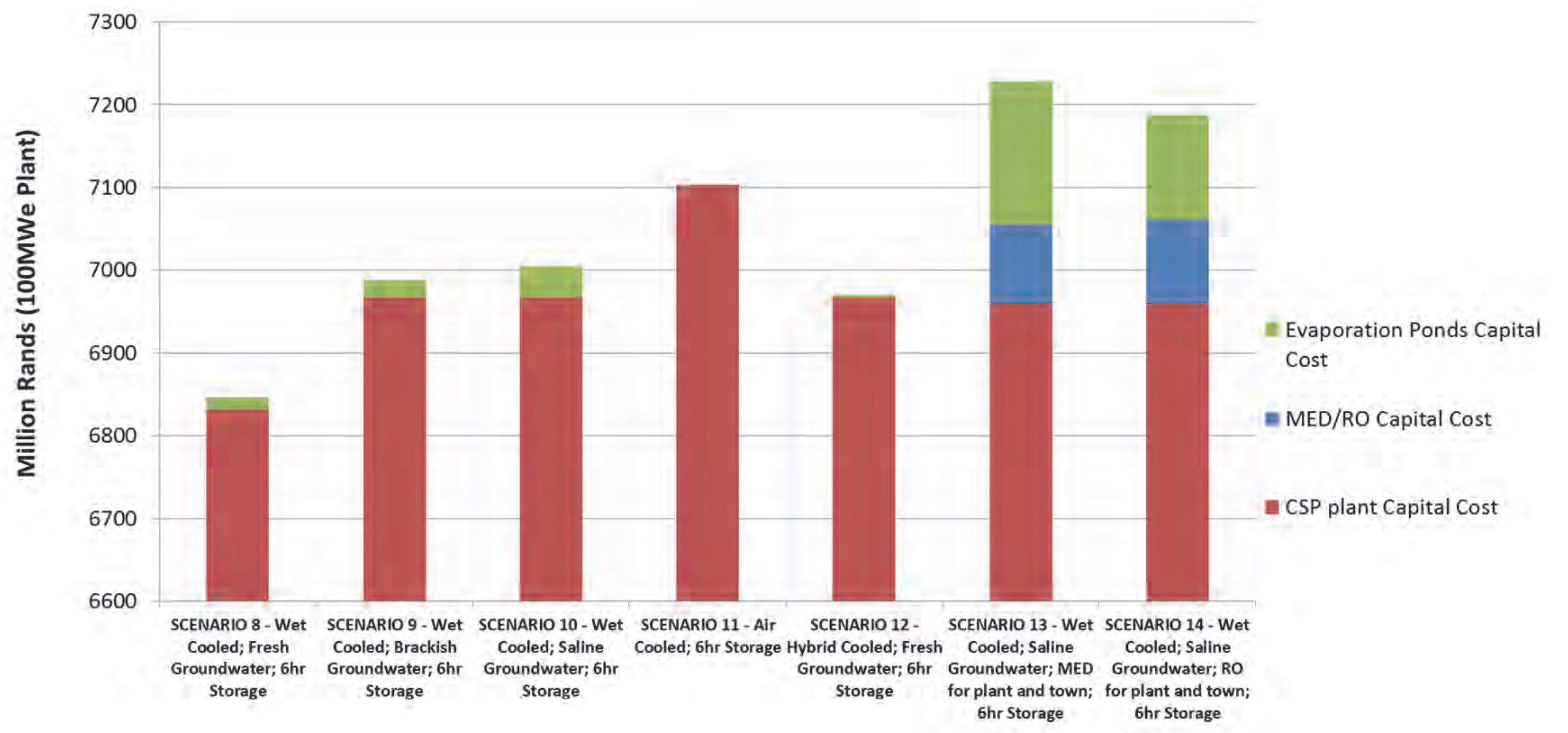


Figure 3-19: Capital costs graph for Storage Scenarios

Figure 3-20 shows the O&M costs for the storage scenarios. It must be noted that scenarios 11 and 12 do include evaporation ponds however the costs are comparatively small and as such are not visible on the chart. It must also be noted that freshwater production only occurs in scenarios 13 and 14.

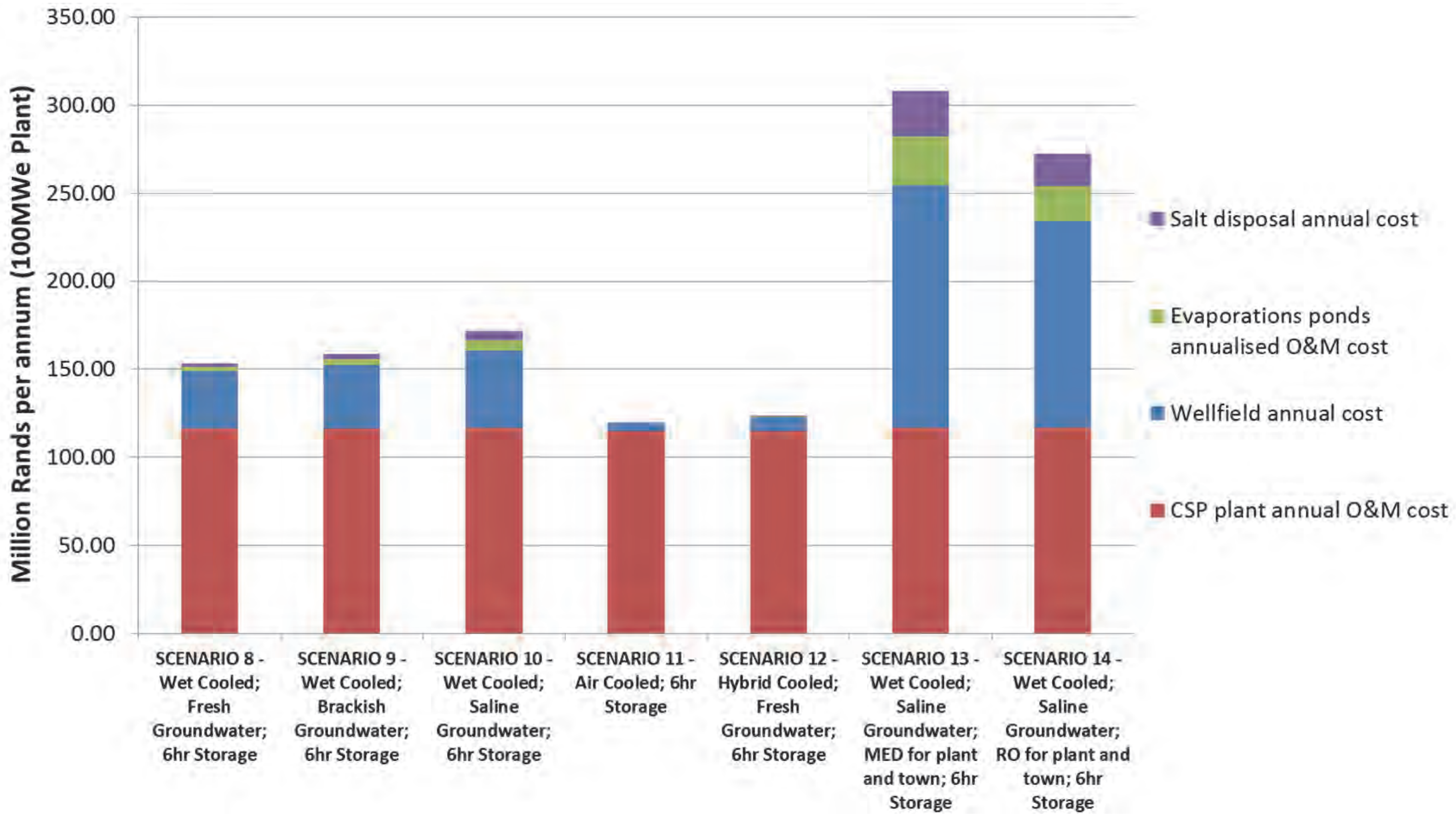


Figure 3-20: O&M costs graph for Storage Scenarios

Hourly Solar DNI

Direct Normal Irradiance is the amount of energy received at a surface that is perpendicular to the incoming radiation, in this case the sun's rays. Sources of DNI include *in situ* observations, satellite derived measurements and model data. The advantage of satellite and model data is that it covers a large geographic area and thus provides information where observed data is not available. The disadvantage of satellite and model data is that assumptions are made regarding effects of clouds and aerosols on incoming radiation, which can act as a source of error in the data. Optionally, a hybrid of satellite and model data is used.

For this study, DNI was sourced from the Weather Research and Forecasting model, WRF. Radiation schemes are fundamental in weather forecasting models, as they provide the energy for atmospheric processes. As such, WRF accurately models solar angle and daylight hours and includes global horizontal irradiance as a standard output variable, where GHI is the amount of energy received at a surface parallel to the earth's surface. Since version WRFv3.5.1 updates to the WRF radiation schemes allow for the calculation of direct normal irradiance, as well as direct horizontal irradiance and diffuse irradiance. The Weather Research and Forecasting model is preferred for DNI to satellite data because satellite data costs are prohibitive and, WRF has been shown to suitably model GHI and DNI for clear skies, while performing less rigorously for cloudy conditions (Lara-Fanego et al., 2011). The areas of South Africa that are suitable for solar farms, the Northern Cape and parts of North-West and the Free State Provinces, are located in areas that receive a high amount of sun days, thus minimising model error caused by cloudy skies (Figure 4-2 and Figure 3-22). The WRF is therefore a suitable tool for providing hourly DNI data for the region of interest.

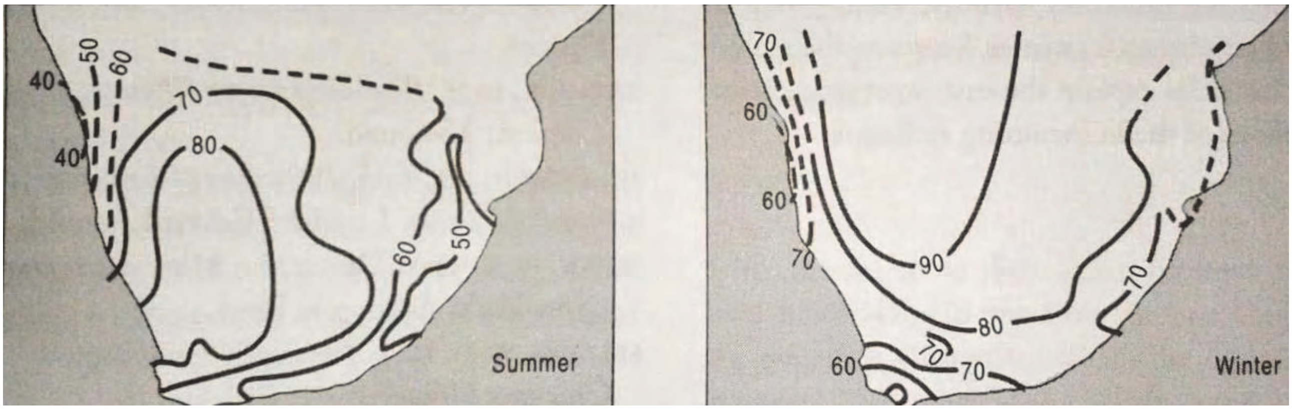


Figure 3-21: Sunshine days as a percentage of total possible for each Summer and Winter (Tyson & Preston-Whyte, 2000)

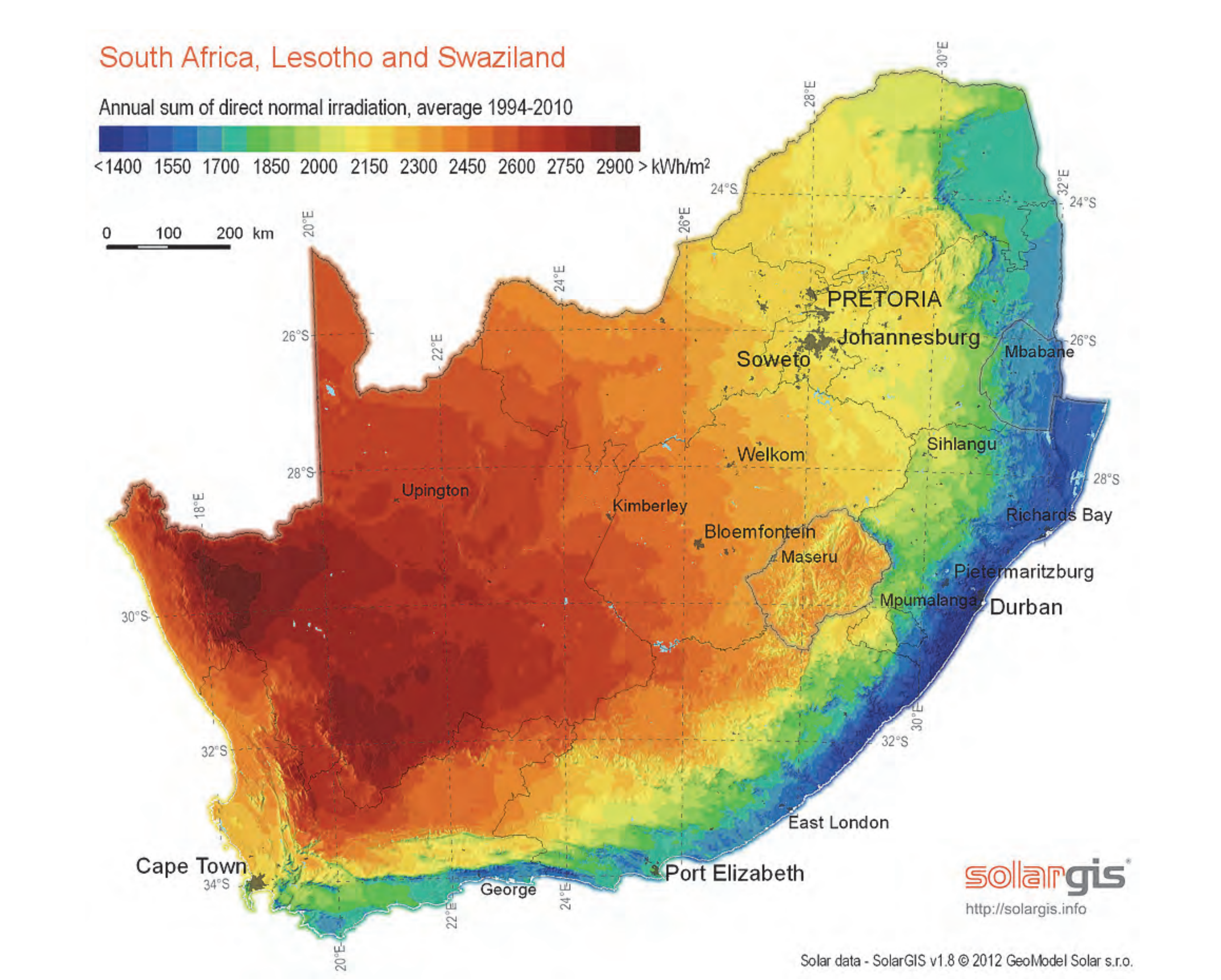


Figure 3-22: Annual total DNI (Solar GIS, 2012)

Hourly ambient conditions

The efficiency of processes at a solar plant is dependent on ambient atmospheric conditions. As such, hourly conditions of air temperature (dry bulb and dew point), relative humidity, atmospheric pressure, wind speed and albedo are required as input into the financial model. These variables were obtained from weather forecast output from the WRF model. The WRF model was run at a suitably high resolution of 4 km to resolve these variables in relation to terrain (Figure 3-23 and Figure 3-24).

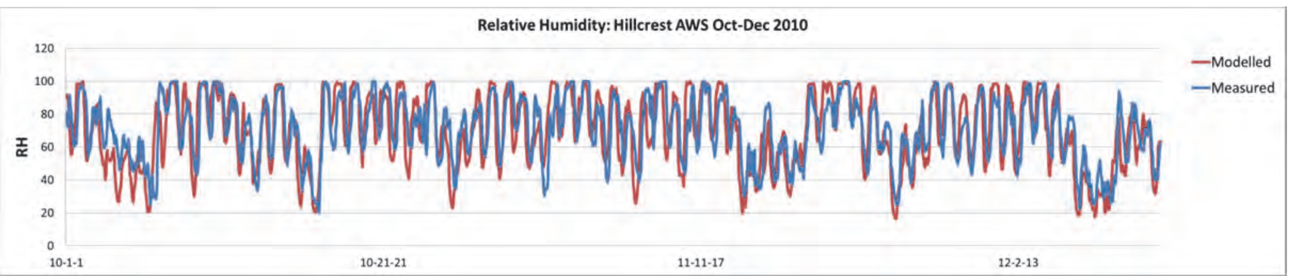


Figure 3-23: WRF Model verification of relative humidity at Hillcrest automatic weather station (Agricultural Research Council station). Oct-Dec 2010.

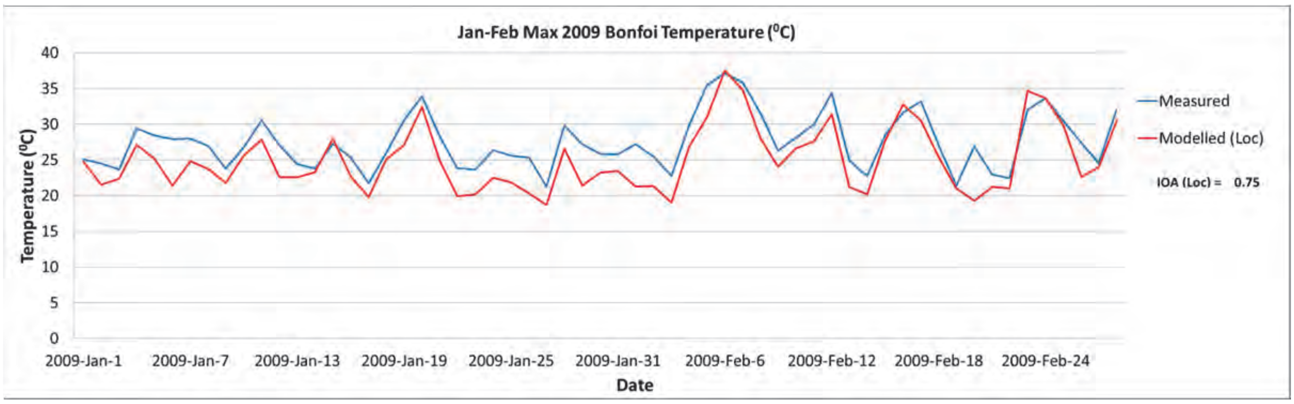


Figure 3-24: WRF Model verification of maximum temperatures at Bonfoi automatic weather station (Agricultural Research Council station). Jan-Feb 2009.

Financial parameters

The default interest rate from SAM of 4% was utilised, the gearing was adjusted to 50% and a rand to dollar exchange rate of 10 ZAR to 1 USD was used.

4 VERIFICATION OF INTEGRATED COST OF ENERGY/COST OF WATER MODEL

4.1 Introduction

Before running the model for the different scenarios, the system architecture and WRF forecasting for DNI were verified. (Figure 4-1)

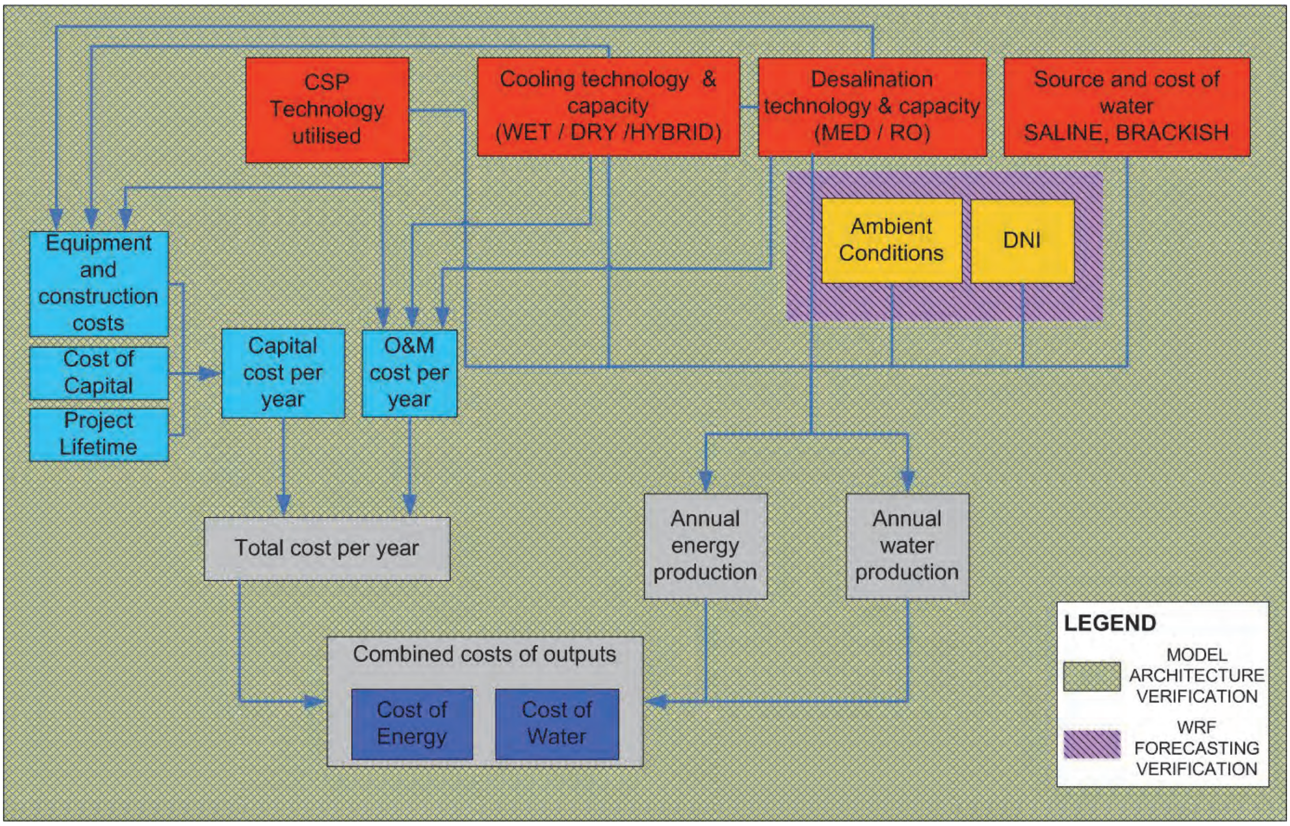


Figure 4-1: Model Data Flowchart – indicating verification components

4.2 System Advisor Model and WRF

The SAM was utilised as the basis of the model to calculate energy outputs and energy costs. For each configuration of CSP and cooling/desalination technology that was modelled there was fixed Capital and Operations and Maintenance (O&M) costs. The ambient conditions, DNI and cost of water will then vary according to the location. The Weather Research and Forecasting model was used to obtain DNI data for input to the integrated model. The SAM developed by the NREL can be downloaded for free from https://sam.nrel.gov/

The SAM is a platform for modelling financial and system performance of the renewable energy systems ranging from wind energy systems to PV as well as variable CSP and geothermal systems. The SAM software is based on the Transient System Simulation Tool (TRNSYS), which is available from http://www.trnsys.com/ .The TRNSYS components are available for purchase with single user licences.

4.3 Model Architecture Verification

The SAM Verification

The verification is based on the report compiled by Australian Solar Thermal Energy Association (AUSTELA) for the Australian Renewable Energy Agency (ARENA). This report is available at: http://www.austela.com.au/docs/projects/sam/SAM_for_Aus_Companion_Guide_20140306.pdf and the SAM project and weather data files have be made available by AUSTELA.

Using SAM (2014.1.14) we verified the results produced in the report using the supplied project file for CSP Trough Systems (Trough_Models_Aus_20140306.zsam) and the supplied weather data. The project file contained all system input parameters. The weather data at the Longreach Queensland site was used. The case model used was the Nevada Solar1 64MW with no Thermal Energy Storage (TES), which is the configuration used for the base study in the Australian CSP report. The output results for the Longreach Queensland site compared to the results from page 23 of the AUSTELA (2014) report are shown in Table 4-1.

Table 4-1: SAM Verification results – comparison of modelled output with published output

	AUSTELA Report (Figure 10)	Reproduced Results	Difference (%)
Annual Energy (kWh)	128777696	128723784	0.04
PPA Price ($0.01/kWh)	31.29	31.29	0
LCOE Nominal ($0.01/kWh)	31.29	31.29	0
LCOE Real ($0.01/kWh)	25.14	25.14	0
Internal rate of return (%)	10.29	10.29	0
Minimum DSCR	1.64	1.64	0
Net present value ($)	0.72	0.72	0
Calculated PPA Escalation (%)	0	0	0
Calculated Debt Fraction (%)	60	60	0
Capacity factor (%)	22.9	22.9	0
Gross to Net Conv. Factor	0.9	0.9	0
Annual Water Usage (m^3)	549492	549805	0.06
Total Land Area (acres)	370.95	370.95	0

It is noted that differences in the annual energy production are tightly coupled to the input weather data. As the AUSTELA report has been revised three times since it was first released in May 2013, it is likely that newer results that have been calculated may not have made it into the revised report.

According to the AUSTELA report (page 30), variances as high as 6% in the predicted annual generation have been seen when running the same model in different releases of SAM (e.g. SAM 2011.6.30). This is attributed to refinements in the SAM model. According to the report these values are within the stated level of accuracies.

Comparison of SAM Manual and batch processing:

The SAM modelling process can be "driven" using three different methods:

1. Manually – a user can change system inputs from the user interface, selecting different sites (weather data) and changing system performance/configuration settings associated with the specific selected technology (CSP, PV, Wind, etc.). For CSP technologies there are in excess of 200 input variables. The model is started manually by the user.
2. SamUL – a scripting language is provided in the SAM environment to adjust input parameters in the model. This includes the ability to adjust the site location and associated weather data. A large number of sites (so far tested for more 2500 sites) can be batch processed in a single iteration. This processing method allows better use of multicore processor hardware and on an "oct-core" machine all 8 cores can be used to process sites in parallel.
3. SSC (SAM Simulation Core) Software Development Kit (SDK) – an open programming interface (API) is provided to access SAM models directly and build free standing applications dedicated to specific modelling tasks that can be run on any platform (Windows / Linux) unlike the SAM application that is only Windows based.

We verified the results of running the Nevada1 64MW (no TES) case model manually and in batch mode using the SamUL scripting language. Results are detailed below:

Table 4-2: Manual vs. Batch Mode Verification – Australian Sites

Australian Sites	NSW – Wagga Wagga			QLD – Longreach			WA – Geraldton		
	Manual	Batch	% difference	Manual	Batch	% difference	Manual	Batch	% difference
Annual Energy (kWh)	86557792	86557800	0.00001	128777696	128778000	0.00024	116367368	116367000	0.00032
PPA Price ($0.01/kWh)	45.49	45.4897	0.00066	31.29	31.2924	0.00767	34.4	34.3966	0.00988
LCOE Nominal ($0.01/kWh)	45.49	45.4897	0.00066	31.29	31.2924	0.00767	34.4	34.3966	0.00988
LCOE Real ($0.01/kWh)	36.55	36.5502	0.00055	25.14	25.1429	0.01154	27.64	27.6371	0.01049
Internal rate of return (%)	10.29	10.29	0.00000	10.29	10.29	0.00000	10.29	10.29	0.00000
Minimum DSCR	1.64	1.64339	0.20671	1.64	1.63672	0.20000	1.64	1.63868	0.08049
Net present value ($)	0.72	0.719652	0.04833	0.72	0.716443	0.49403	0.72	0.717386	0.36306
Calculated PPA Escalation (%)	0	0	n/a	0	0	n/a	0	0	n/a
Calculated Debt Fraction (%)	60	60	0.00000	60	60	0.00000	60	60	0.00000
Capacity factor (%)	15.4	15.4198	0.12857	22.9	22.9411	0.17948	20.7	20.7303	0.14638
Gross to Net Conv. Factor	0.87	0.873887	0.44678	0.9	0.903279	0.36433	0.9	0.898412	0.17644
Annual Water Usage (m^3)	374941	374941	0.00000	549492	549492	0.00000	497863	497863	0.00000
Total Land Area (acres)	370.95	370.95	0.00000	370.95	370.95	0.00000	370.95	370.95	0.00000

Table 4-3: Manual vs. Batch Mode Verification – US Sites

US Sites	AK – Anchorage			AK – Annette			AK – Barrow		
	Manual	Batch	% difference	Manual	Batch	% difference	Manual	Batch	% difference
Annual Energy (kWh)	7896087	7896090	0.00004	12234621	12234600	0.00017	-14318436	-14318400	-0.00025
PPA Price ($0.01/kWh)	100	100	0.00000	100	100	0.00000	100	100	0.00000
LCOE Nominal ($0.01/kWh)	100	100	0.00000	100	100	0.00000	100	100	0.00000
LCOE Real ($0.01/kWh)	80.35	80.3482	0.00224	80.35	80.3482	0.00224	80	80.3482	0.43525
Internal rate of return (%)	-6.99	-6.99322	-0.04607	-3.87	-3.87015	-0.00388	0	0	n/a
Minimum DSCR	0.34	0.340198	0.05824	0.53	0.527121	0.54321	-0.62	-0.621607	-0.25919
Net present value ($)	-184951568	-184952000	-0.00023	-158577536	-158578000	-0.00029	-319994080	-319994000	-0.00003
Calculated PPA Escalation (%)	0.00%	0	n/a	0	0	n/a	0	0	n/a
Calculated Debt Fraction (%)	6000.00%	60	0.00000	60	60	0.00000	60	60	0.00000
Capacity factor (%)	1.4	1.40665	0.47500	2.2	2.17954	0.93000	-2.6	-2.55076	-1.89385
Gross to Net Conv. Factor	0.33	0.328149	0.56091	0.43	0.433783	0.87977	-1.71	-1.70761	-0.13977
Annual Water Usage (m^3)	94847	94846.9	0.00011	107139	107139	0.00000	40225	40225.3	0.00075
Total Land Area (acres)	370.95	0	100.00000	370.95	0	100.00000	370.95	370.95	0.00000

The weather data for the South African sites is based on data that has been modelled in WRF. As only the first weeks' worth of modelling data was available at the time of verification these data were replicated / repeated over the remaining 51 weeks of the year.

Table 4-4: Manual vs. Batch Mode Verification – South African Sites

South African Sites	Lat/long (15.8346 / -35.0812) – Grid 000-000			Lat/Long (15.8346/-35.0452) – Grid 000-001			Lat/Long (15.8346/-35.0092) – Grid 000-002		
	Manual	Batch	% difference	Manual	Batch	% difference	Manual	Batch	% difference
Annual Energy (kWh)	41328684	4.13E+007	0.00004	42253132	4.23E+007	0.00008	40215380	4.02E+007	0.00005
PPA Price ($0.01/kWh)	92.88	92.8807	0.00075	90.9	90.8964	0.00396	95.39	95.3915	0.00157
LCOE Nominal ($0.01/kWh)	92.88	92.8807	0.00075	90.9	90.8964	0.00396	95.39	95.3915	0.00157
LCOE Real ($0.01/kWh)	74.63	74.6281	0.00255	73.03	73.0337	0.00507	76.65	76.6454	0.00600
Internal rate of return (%)	10.29	10.29	0.00000	10.29	10.29	0.00000	10.29	10.29	0.00000
Minimum DSCR	1.65	1.65055	0.03333	1.65	1.6504	0.02424	1.65	1.65072	0.04364
Net present value ($)	0.72	0.731257	1.56347	0.0072	0.739041	10164.45833	0.72	0.728683	1.20597
Calculated PPA Escalation (%)	0	0	n/a	0	0	n/a	0	0	n/a
Calculated Debt Fraction (%)	60	60	0.00000	60	60	0.00000	60	60	0.00000
Capacity factor (%)	7.4	7.36249	0.50689	0.075	7.52718	9936.24000	7.2	7.16417	0.49764
Gross to Net Conv. Factor	0.73	0.731257	0.17219	0.74	0.739041	0.12959	0.73	0.728683	0.18041
Annual Water Usage (m^3)	238146	238146	0.00000	238743	238743	0.00000	233063	233063	0.00000
Total Land Area (acres)	370.95	370.95	0.00000	370.95	370	0.25610	370.95	370.95	0.00000

While we expected the differences between the batched results and manual results to be identical, we attributed the differences to rounding errors, which can clearly be identified in the tables. In the extraction of output parameters (in the manual process), results were extracted from the metrics value table. As seen in the tables above the standard formatting rounds these values to 2 decimal places.

Comparison of batch processing with SAM Simulation Core (SSC) Software Development Kit (SDK)

Progress has been made with making use of the SSC SDK interface for batch processing. Replicating the Nevada1 64MW model using this method brings with it significant advantages however it comes with a caveat of increased complexity to implement. The SSC model consists of 38 separate modules, which include financial models as well as different technology modules (e.g. PV, CSP Trough, CSP empirical, Wind, etc.). The SAM application wraps the modules together and configures (converts units, etc.) the parameters in such a way that the output from one module can be used as the input to the next module. For the CSP physical tough module which is one of the modules used in the Nevada1 case, this module has in excess of 200 separate input variables.

4.4 Verification of WRF Forecasting

Introduction

Numerical weather prediction models are useful for solar energy applications for two reasons:

1. They provide spatially continuous information which is otherwise not represented by observations
2. They can forecast same day and next day direct normal irradiance, which is useful in plant management and predicting power production.

In this section we present verification of WRF, the numerical weather prediction model to demonstrate its suitability for forecasting DNI. WRF is verified against three months of observations of direct normal irradiance data from January to March 2014. Observed data is from the GIZ Graaff-Reinet and Vanrhynsdorp stations and is made available through The Southern African Universities Radiometric Network (SAURAN) (The Southern African Universities Radiometric Network , 2014). Data is averaged over 1 minute which is favourable as WRF produces instantaneous values.

Method of Verification

Two major factors determine WRF performance: forecast horizon and sky conditions. Numerical weather prediction models remain to be the best tool for forecasting next day direct normal irradiance (DNI) (Law et al., 2014). For solar forecasting, the forecast horizon is between 1-3 days, where forecast accuracy decreases as forecast horizon increases (Lara-Fanego et al., 2012). There are two measures that are commonly used for comparing model performance, namely mean bias error (MBE) and root mean square error (RMSE), with the option to normalise against an observed average or maximum (Law et al., 2014). Where MBE and RMSE are represented in W/m^2 and the normalised, nMBE and nRMSE respectively are represented as percentage against a reference point described above.

Different sky conditions are considered when verifying the forecast and are typically split into two categories: clear sky and cloud conditions. Cloud conditions can be further categorised into partly cloudy and overcast conditions (Lara-Fanego et al., 2012). WRF typically performs well for clear sky conditions when the aerosol optical depth is suitably represented. However, MBE increases by an order of 100 % when cloud is present, as cloud produces the most variability in observed DNI, after aerosols.

Results of DNI from two different WRF configurations are presented here: initialisation at t00z and t06z. In other words, these forecast horizons are not next day or one day, but rather same day horizons. We present results as MBE and not nMBE, as it is not always possible to determine the reference DNI used for normalising MBE in some of the literature. Here, MBE is defined as:

$$MBE = \frac{1}{N}\sum_{i=1}^{N} P_i - O_i \qquad \textbf{[1]}$$

Results from previous studies range from ~ ±300-23 W/m^2 for next day forecasts where the highest and lowest error is associated with overcast conditions and clear sky conditions respectively (Figure 4-2). We categorised our results per day into clear and cloud conditions based on the observed DNI values. When observed DNI does not show a full distribution we classified it as cloud affected. We then compared WRF instantaneous values to 1 minute average values observed at the Graaff-Reinet and Vanrhynsdorp measuring sites. Comparisons are limited to 07:00 UTC to 18:00 UTC for each day.

Weather Research and Forecasting Model Mean Bias Error Results

The MBE calculated from cloud days was 146 and 226 W/m^2 and -41 and -45 W/m^2 for clear days for Graaff-Reinet and Vanrhynsdorp respectively. Results of MBE compare favourably to previous studies (Figure 4-2) showing a lower MBE where our cloud days compare to the literature for clear days. Verification is categorised into clear sky, cloud and overcast days (Lara-Fanego et al., 2012) (Ruiz-Arias, et al., 2012). Although our MBE is expected to deteriorate when running a forecast into the next day, the results are acceptable for the current use, which is to map the solar resource. More noteworthy however are the results from clear days: clear day forecasts can be seen as a way of calibrating the forecast model, as no cloud is present. Our MBE indicated an under prediction in DNI of about 50 w/m^2 which is due to an under prediction in maximum daily DNI values (Figure 4-3). This under prediction appears to be caused in part by the climatological aerosol optical depth used in WRF. Zamora et al. (2003) and Ruiz-Arias et al. (2012) report that the Dudhia shortwave radiation scheme is WRF, which was used in this study, uses a climatological aerosol optical depth of 0.1. However, satellite measurements report AOD values of ~0.03 for our site in January 2014 (NASA's Earth Observatory, MODIS Atmospheric Science Team and NASA Goddard Space Flight Centre, 2014). Thus, the overestimation of AOD in the model will cause extra scattering of light and therefore decrease modelled DNI.

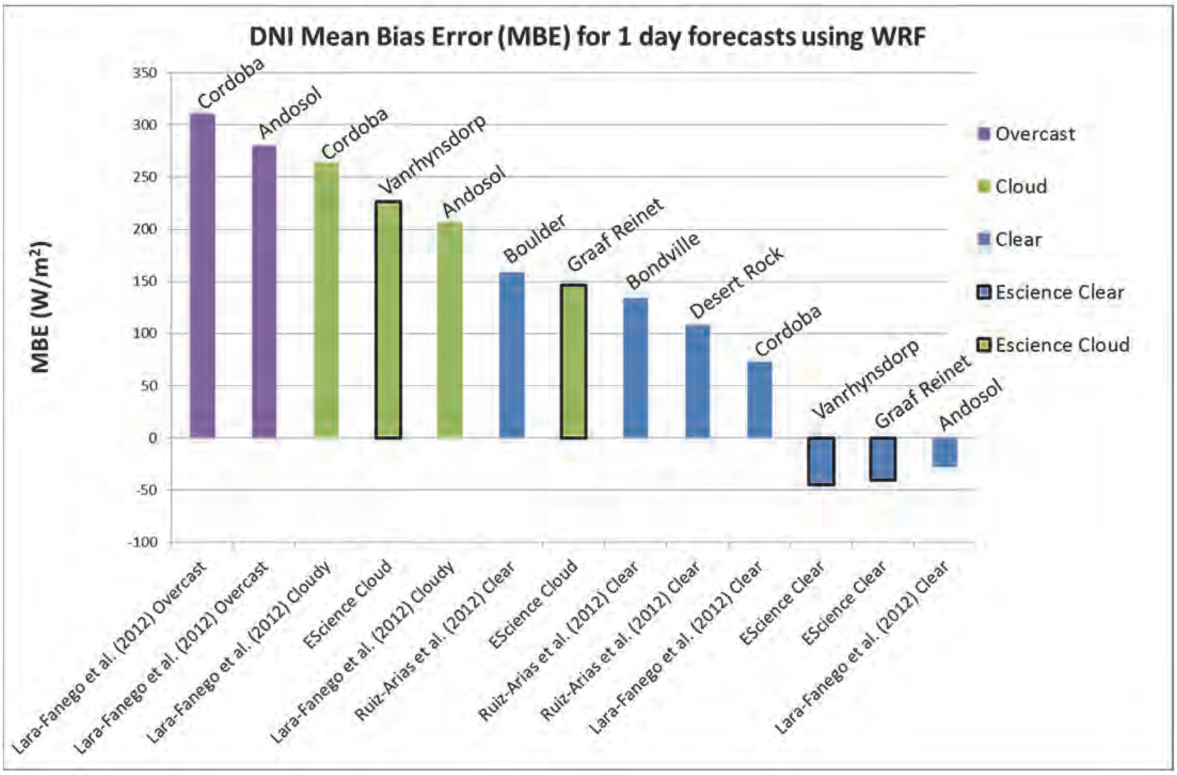


Figure 4-2: Mean bias error of DNI for next day forecasts (literature) and same day forecasts (EScience, initialised at t00z).

Limitations

The favourable MBE in Figure 4-2 may be due to the definition of cloud days. For example, 19 January is categorised as a cloud day due to early morning cloud, but more than 50 % of daylight hours receives full sun (Figure 4-3). Thus, WRF is shown to perform well as it is categorised as cloud but is mostly being compared to clear conditions. To correct this, one would have to define clear/cloud on an hourly basis rather than a daily basis. This is possible and needs to be developed by identifying suitable non-cloud days so as to define a diurnal data set which can be used to identify cloud hours.

The final method (Figure 4-3 c) of assimilating a composite time series as it produced the best results over the short verification period and was thus utilised in the project. The models shown in Figure 4-3 a and b contained inaccuracies that exerted a greater influence on the results than the factors being investigated.

a.

b.

c.

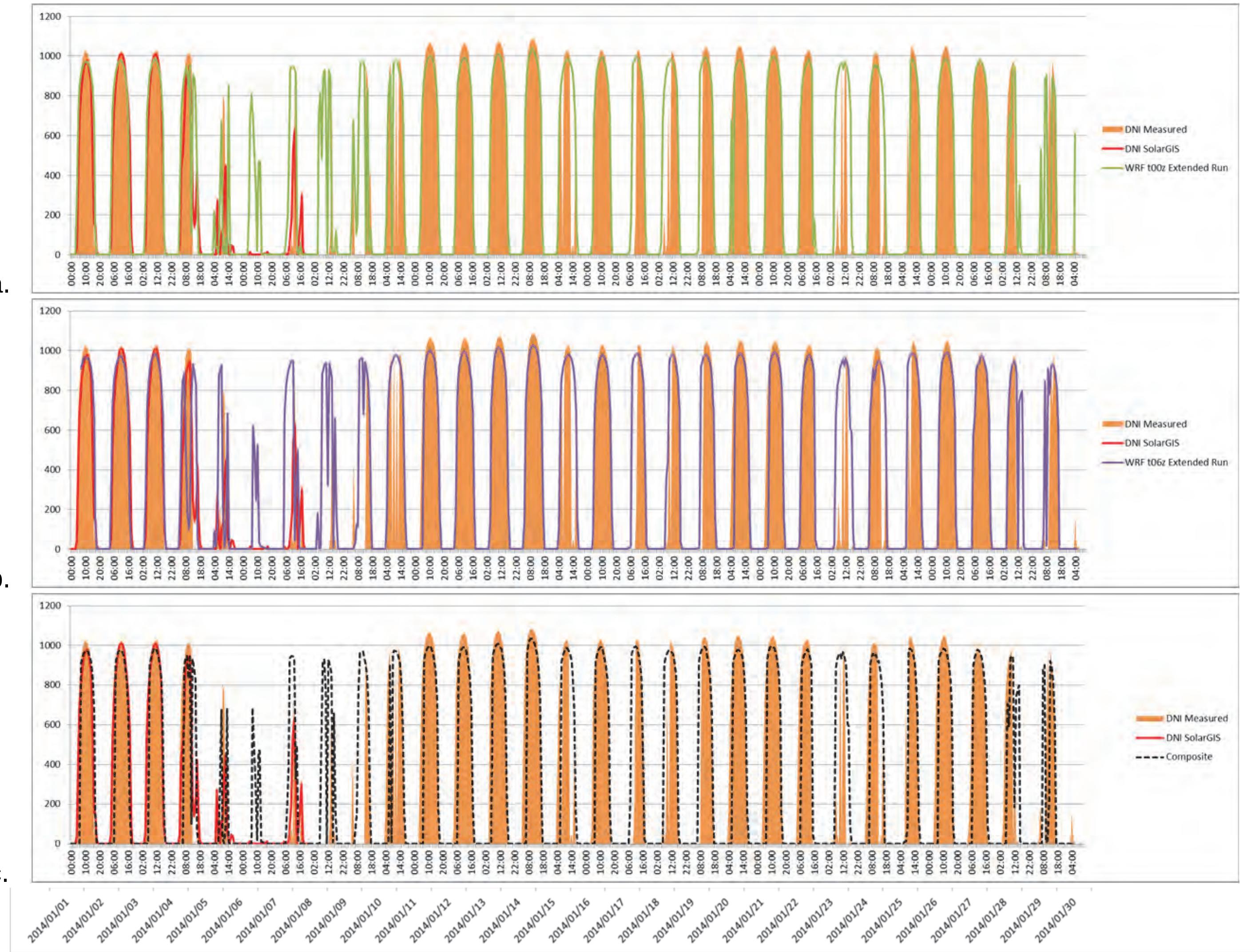


Figure 4-3: Weather Research and Forecasting Model verification of DNI at the GIZ site in Graaff-Reinet during January 2013 for a.) WRF t00z, b.) WRF t06z and c.) WRF composite

5 RESULTS AND DISCUSSION

5.1 Weather and Solar Radiation Results

Direct Normal Irradiance results from WRF Modelling

The DNI input into the model was obtained through the process described in section 4.4. The section also presented the limitations in the performance of WRF in DNI forecasting on cloudy days. The verification process highlighted a measure of over prediction of the DNI on cloudy days. The impact from the sample data was believed to be within reasonable tolerance levels for a strategic study. During the actual model run, it emerged that cloud days had a significant impact on modelling of the DNI, whereby the WRF model was not capturing the frequency of cloud days and therefore over predicting DNI and consequently power produced (Figure 5-1 a and b). However, the model does perform well when there is a match of clear days with reality or cloud days with reality. Therefore, corrections only need to be made when the WRF model misses clouds, or WRF overestimates clouds. The process of correcting WRF data is described in the next section. The white areas in Figure 5-1 b.) and c.) represent values greater than 3200 kWh/m^2.

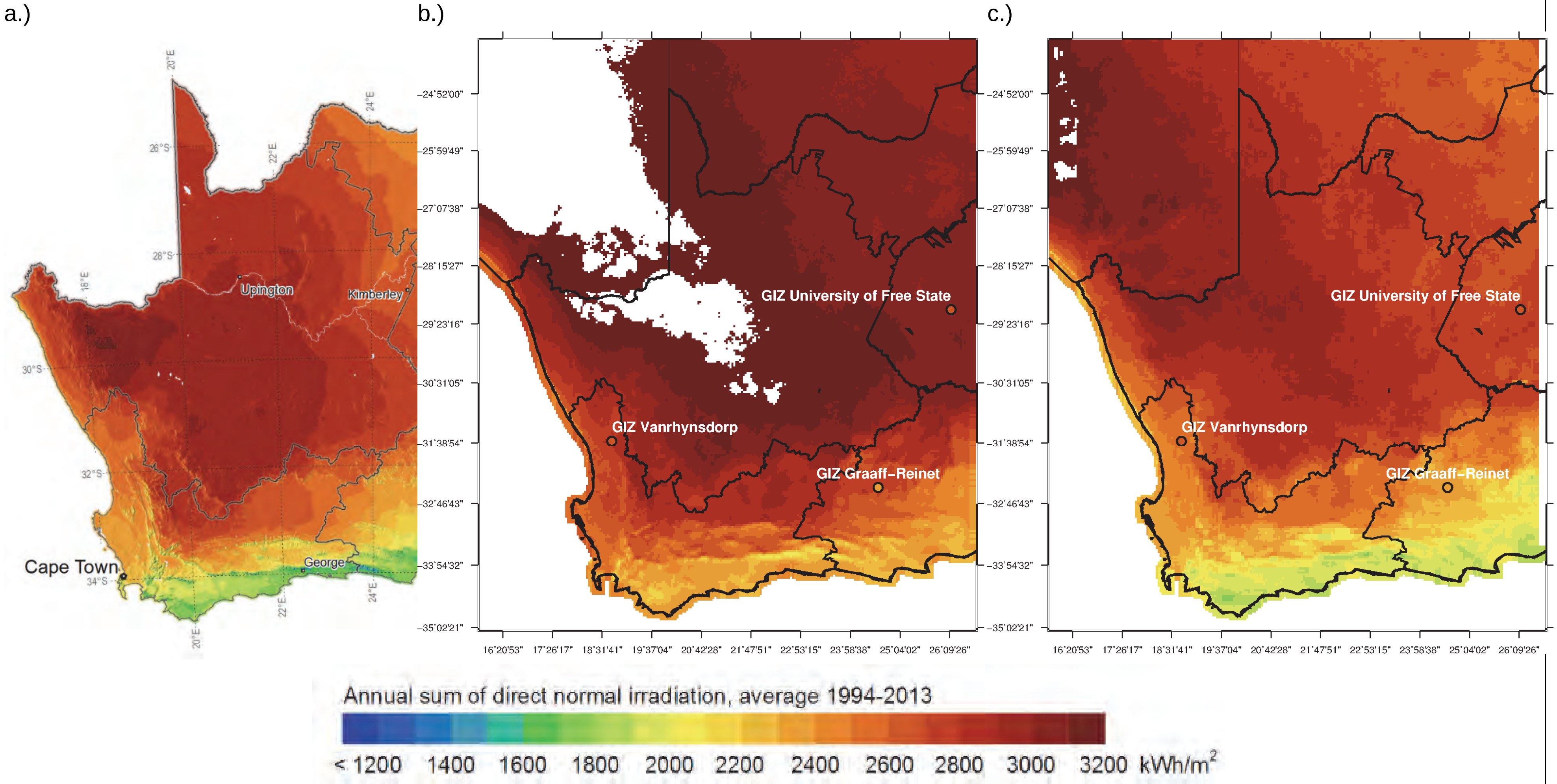


Figure 5-1: Comparison of total annual DNI as calculated by a.) Solar GIS (avg. 1994-2013), b.) WRF with data assimilation (2014) and c.) WRF with DNI correction (2014).

Corrections to WRF DNI

Cloud dynamics is a major challenge in meso scale forecasting, as it is driven by micro scale processes which are parameterised in the model instead of being fully solved. Yet the impact is at a meso scale extent (e.g. cloud/no cloud). One way to account for the WRF over prediction is to apply corrections in post processing using satellite derived cloud cover (Figure 5-2). In this approach, we linked observed surface DNI to satellite cloud cover and define a relationship between cloud cover and DNI. This relationship was then normalised where DNI for no cloud = 1 and night = 0, and the DNI in between is a fraction of the maximum (i.e. clear sky conditions) (Figure 5-3). A new map of this normalised DNI was then made based on the satellite cloud image, and was used to correct the WRF data. We then applied an observed cloud mask to the WRF cloud mask and areas where WRF missed cloud were adjusted using the normalised DNI/Cloud cover table to correct the WRF DNI (Figure 5-1 b and c).

We made use of the EUMETSAT cloud analysis image (CLAI) for the satellite cloud cover data. This product provides information on the type of cloud (low fog stratus, mid nimbo stratus, mid alto, high cumulo and high cirrus) (Figure 5-3). The surface observed DNI measurements were from three SAURAN (South African Universities Radiometric Network) sites at the University of the Free State, Vanrhynsdorp and Graaff-Reinet.

This process corrected the initial overestimation in the WRF DNI and provided a more reliable spatial distribution of DNI (Figure 5-1 b and c) which could be used for resource mapping of concentrated solar power plants.

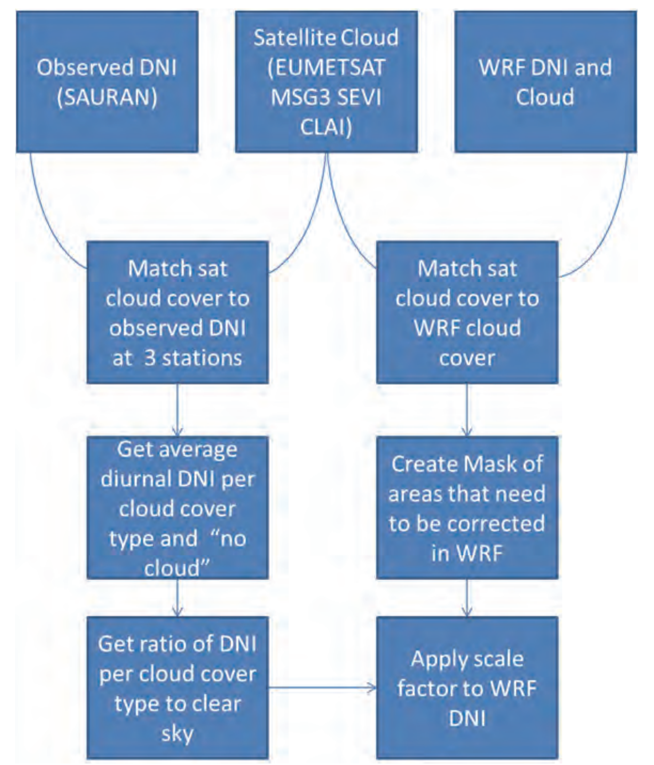


Figure 5-2: Flow diagram for correcting WRF DNI using Satellite cloud cover and observed DNI.

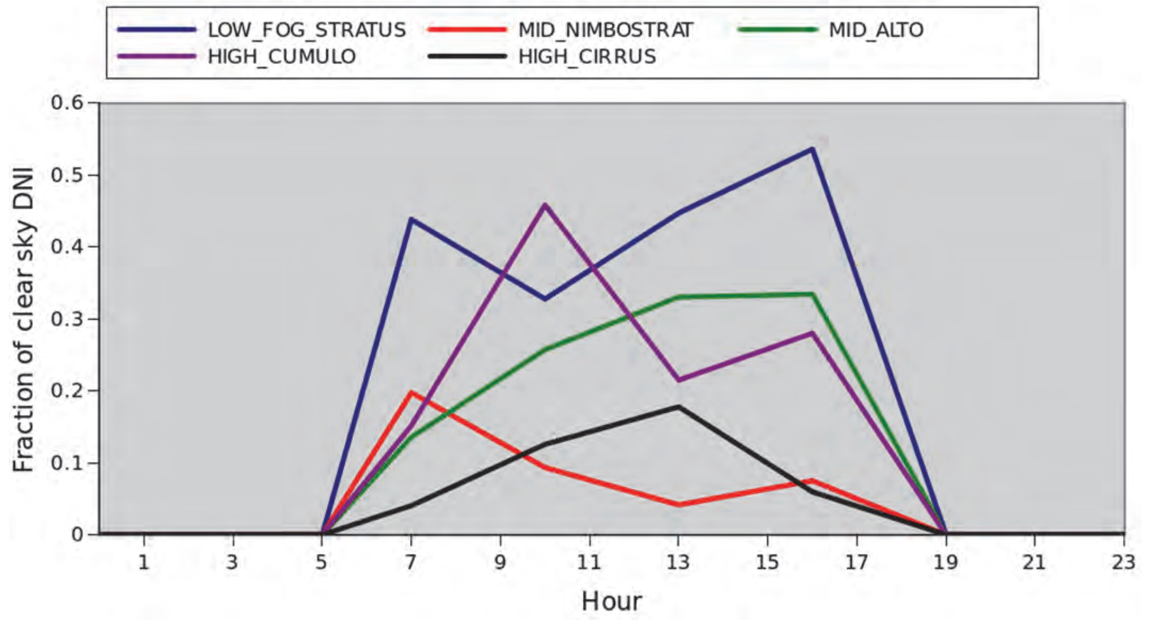


Figure 5-3: Fraction of clear sky DNI per cloud cover type as determined from linking the satellite cloud cover to observed DNI data at University of the Free State, Vanrhynsdorp and Graaff-Reinet.

5.2 Modelled Scenario Results

The scenarios (Table 5-1) were at 4 km spatial resolution and resulted in generated numerical outputs for greater than 48 000 data points per scenario and are represented visually as maps appended to this document. The maps produced include the following parameters:

1. Power production
2. Water consumption
3. Freshwater Demand Avoided (FWA)
4. Power/Water efficiency function (PWE)
5. Internal Rate of Return (IRR)
6. Power/Water Efficiency Cost function (PWC)

The *Power/Water Efficiency* factor was derived as follows:

$$PWE = Pn/Pmax \times FWAn/FWAmax \qquad \textbf{[2]}$$

The *Power/Water Efficiency Cost* factor was derived as describe by:

$$PWC = Pn/Pmax \times FWAn/FWAmax \times IRRn/IRRmax \qquad \textbf{[3]}$$

where:

$\boldsymbol{Pn}$ = power output in the modelled grid cell

$\boldsymbol{Pmax}$ = maximum power within all scenarios – in deriving this maximum, the scenarios was separated in terms of those with storage and those without storage.

$\boldsymbol{FWAn}$ = amount of fresh water avoided in the modelled grid cell

$FWAmax$ = maximum amount of Freshwater Demand Avoided within all scenarios – in deriving this maximum, the scenarios was separated in terms of those with storage and those without storage.

$IRRn$ = internal rate of return in the modelled grid cell

$IRRmax$ = maximum internal rate of return within all scenarios – in deriving this maximum, the scenarios was separated in terms of those with storage and those without storage.

The Power/Water Efficiency Cost function is designed to reflect the cumulative effect of power produced, Freshwater Demand Avoided and internal rate of return.

The maps developed show each of the 6 above mentioned parameters for each scenario. Due to the large number of maps they have been included as an appendix to this report. Some samples of the maps developed are shown below. The maps and discussion below relate to the scenarios in which 6 hours storage was included.

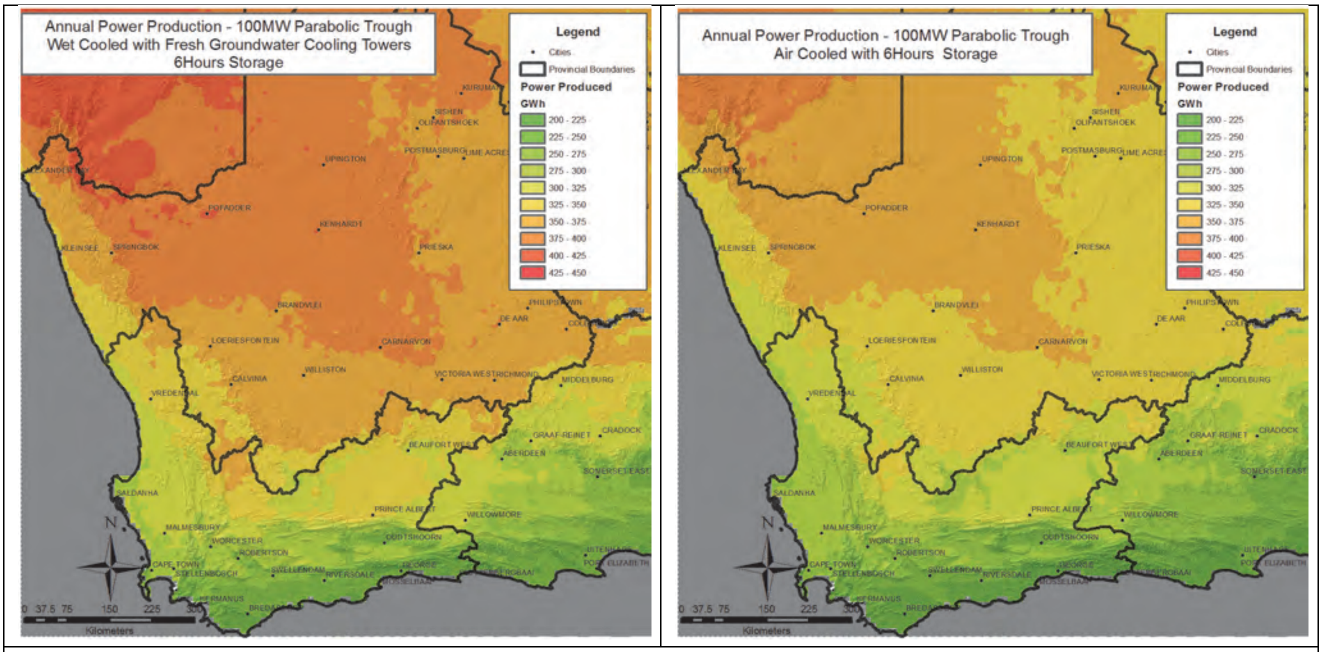


Figure 5-4: Annual Power Production for Scenarios 8 and 11

Figure 5-4 shows the difference in power production between Scenario 8 (Wet cooled using fresh ground water and 6 hours storage) and Scenario 11 (Air cooled with 6 hours storage). It can be seen that scenario 8 has a higher annual power production. This is due to the decrease of efficiency with the air cooled plant during periods of high ambient temperatures.

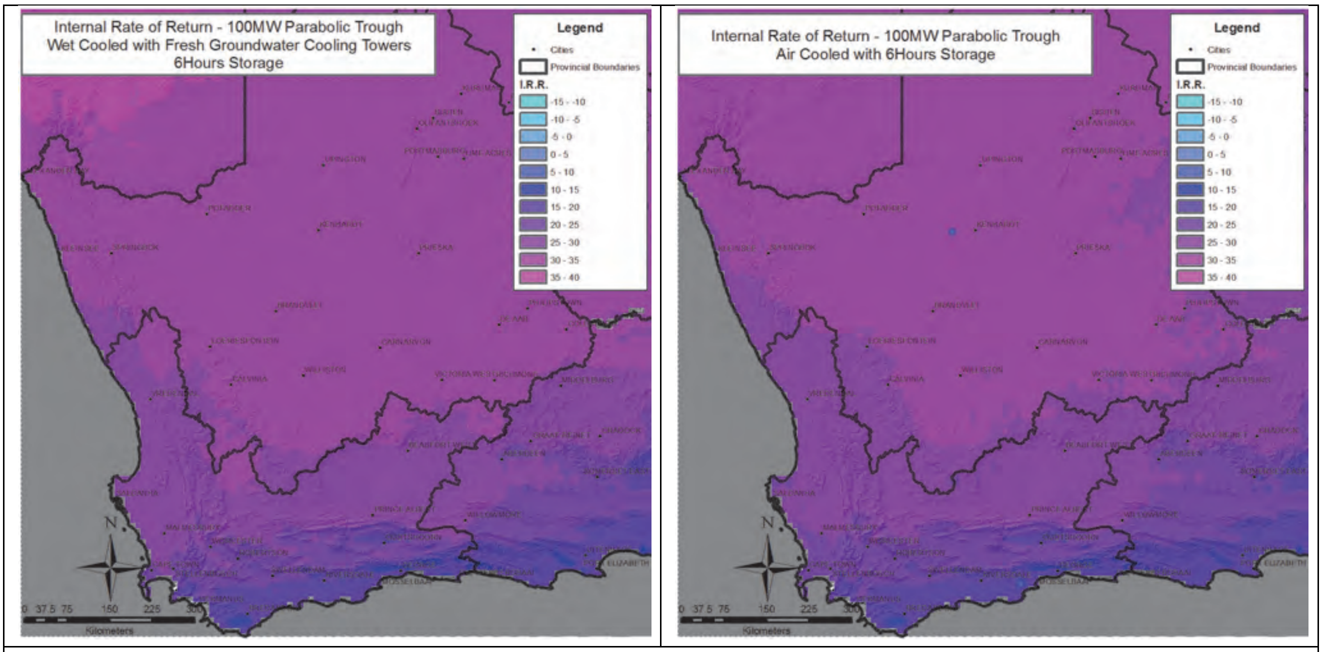


Figure 5-5: Internal Rate of Return for Scenarios 8 and 11

Figure 5-5 shows how the higher annual power production of Scenario 8 versus Scenario 11 (shown in Figure 5-4) translates into an improved IRR. Suitable sites for Scenario 8 would have to, however, be located close to fresh water sources, thus excluding many high DNI areas. Figure 5-6 shows the Power/Water Efficiency Cost Factor for Scenarios 8 and 11. The amount of fresh water avoided in the fresh water wet cooled scenarios is zero and as such the Power/Water Efficiency Cost Factor is zero for Scenario 8.

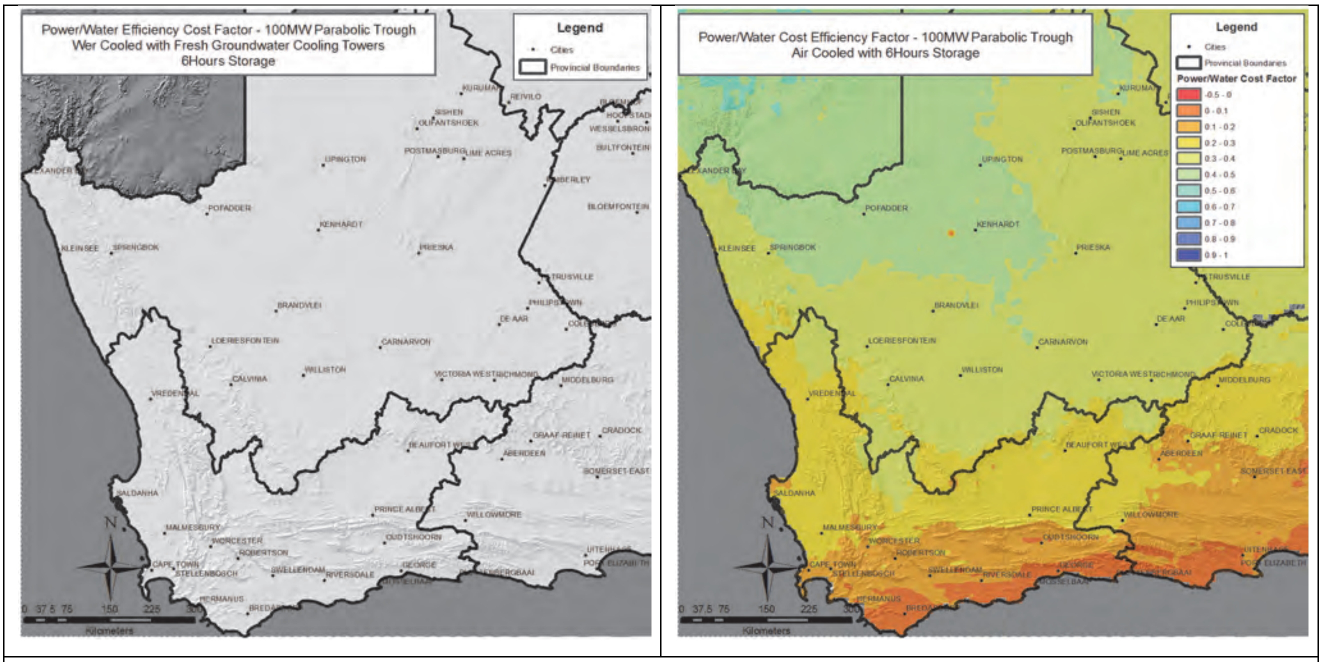


Figure 5-6: Power/Water Efficiency Cost Factor for Scenarios 8 and 11

Due to scenario 8 being unrealistic in most parts of South Africa due to water scarcity it is not included in the comparisons shown in Figure 5-7 and Figure 5-8.

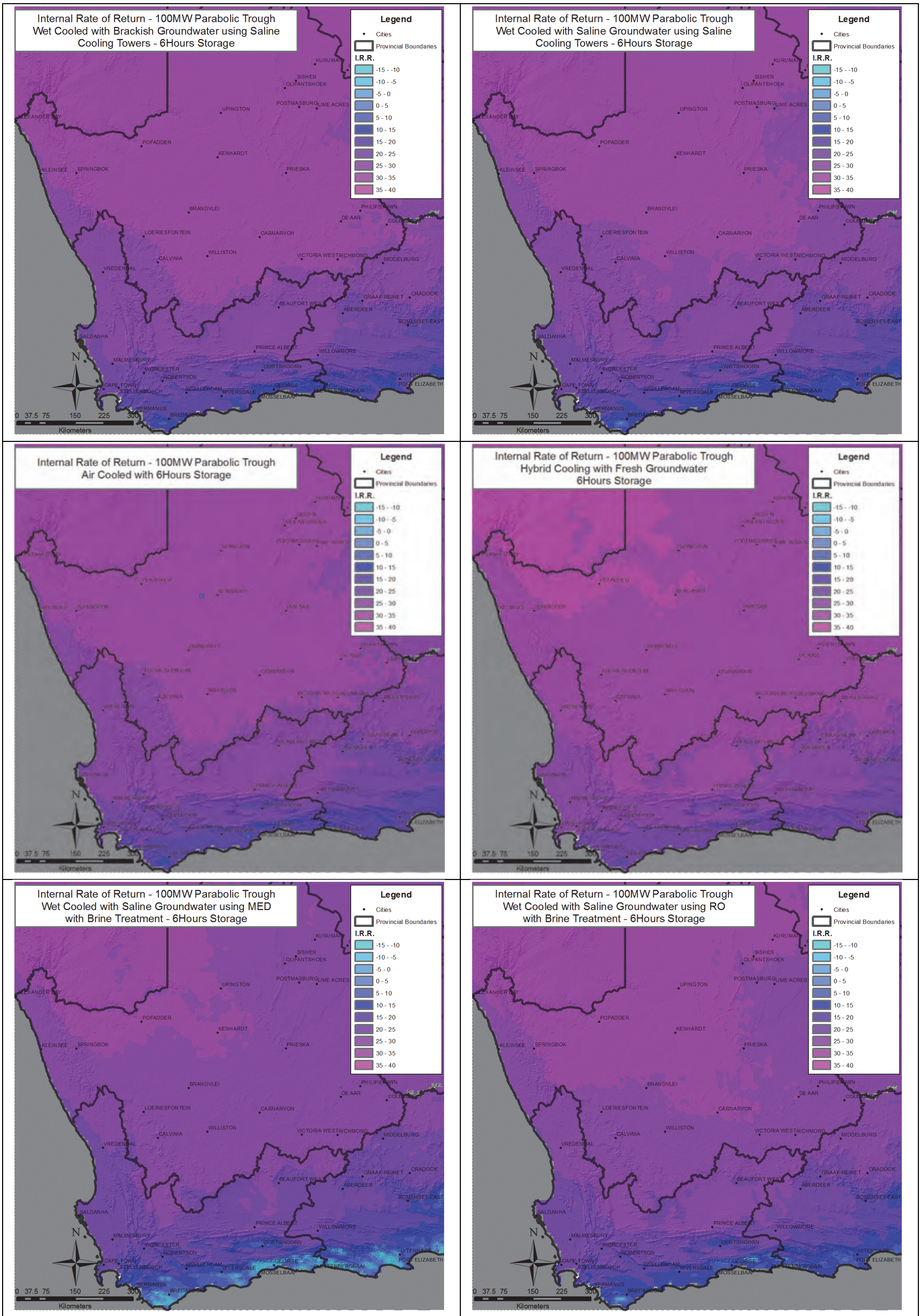


Figure 5-7: Internal Rate of Return for scenarios 9, 10, 11, 12,13 and 14

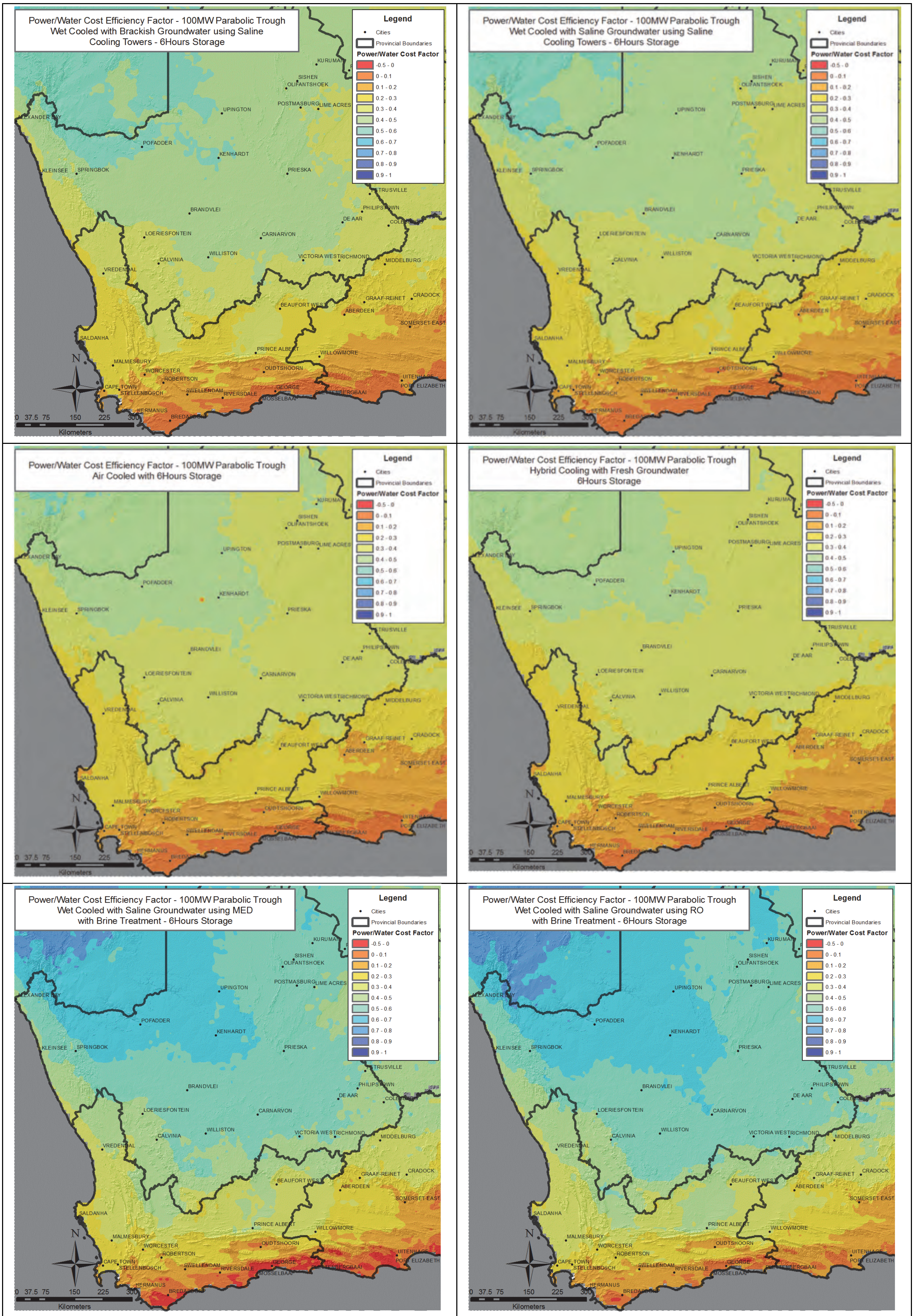


Figure 5-8: Power/Water Efficiency Cost Factor for scenarios 9, 10, 11, 12,13 and 14

Figure 5-7 shows that the hybrid cooled using freshwater with 6 hours storage scenario (scenario 12) has the highest IRR of the six scenarios shown. However, the hybrid cooling system still requires that fresh water is available.

When analysing the Power/Water Efficiency Cost Factor for scenarios 9-14 (Figure 5-8) it can be seen that MED (scenario 13) and RO (scenario 14) scenarios are the most attractive when considering the power produced, IRR and Freshwater Demand Avoided together.

Although scenarios 9, 10 and 11, like scenarios 13 and 14, do not utilise fresh water they do not exhibit Power/Water Efficiency Cost Factors as high as scenarios 13 and 14. This is due to the fact Scenarios 13 and 14 include saline water desalination and subsequent sale of 1 600 kℓ/day of freshwater to a town. This 1 600 kℓ/day is thus added to the Freshwater Demand Avoided in these scenarios.

As the maps contain a large amount of embedded information, the IRR (a key determinant in project feasibility) was extracted for Upington in the Northern Cape and is shown in Table 5-1 to highlight some of the key findings and provide some context to the maps in the Appendix.

Table 5-1: Scenarios modelled showing IRR for Upington

Scenario	Cooling method	Cooling water supply	Storage	Desalination	IRR
BASE CASE	Wet cooled	Fresh groundwater	0 hrs		22.52
2	Wet cooled	Brackish groundwater	0 hrs		21.16
3	Wet cooled	Saline water	0 hrs		20.12
4	Air cooled		0 hrs		20.98
5	Hybrid cooled	Fresh groundwater	0 hrs		25.64
6	Wet cooled	Saline water	0 hrs	MED	16.86
7	Wet cooled	Saline water	0 hrs	RO	19.49
8	Wet cooled	Fresh groundwater	6 hrs		33.73
9	Wet cooled	Brackish groundwater	6 hrs		32.54
10	Wet cooled	Saline water	6 hrs		31.91
11	Air cooled		6 hrs		31.86
12	Hybrid cooled	Fresh groundwater	6 hrs		34.66
13	Wet cooled	Saline water	6 hrs	MED	29.97
14	Wet cooled	Saline water	6 hrs	RO	31.29

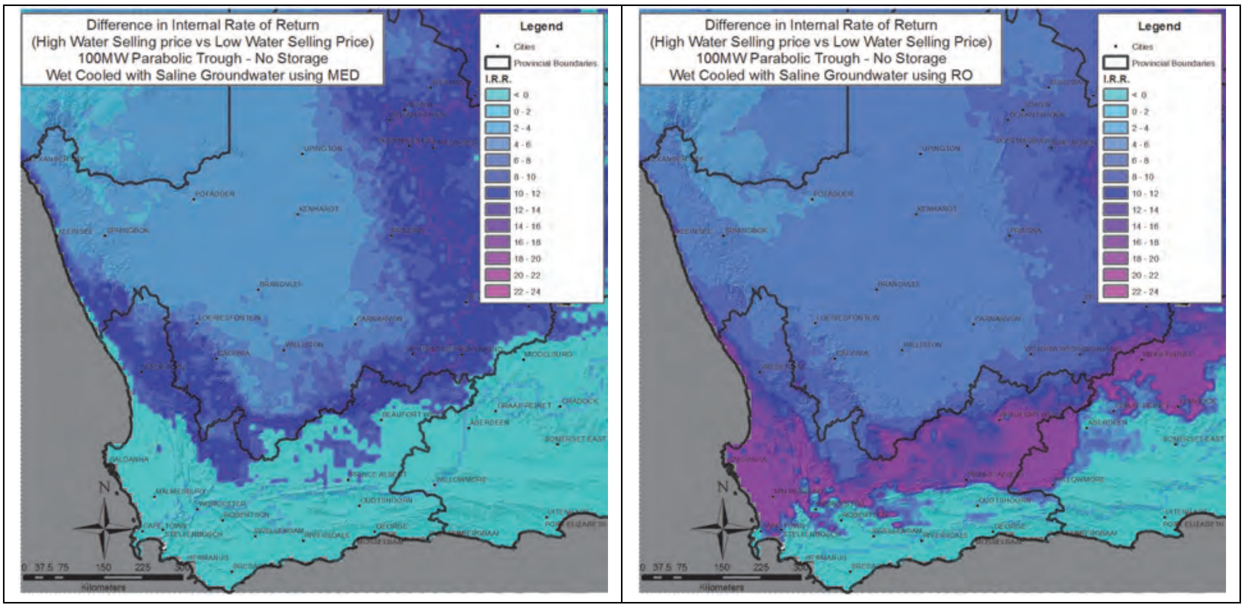
With the REIPPPP two-tier tariff regime for Round 4 CSP projects all of the scenarios considered offer reasonable returns on investment. As to be expected, the scenarios involving thermal storage offer better IRRs, but come at a significant increase in capital cost. The results obtained reveal that it would be economically feasible to operate CSP plants in South Africa under the two-tier tariff for all the scenarios that were modelled. Storage allows the plant to be optimised for part load operation which could see better IRRs achieved than those achieved in the non-optimised scenario runs.

The Hybrid wet/dry cooling scenario employing between 0 and 30% fresh water cooling during different hours of the day is the most attractive option in terms of IRR. The sites would have to, however, be located close to fresh water sources, thus excluding many high DNI areas.

For Upington, the results indicate that wet cooling using brackish or saline water with saline cooling towers is still an attractive option with slight penalties for the additional cost of the cooling towers and brine disposal. These are nevertheless viable options as there is a significant amount of freshwater demand that is avoided and the IRR achieved is competitive with that of an air cooled plant.

The results also indicate that CSP plants with storage capacity coupled to small MED or RO plants designed to produce the water requirements to supply a medium to large sized town offer between 30% and 35% IRR in areas of high DNI and in their own right are economically competitive with air cooled plants. Desalination costs are greatly improved by co-locating the desalination plant at a CSP facility in order to exploit the CSP infrastructure. RO plants appear to have a marginally better return than MED plants, but MED plants are still very competitive. With increasing electricity prices and potential insecurity of supply, RO based water production could face some challenges in future. The other important benefit of CSP coupled to MED or RO plants is derived from the amount of Freshwater Demand Avoided in the cooling as well as fresh water being produced as a saleable product. There is also an avoided burden on the local authority currently supplying the town's water. As mentioned, in terms of IRR, MED and RO plants coupled to a CSP plant can compete with air cooled CSP plants. However, in terms of the cumulative effects of power produced, Freshwater Demand Avoided and IRR, the scenarios involving the MED and RO plants (scenarios 6, 7, 13 and 14) are the most attractive.

The effects of the water selling prices modelled (high at R22.50/kℓ and low at R7.55/kℓ) is shown in Figure 5-9.



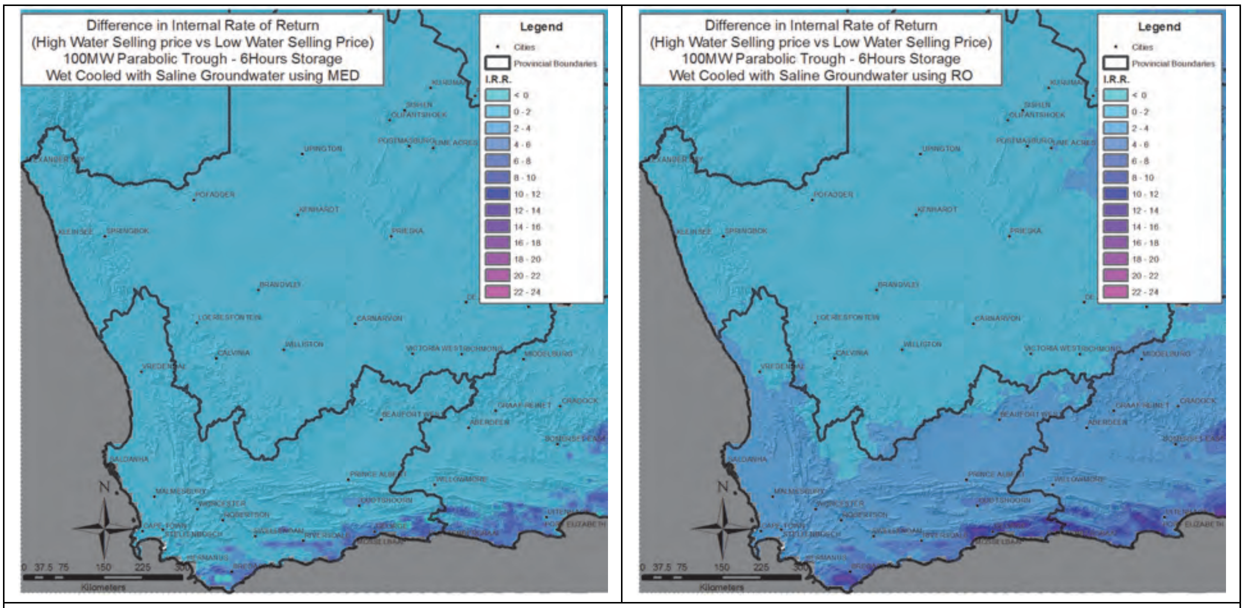


Figure 5-9: Difference in IRR achieved – high water selling price vs low water selling price for MED and RO plant scenarios

It was decided that the high selling price of R22.50/kℓ would be used in the analysis as this is deemed to be a realistic selling price due to the fact that some towns in the Northern Cape currently use RO plants for potable water production.

All the scenarios modelled included costs for brine treatment to an evaporation pond. For the MED and RO scenarios the cost of the brine disposal is shown to have a significant effect on the financial viability of the plant as is the well-field establishment and operation cost, however the results indicate that projects are still economically competitive under all the scenarios using an evaporation landfill as method of brine handling. There are other brine treatment technologies such as salt freeze with waste heat absorption chillers (a Eutectic Freeze Crystallization process as reported by Lewis et al. (2010), SAL-PROC and other commercial processes to recover salts and minerals that were not considered in this study.

6 CONCLUSIONS

The study indicated that in terms of IRR the hybrid cooling scenarios are the most attractive, followed by the freshwater wet-cooled scenarios. Freshwater wet cooled plants are however limited to areas that have a sufficiently large fresh water supply and thus, especially in water scarce regions, dry-cooling or hybrid-cooling are more desirable options. Hybrid cooled plants still require a fairly large fresh water supply that in many high DNI regions is not available

Wet-cooling technology using brackish or saline water are also economically competitive alternatives to freshwater evaporative cooling, even with the increased costs due to more expensive cooling towers as well as brine disposal. These scenarios showed IRRs above that of the saline water wet-cooled with MED or RO scenarios, however, these scenarios do not produce freshwater and thus do not show as high Power/Water Efficiency Cost Factors as the MED and RO scenarios that provide water to a town.

It was found that coupling a CSP plant to an RO or MED plant to supply a medium to large town’s water requirement gave IRR’s that are competitive with that of an air cooled CSP plant. When considering the amount of Freshwater Demand Avoided, together with power production and IRR, then the coupling of an RO or MED plant to a CSP plant is the most attractive of all the scenarios modelled as additional benefit is derived from the sale of water. Desalination using an MED or RO plant when coupled to CSP plants is more cost effective than green-field deployment of desalination technologies as cost reductions arise from the use of existing CSP infrastructure. The cost of the brine disposal is shown to have a significant effect on the financial viability of the plant as is the well-field establishment and operation cost.

It is important to note that the selling price of water has a large influence on the IRR for the MED and RO scenarios. If the selling price of water is increased above R22.50/ kℓ the MED and RO scenarios will become more attractive.

7 RECOMMENDATIONS

It is proposed to further investigate CSP coupled desalination and brine treatment in order to exploit existing CSP infrastructure to reduce costs relative to green-field implementations. It is recommended that the future research include a techno-economic assessment to determine sustainability, cost effectiveness and practicality of these opportunities.

One of the most critical decisions made by a water authority in a desalination design is the method of brine disposal. This can cost up to 15% of the plant's capital cost, and have major ongoing operational and environmental management requirements. For these reasons, brine disposal should be a key consideration in the overall design, and should be investigated as early as possible in the design process. Further investigation into brine treatment options to reduce these costs is recommended.

Lewis (2010) indicated that capital equipment cost for eutectic freeze crystallisation technology for treating 100 m^3/day of brine was between R6.6 million and R7.9 million. In comparison, the capital costs for treating the same volume of brine using EC were between R5.2 million and R4.9 million. As green-field applications, EFC may struggle to gain commercial attractiveness as there are cheaper competing alternatives. However, coupled with CSP, the capital costs of the technology add very little to the overall project cost and could present an economically viable alternative. The potential for salt to be sold as a by-product should also be investigated further.

The study can be expanded to assess the feasibility of pumping seawater inland for desalination at a CSP desalination plant. The costs of this could be somewhat offset against the high costs used in the model for well-field establishment and operation.

CSP plants combined with desalination are shown to be economically competitive. A plant of this nature would be in line with the policy laid out in the National Water Resources Strategy. Unlike desalination plants powered by PV or wind, A CSP desalination plant can provide both electricity and freshwater. Further allocation to CSP in the REIPPP would aide in the implementation of such plants.

8 LIST OF REFERENCES

Carter, N. & Campbell, R., 2009. *Water Issues of Concentrating Solar Power (CSP) Electricity in the U.S Southwest,* s.l.: Congressional Research Service.

Department of Minerals and Energy, 2001. *A review of the South African salt industry in 2001,* Pretoria: Department Of Minerals And Energy.

Ernest and Young, 2011. *Financing Renewable Energy in the European Energy Market: Final Report,* Utrecht: Ecofys.

ETSAP and IRENA, 2013. *Concentrating Solar Power – Technology Brief,* s.l.: The International Renewable Energy Agency.

Fichtner, 2010. *Technology Assessment of CSP Technologies for a Site Specific Project in South Africa: Final Report,* Washington, D.C: The World Bank and ESMAP.

Hinkley, J. et al., 2011. *Concentration solar power – drivers and opportunities for cost-competitive electricity,* s.l.: CSIRO.

IRENA, 2013. *Renewable Power Generation Costs in 2012: An Overview,* s.l.: The International Renewable Energy Agency.

Kolb, G. J., Ho, C. K., Mancini, T. R. & Gary, J. A., 2011. *Power Tower Technology Roadmap and Cost Reduction Plan,* Alburqurque, NM: Sandia National Laboratories.

Lara-Fanego, V. et al., 2011. Evaluation of the WRF model solar irradiance forecasts in Andalusia (southern Spain). *Solar Energy.*

Lara-Fanego, V. et al., 2012. Evaluation of the WRF model solar irradiance forecasts in Andalusia (southern Spain). *Solar Energy,* pp. 2200-2217.

Law, E. W., Prasad, A. A., Kay, M. & Taylor, R. A., 2014. Direct normal irradiance forecasting and its application to concentrated solar thermal output forecasting – a review. *Solar Energy,* pp. 287-307.

Leinhard, J. H., Sharqawy, M. H. & Zubair, S. M., 2010. On Thermal Performance of Seawater Cooling Towers. *Journal Of Engineering for Gas Turbines and Power,* 133(4).

Lewis, A. et al., 2010. *Novel Technology for recovery of water and solid salts from hypersaline brines:Eutectic Freeze Crystallization,* Cape Town: Water Research Commission.

Maulbetsch, J. S. & Di Filippo, M. N., 2010. *Performance, cost and environmental effects of saltwater cooling towers,* Berkeley: California Energy Commission.

Mills, D., 2009. Advances in Solar Thermal Electricity Technology. *Solar Energy,* 76(1-3), pp. 19-31.

Murray, R. et al., 2012. *A groundwater Planning Toolkit for the Main Karoo Basin: Identifying and quantifying groundwater development options incorporating the concept of wellfield yields and aquifer firm yeilds,* Pretoria: Water Research Commission.

NASA's Earth Observatory, MODIS Atmospheric Science Team and NASA Goddard Space Flight Centre, 2014. *http://neo.sci.gsfc.nasa.gov/.* [Online] Available at: http://neo.sci.gsfc.nasa.gov/ [Accessed 2014].

Nkondo, M. N., Van Zyl, F. C., Keuris, H. & Schreiner, B., 2012. *National Water Resources Strategy 2,* s.l.: s.n.

Poullikkas, Kourtis & Hadjipaschalis, 2013. A comparitive overview of wet and dry cooling systems for Rankine cycle based CSP plants. *Trends in Heat and Mass Transfer,* Volume 13.

Ruiz-Arias, J. A., Gueymard, C. A., Dudhia, J. & Pozo-Vã zquez, D., 2012. Improvement of the weather research and forecasting (WRF) model for solar resource assessments and forecasts under clear skies. *World Renewable Energy Forum*.

Solar GIS, 2012. *http://solargis.info.* [Online] Available at: http://geosun.co.za/wp-content/uploads/2012/07/SolarGIS-DNI-South-Africa-Lesotho-Swaziland-PR-map.jpg [Accessed 2014].

The Southern African Universities Radiometric Network , 2014. *SAURAN.* [Online] Available at: http://www.sauran.net/ [Accessed 20 November 2014].

Trieb, F. et al., 2010. *Combined Solar Power and Desalination Plant: Techno-Economic Potential in Mediterranean Partner Countries,* Stuttgart: German Aerospace Center.

Trieb, F. & Moser, M., 2009. *WP1: Technology Review and Selection of CSP and Desalination Configurations adapted for Application in the Southern and Eastern Mediterranean Region,* s.l.: s.n.

Turchi, C., 2010. *Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model,* Boulder, CO: National Renewable Energy Laboratory (NREL).

Turchi, C., Mehos, M., Ho, C. K. & Kolb, G. J., 2010. *Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market,* Boulder, CO: National Renewable Energy Laboratory (NREL).

Turnpenny, A. W. et al., 2010. *Cooling Water Options for the New Generation of Nuclear Power Stations in the UK,* s.l.: Environment Agency.

Tyson, P. D. & Preston-Whyte, R. A., 2000. *The Weather and Climate of South Africa.* Cape Town: Oxford.

United States Environmental Protection Agency, 2004. *Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coalbed Methane Reservoirs,* s.l.: s.n.

US Department of Energy, 2009. *Concentrating Solar Power Commercial Application Study: Reducing Water consumption of Concentrating Solar Power Electricity Generation,* Washington, D.C.: United States Department of Energy.

Zamora, R. J. et al., 2003. Comparing MM5 radiative fluxes with observations gathered during the 1995 and 1999 Nashville southern oxidants studies. *J. Geophys. Res,* p. doi:10.1029/2002JD002122.

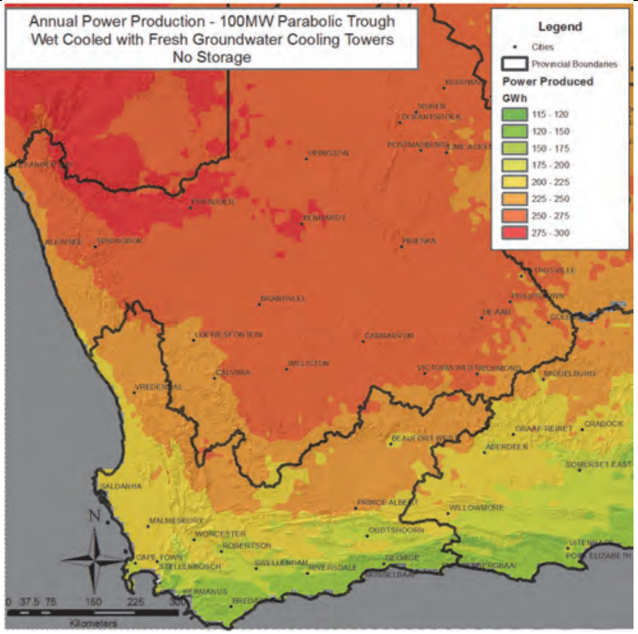
APPENDIX – RESULTS MAPS

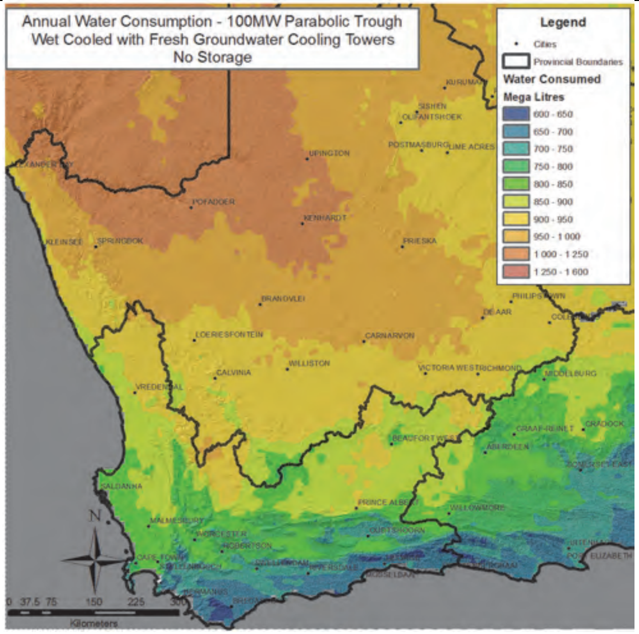
Table 8-1: Scenarios modelled

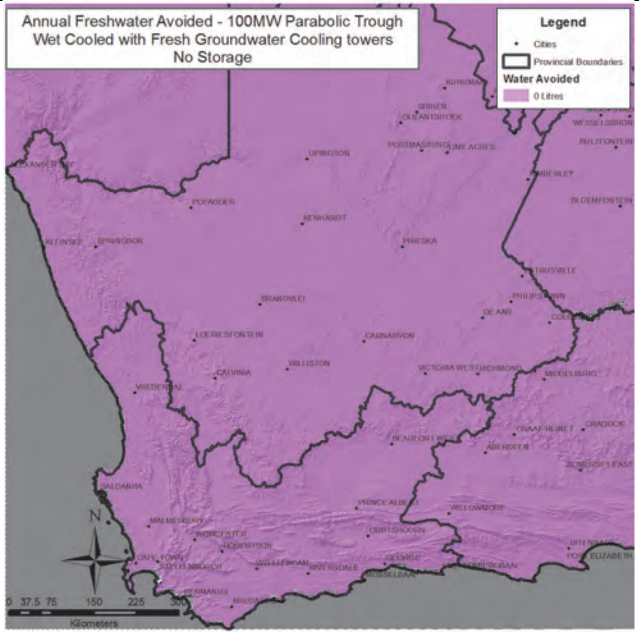
Scenario	CSP Technology	Cooling Method	Cooling Water Supply	Storage	Desalination
BASE CASE	Parabolic trough	Wet cooled	fresh groundwater	0 hrs	
2	Parabolic trough	Wet cooled	brackish groundwater	0 hrs	
3	Parabolic trough	Wet cooled	saline water	0 hrs	
4	Parabolic trough	Air cooled		0 hrs	
5	Parabolic trough	Hybrid cooled	fresh groundwater	0 hrs	
6	Parabolic trough	Wet cooled	saline water	0 hrs	MED
7	Parabolic trough	Wet cooled	saline water	0 hrs	RO
8	Parabolic trough	Wet cooled	fresh groundwater	6 hrs	
9	Parabolic trough	Wet cooled	brackish groundwater	6 hrs	
10	Parabolic trough	Wet cooled	saline water	6 hrs	
11	Parabolic trough	Air cooled		6 hrs	
12	Parabolic trough	Hybrid cooled	fresh groundwater	6 hrs	
13	Parabolic trough	Wet cooled	saline water	6 hrs	MED
14	Parabolic trough	Wet cooled	saline water	6 hrs	RO

Power Production	Water Consumption	Freshwater Demand Avoided

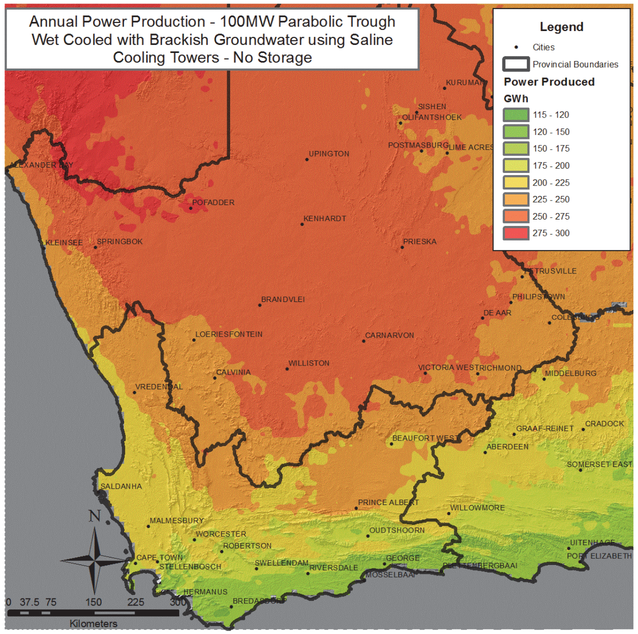
BASE CASE – Wet cooled – fresh water – 0h storage

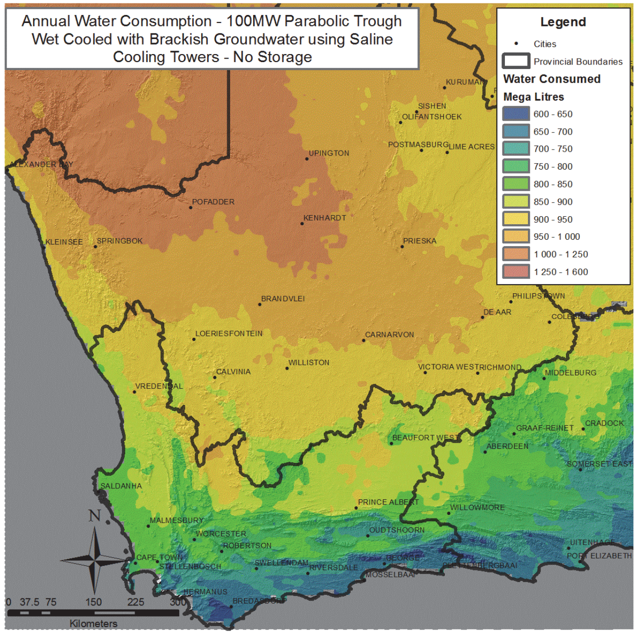


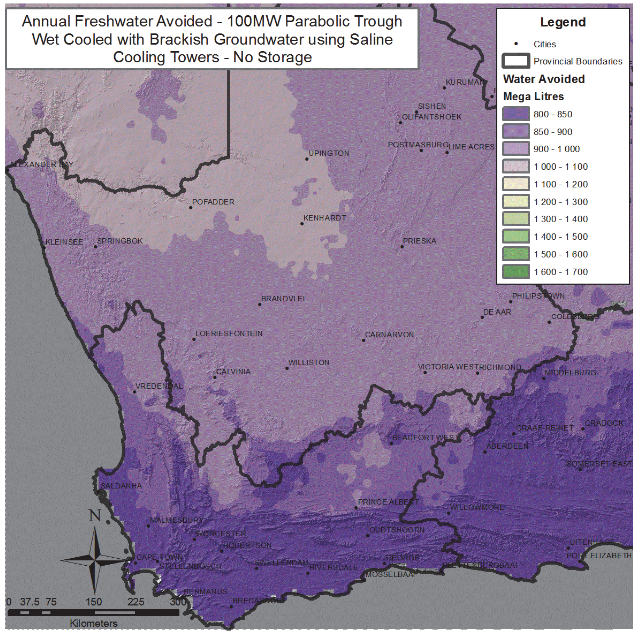




SCENARIO 2 – Wet cooled – brackish water – 0h storage

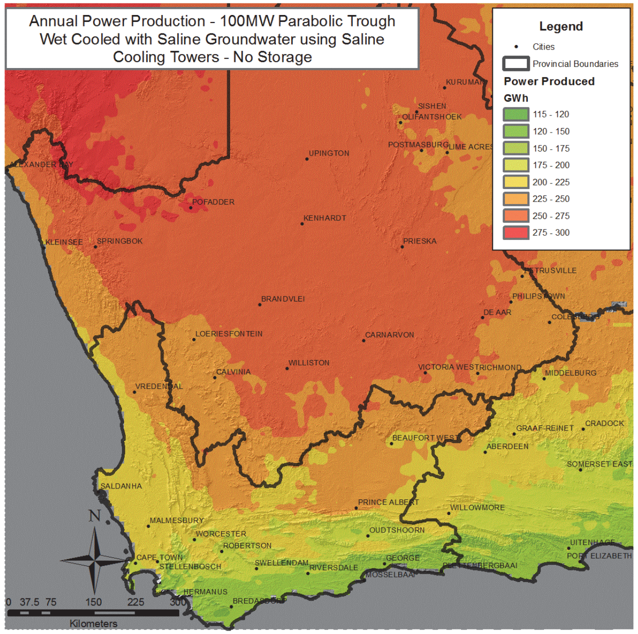


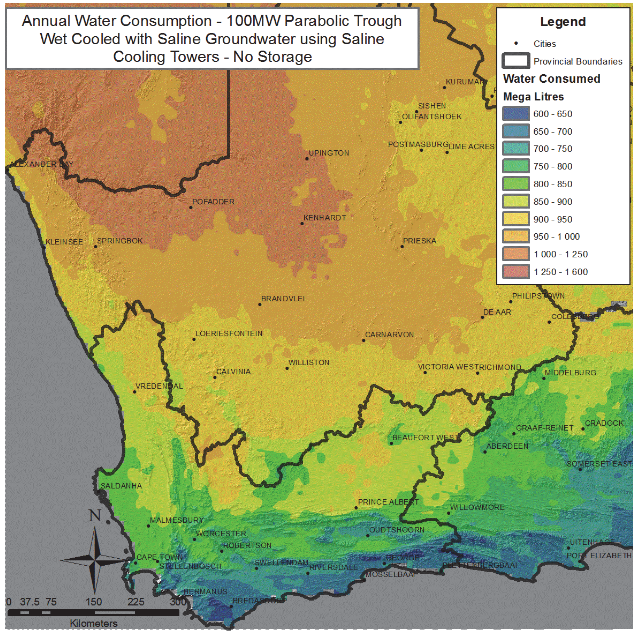


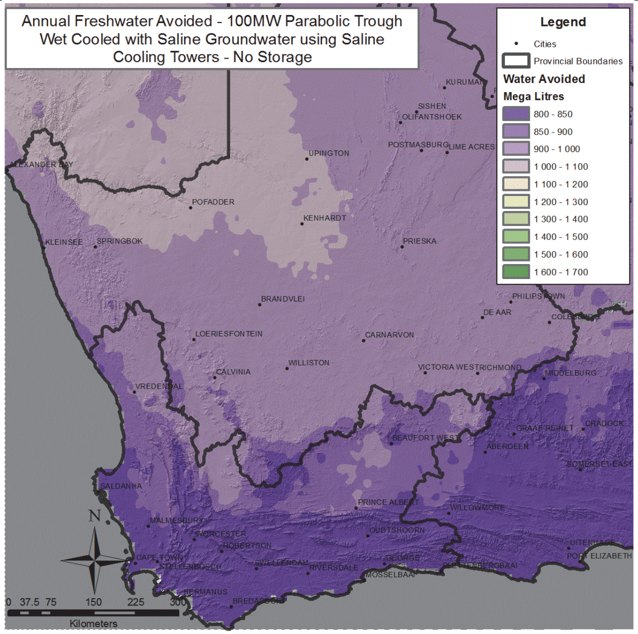


Power Production	Water Consumption	Freshwater Demand Avoided

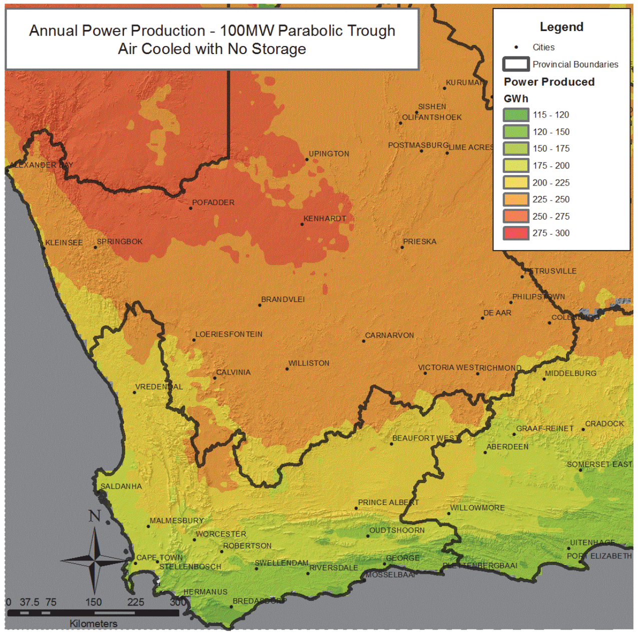
SCENARIO 3 – Wet cooled – saline water – 0h storage

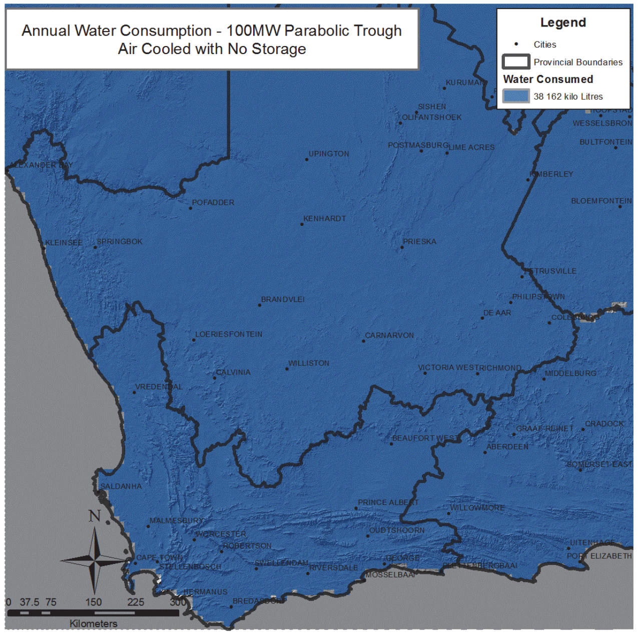


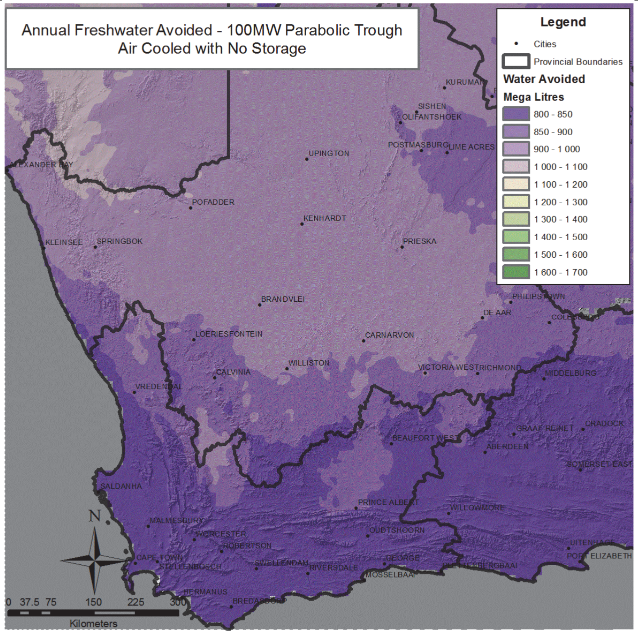




SCENARIO 4 – Air cooled – 0h storage

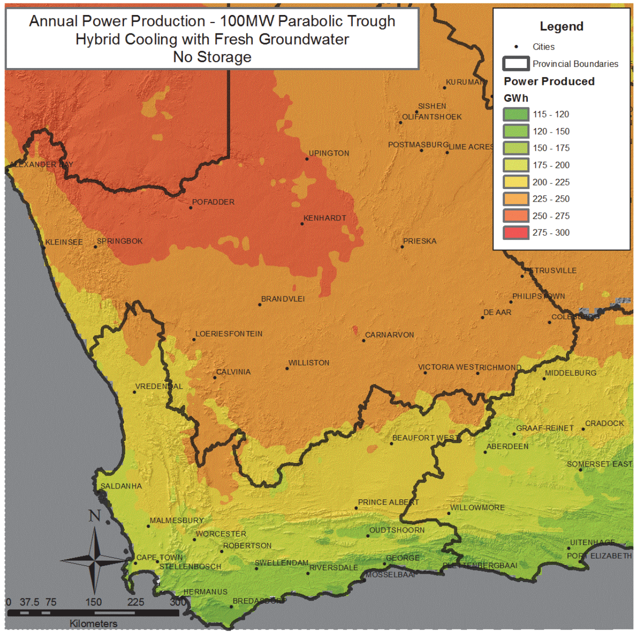


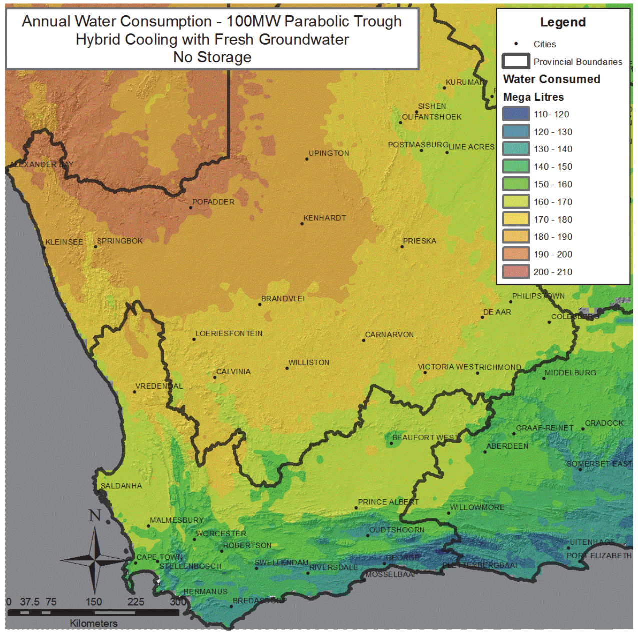


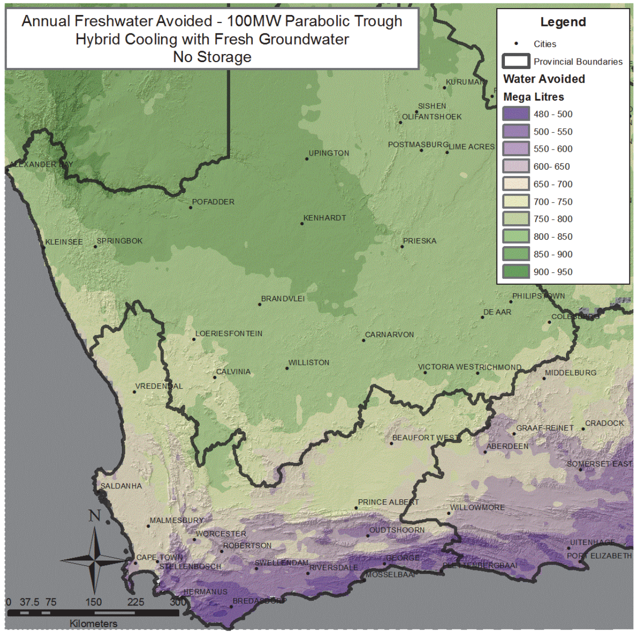


Power Production	Water Consumption	Freshwater Demand Avoided

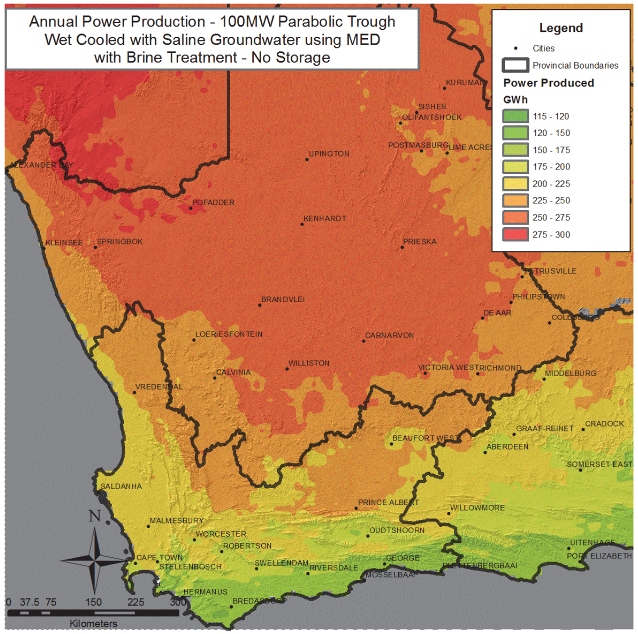
SCENARIO 5 – Hybrid cooling – fresh water/air – 0h storage

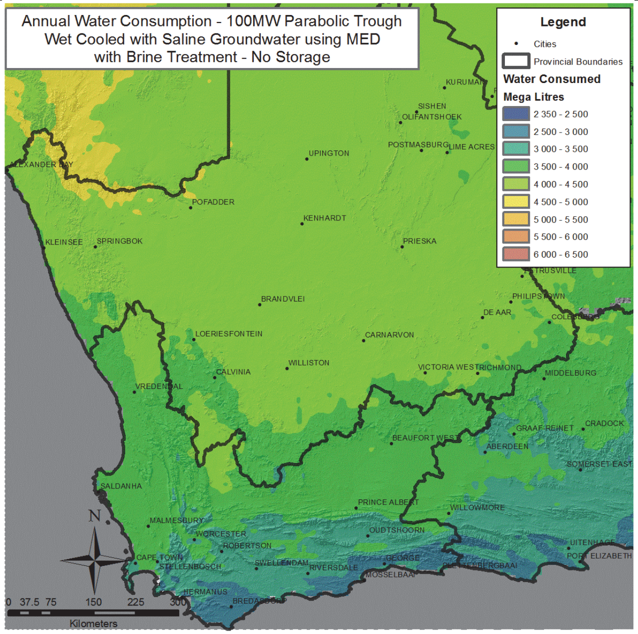


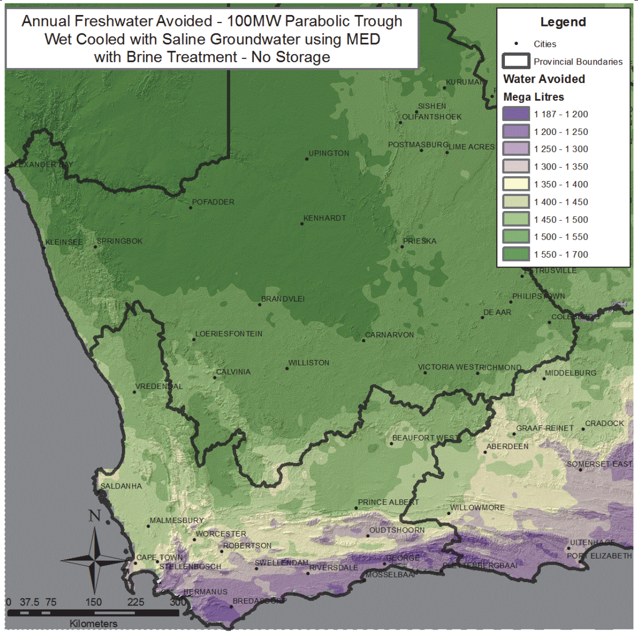




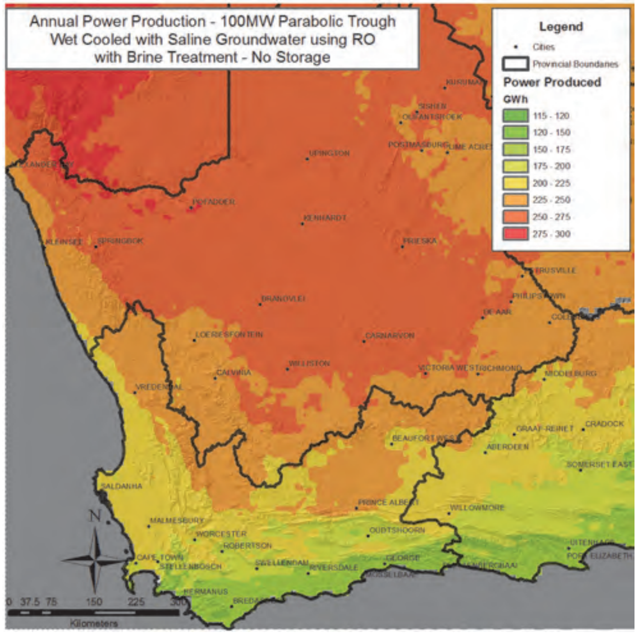
SCENARIO 6 – MED for town fresh water supply (wet cooled – saline water) – 0h storage

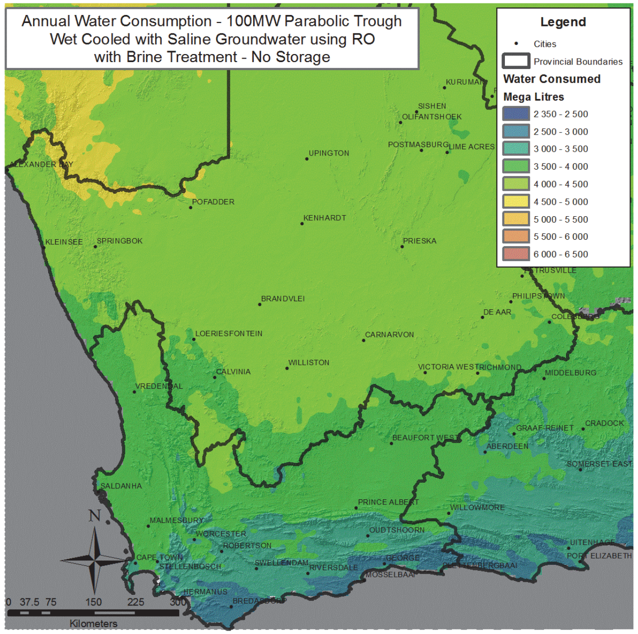


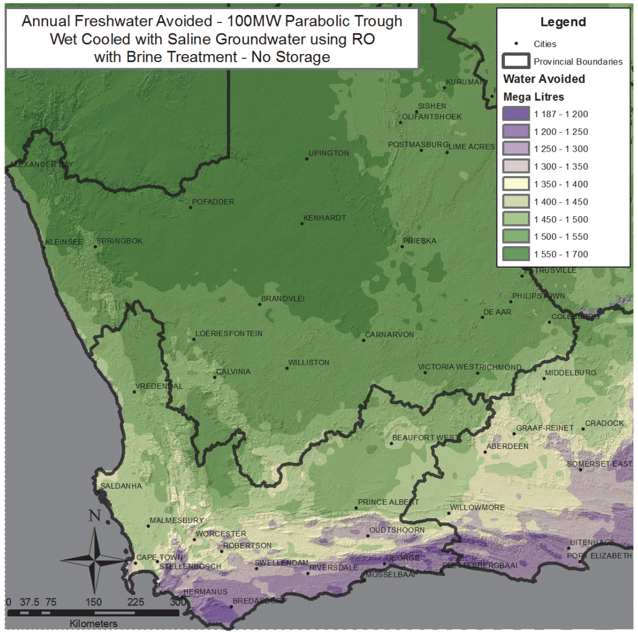




Power Production	Water Consumption	Freshwater Demand Avoided
SCENARIO 7 – RO for town fresh water supply (wet cooled – saline water) – 0h storage		

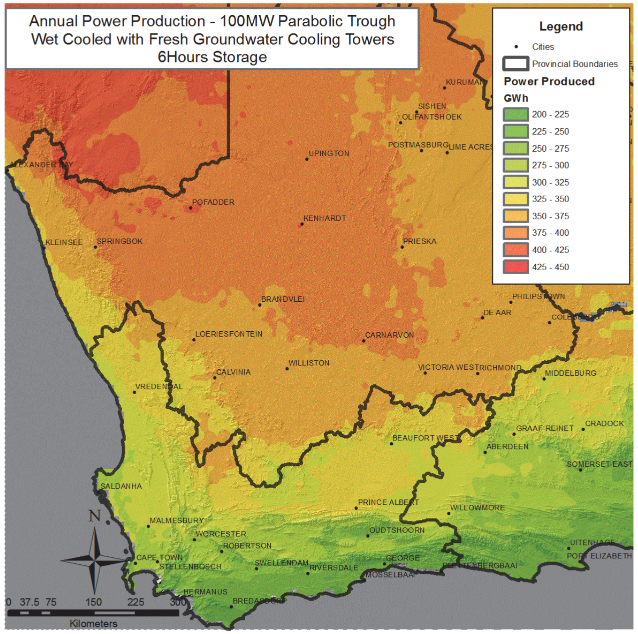


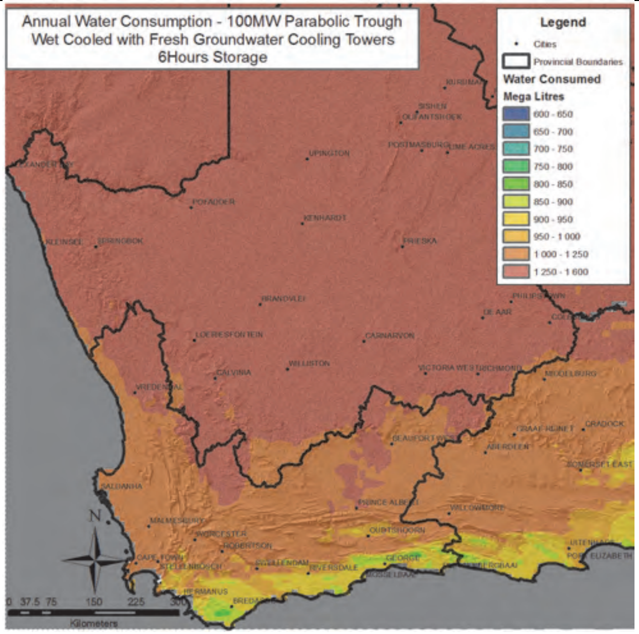


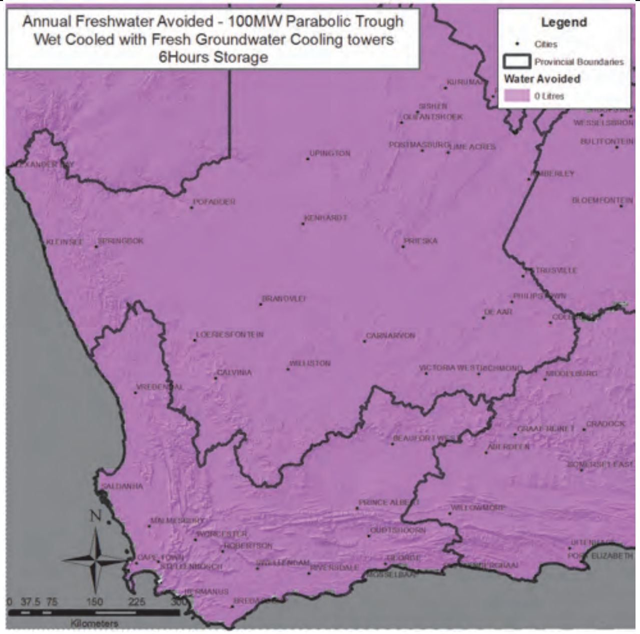


Power Production	Water Consumption	Freshwater Demand Avoided

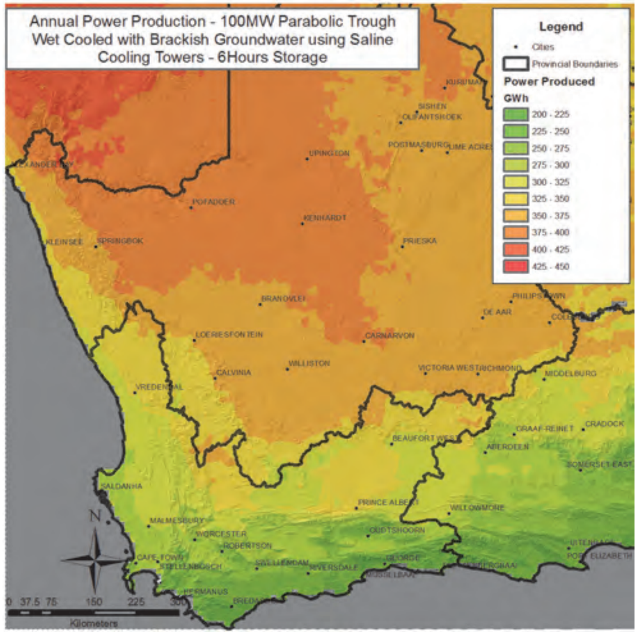
SCENARIO 8 – Wet cooled – fresh water – 6h storage

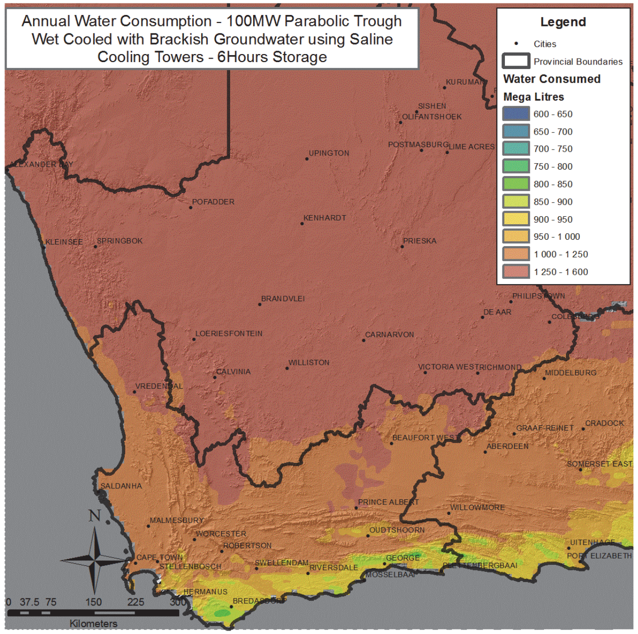


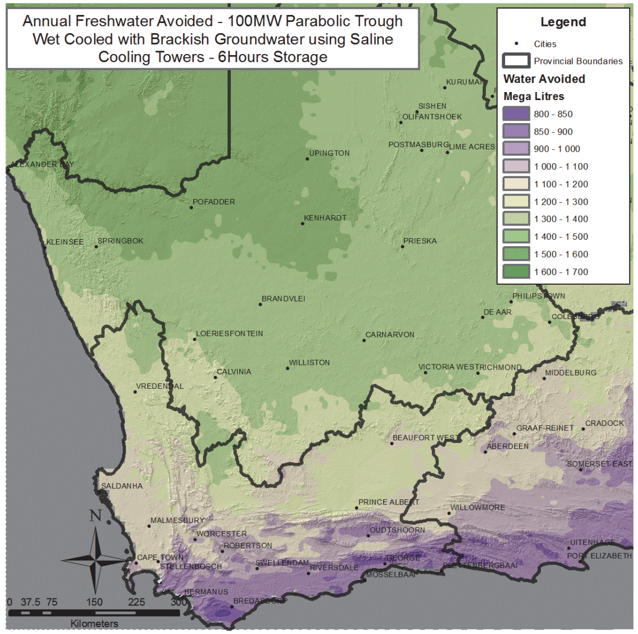




SCENARIO 9 – Wet cooled – brackish water – 6h storage

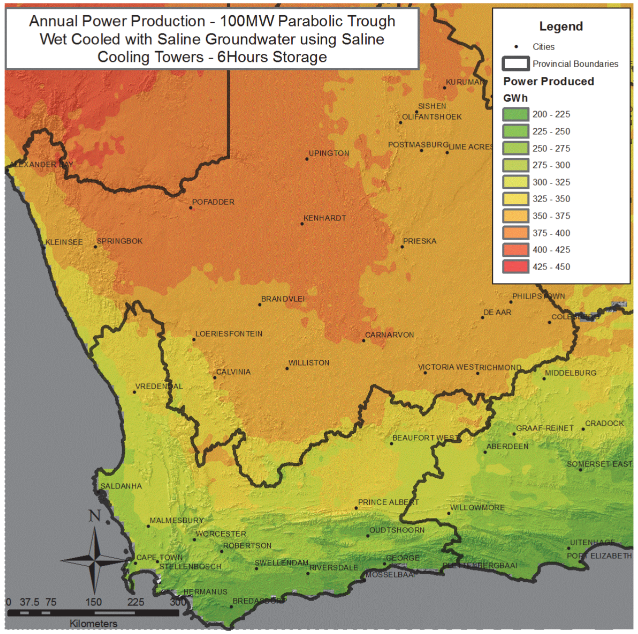


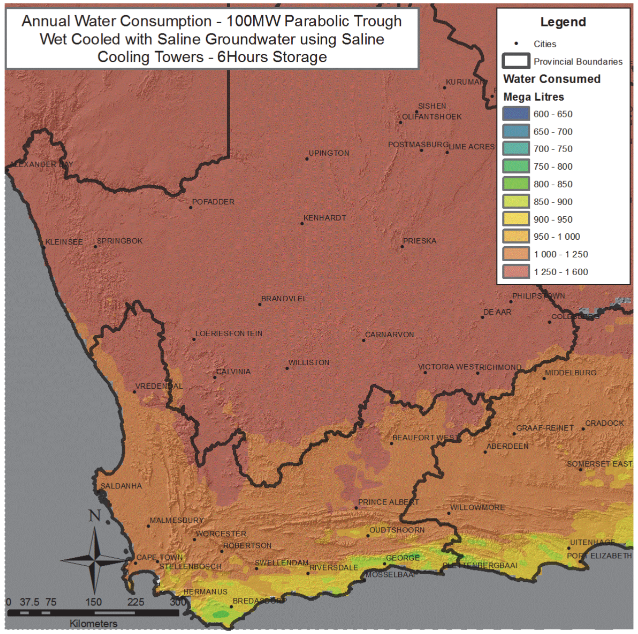


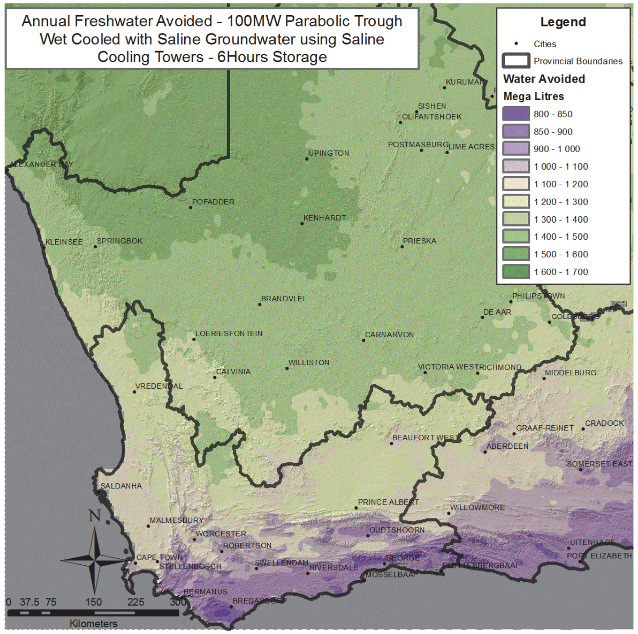


Power Production	Water Consumption	Freshwater Demand Avoided

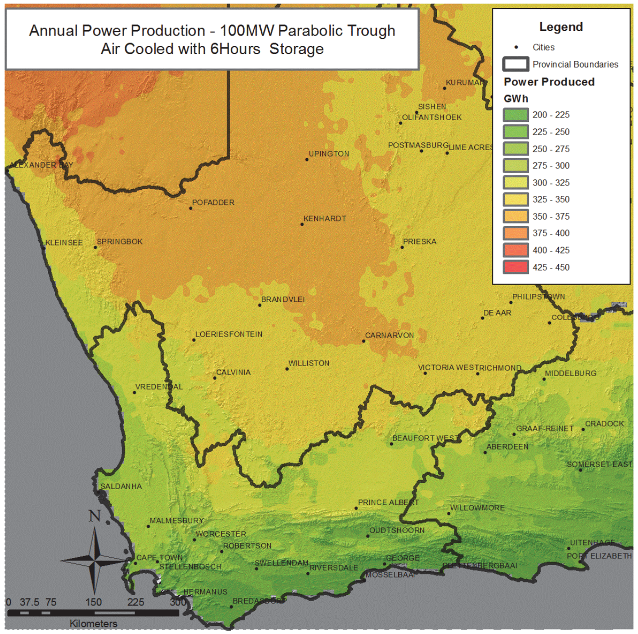
SCENARIO 10 – Wet cooled – saline water – 6h storage

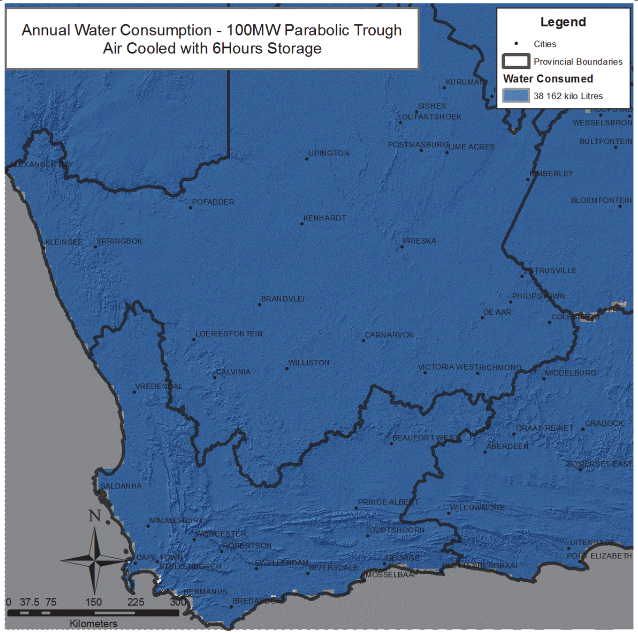


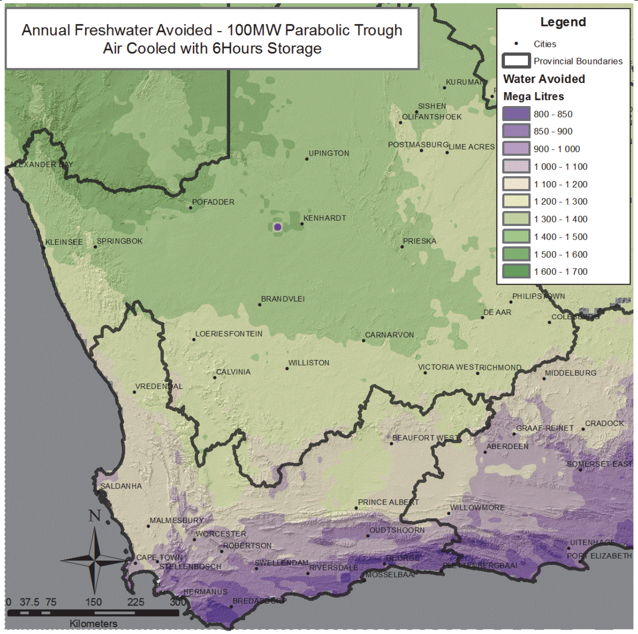




SCENARIO 11 – Air cooled – 6h storage

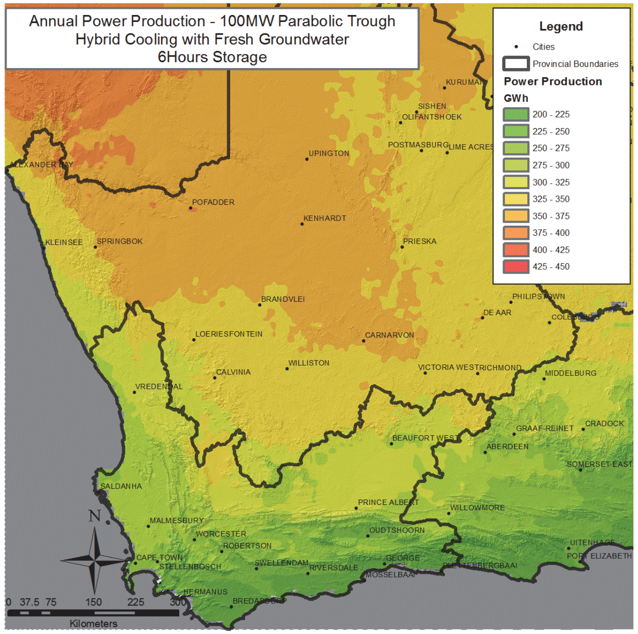


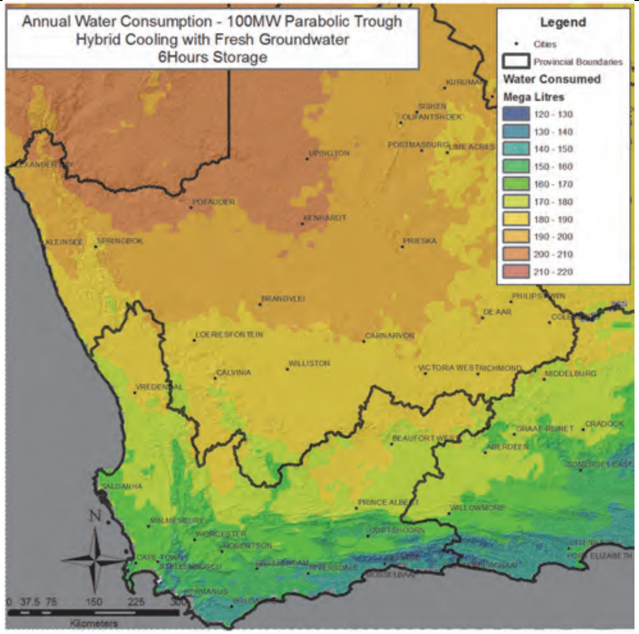


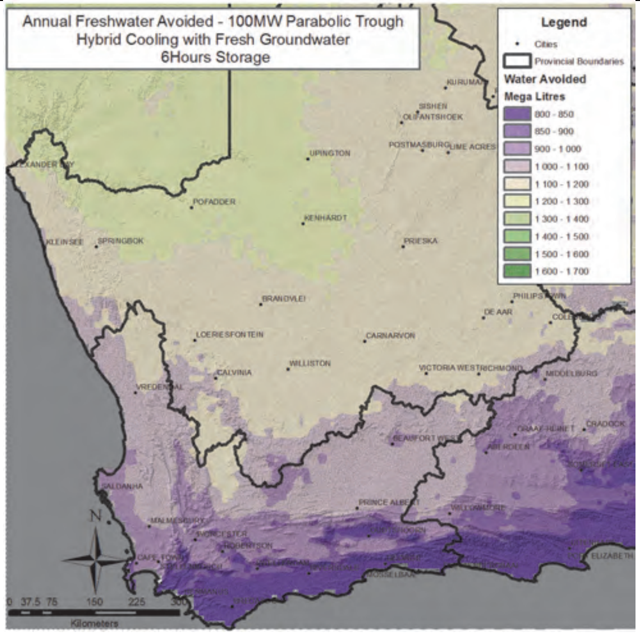


Power Production	Water Consumption	Freshwater Demand Avoided

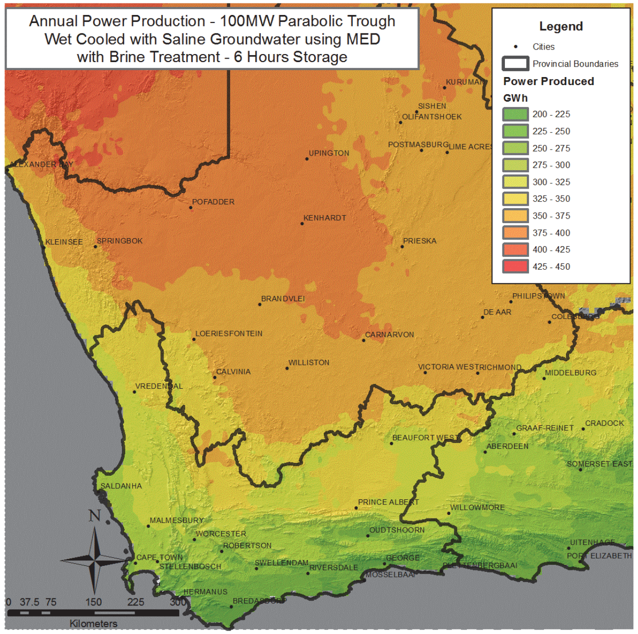
SCENARIO 12 – Hybrid cooling – fresh water/air – 6h storage

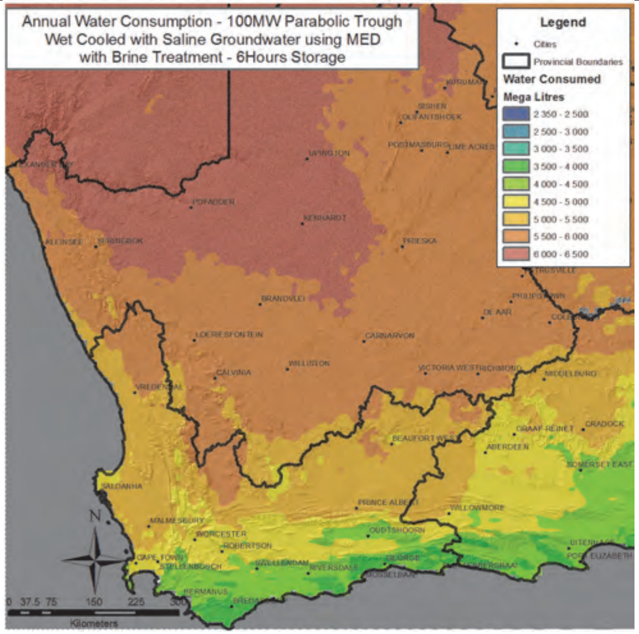


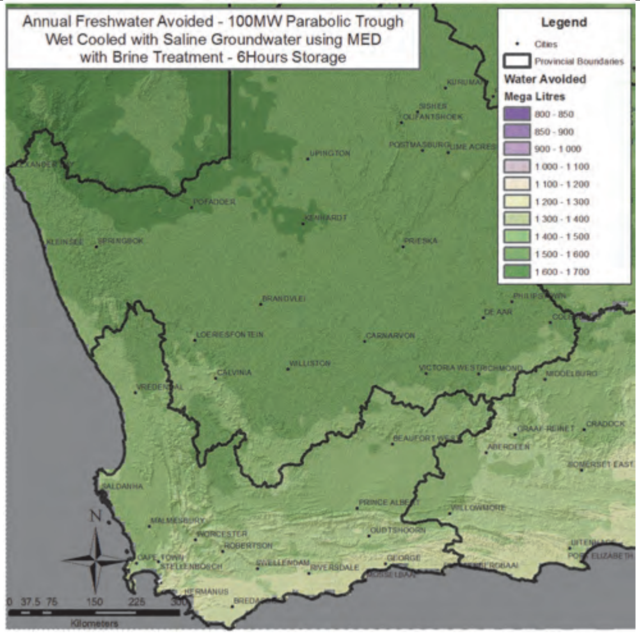




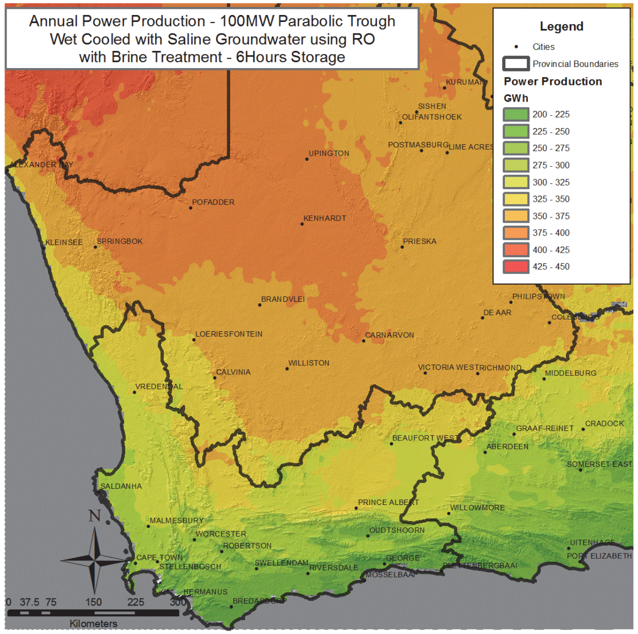
SCENARIO 13 – MED for town fresh water supply (wet cooled – saline water) – 6h storage

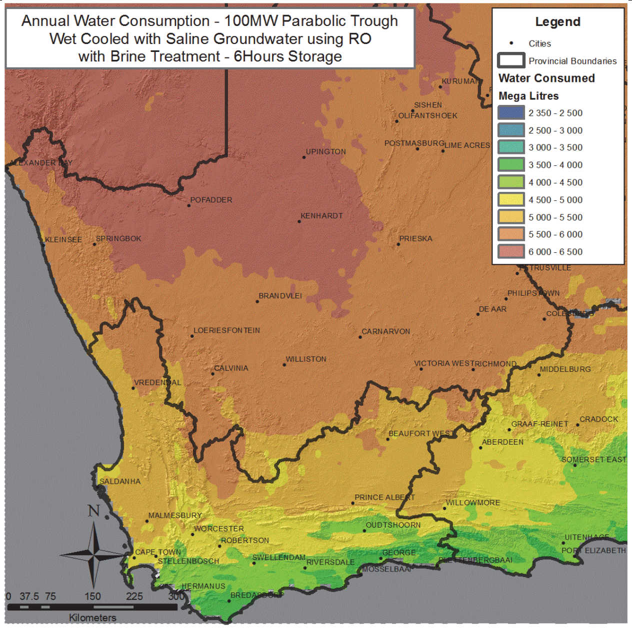


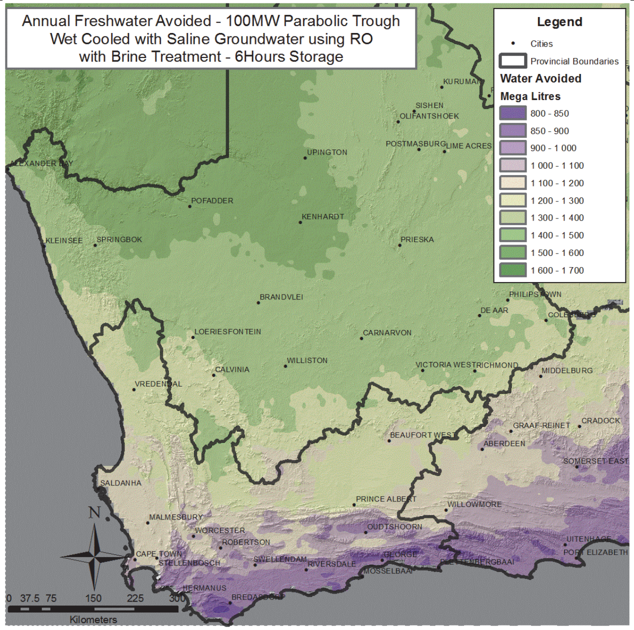




Power Production	Water Consumption	Freshwater Demand Avoided
SCENARIO 14 – RO for town fresh water supply (wet cooled – saline water) – 6h storage		

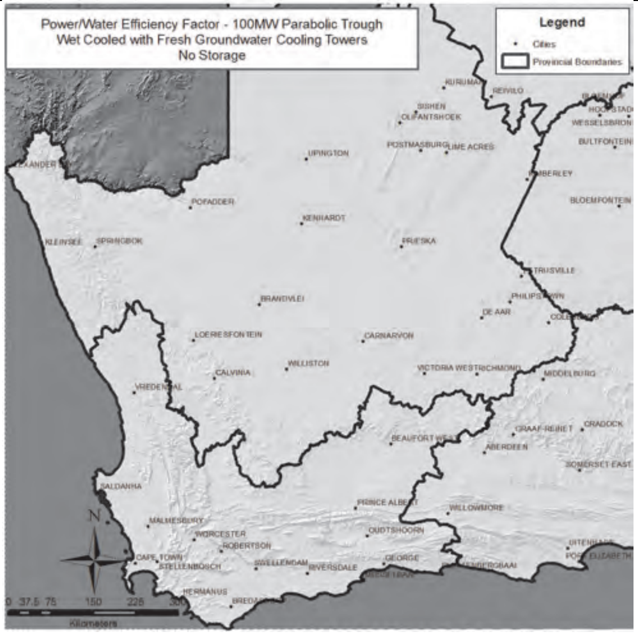


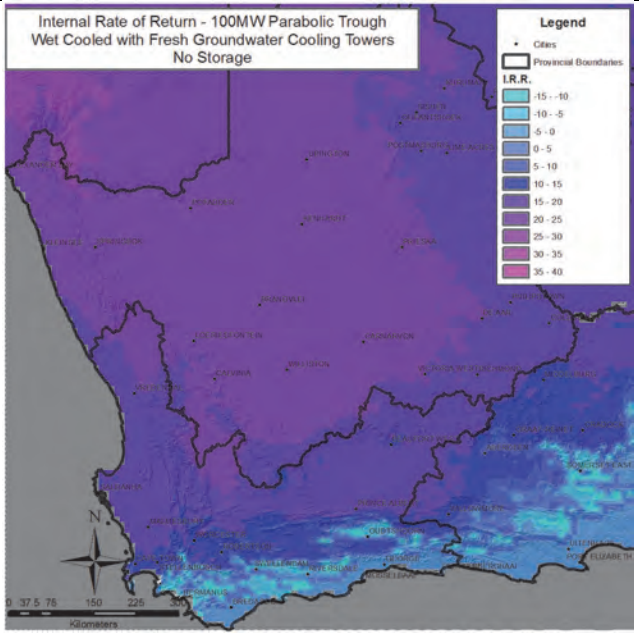


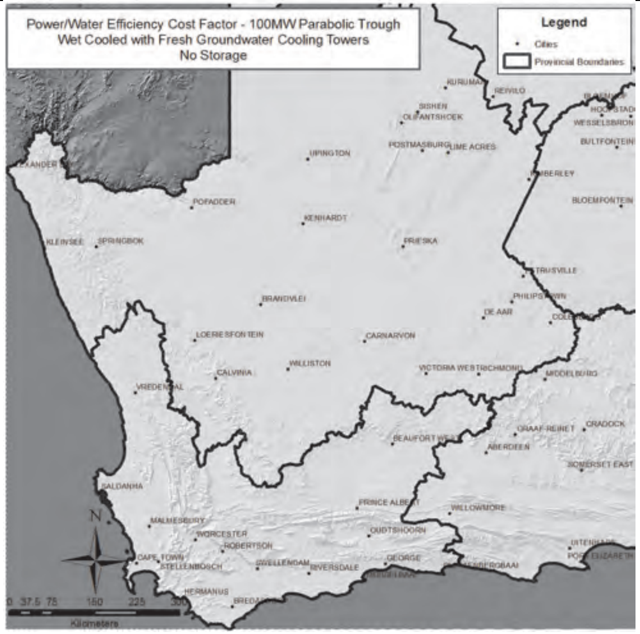


Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function

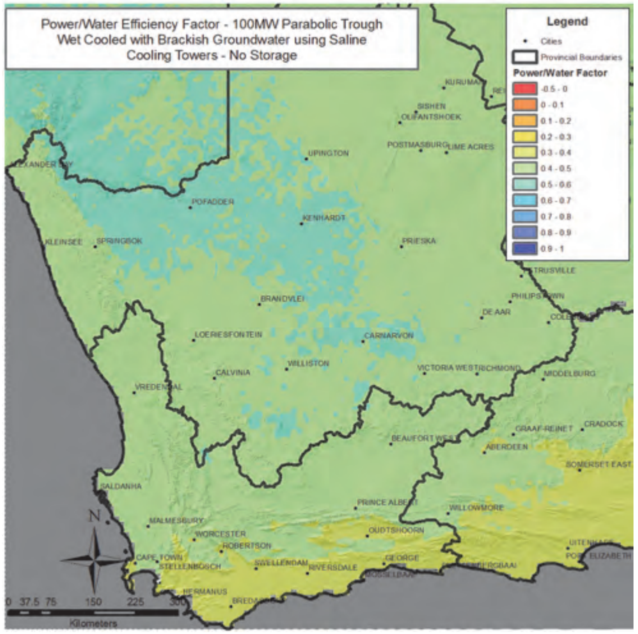
BASE CASE – Wet cooled – fresh water – 0h storage

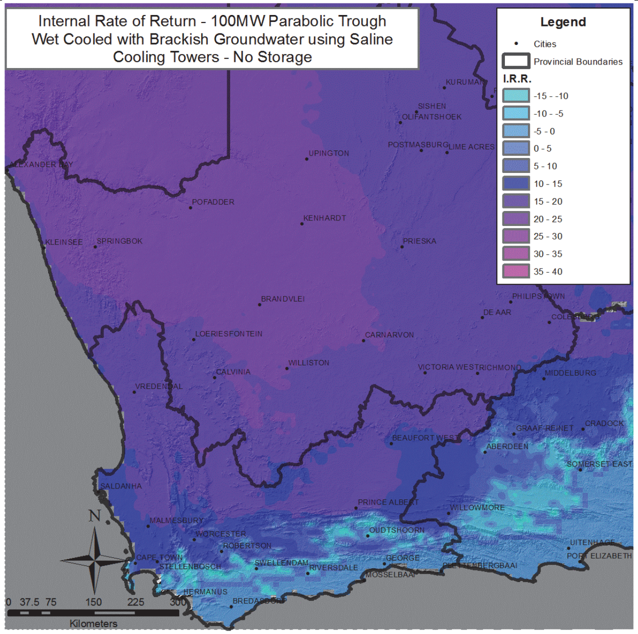


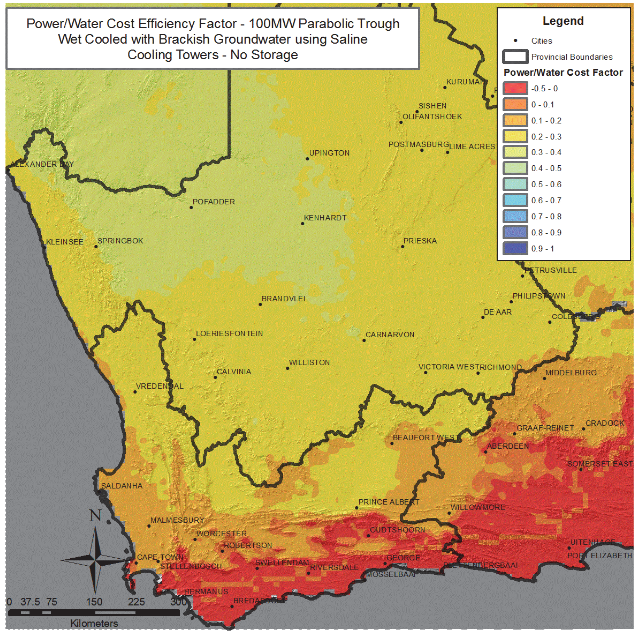




SCENARIO 2 – Wet cooled – brackish water – 0h storage

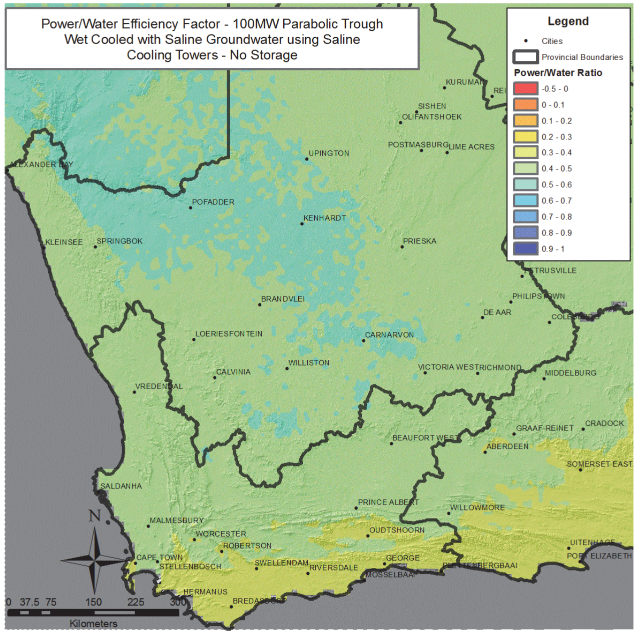


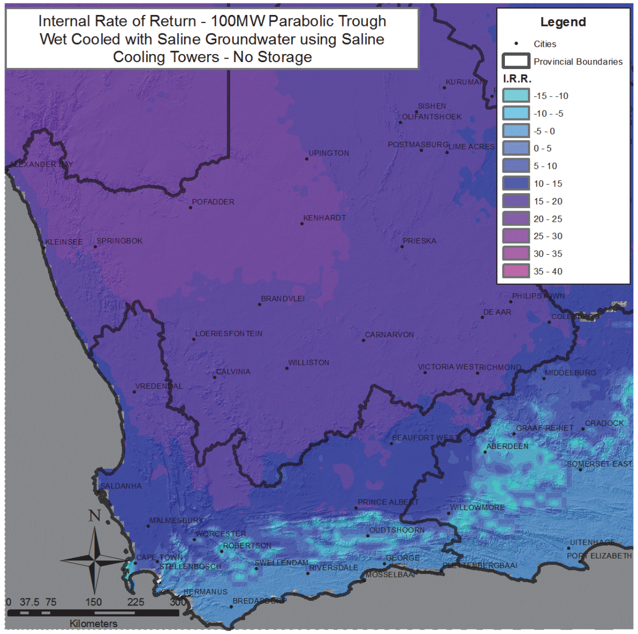


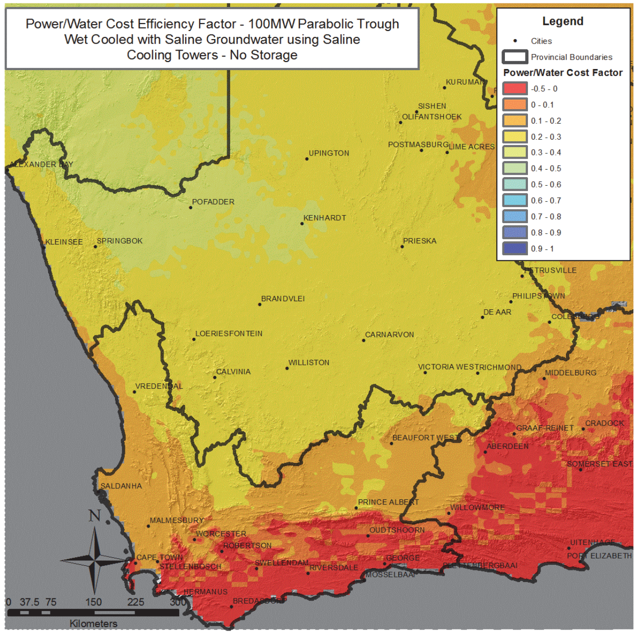


Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function

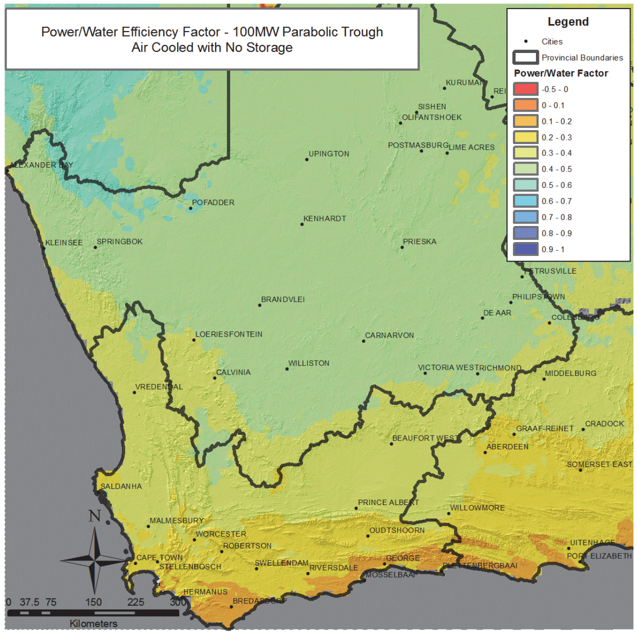
SCENARIO 3 – Wet cooled – saline water – 0h storage

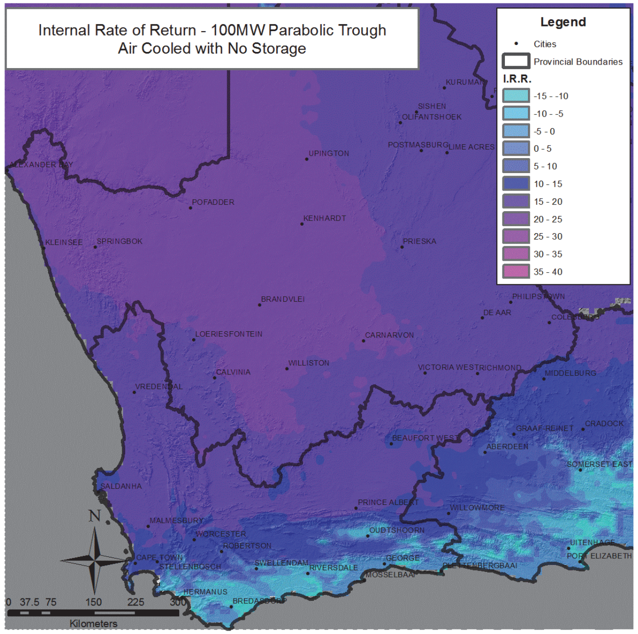


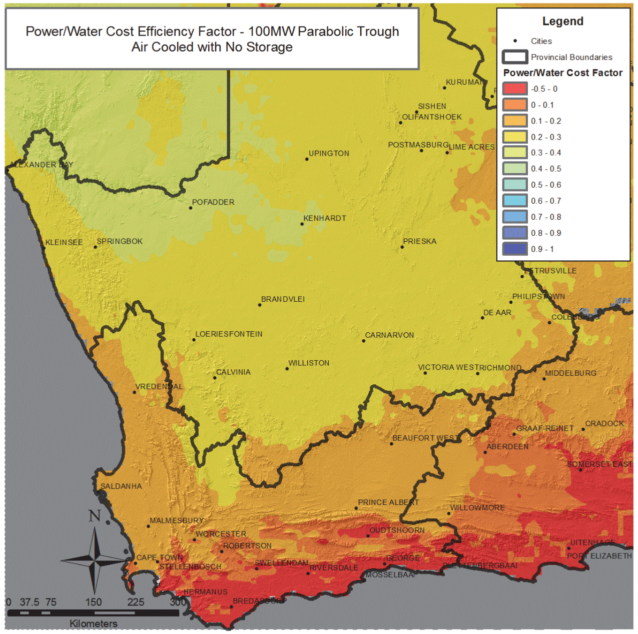




SCENARIO 4 – Air cooled – 0h storage

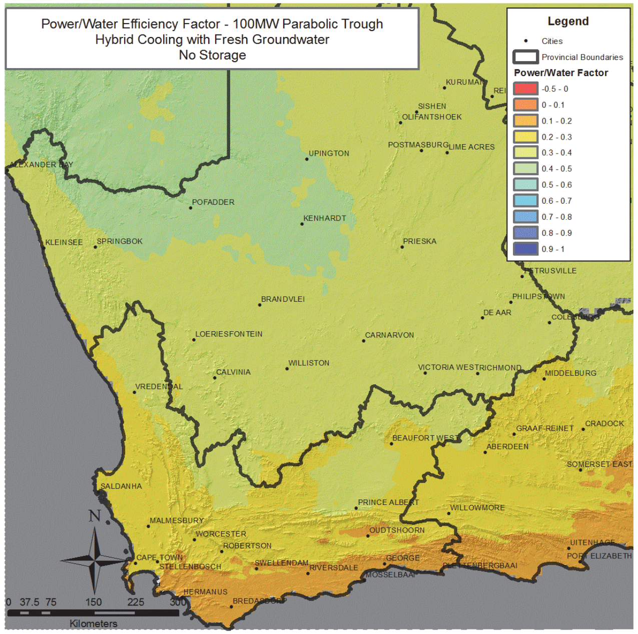


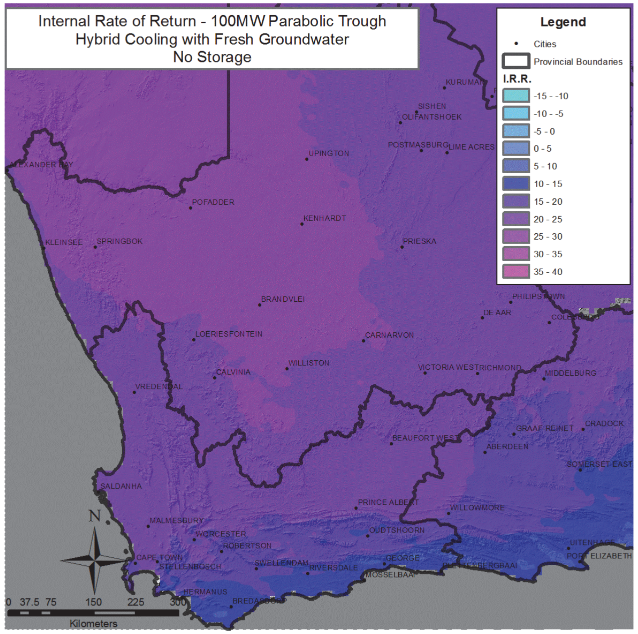


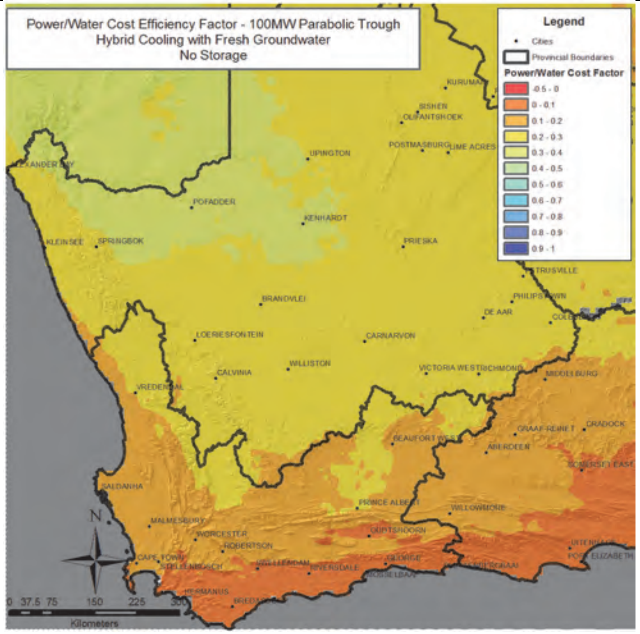


Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function

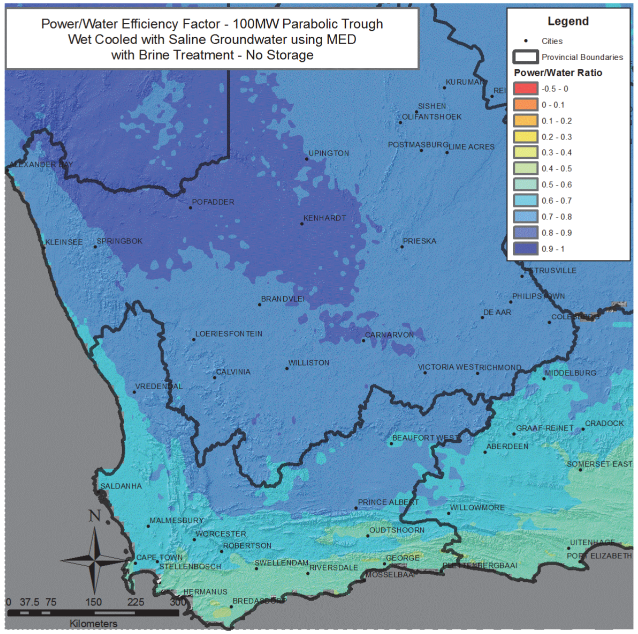
SCENARIO 5 – Hybrid cooling – fresh water/air – 0h storage

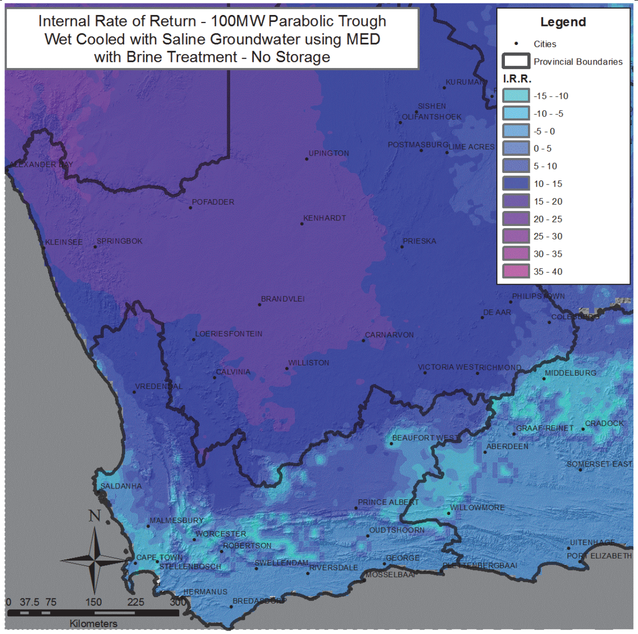


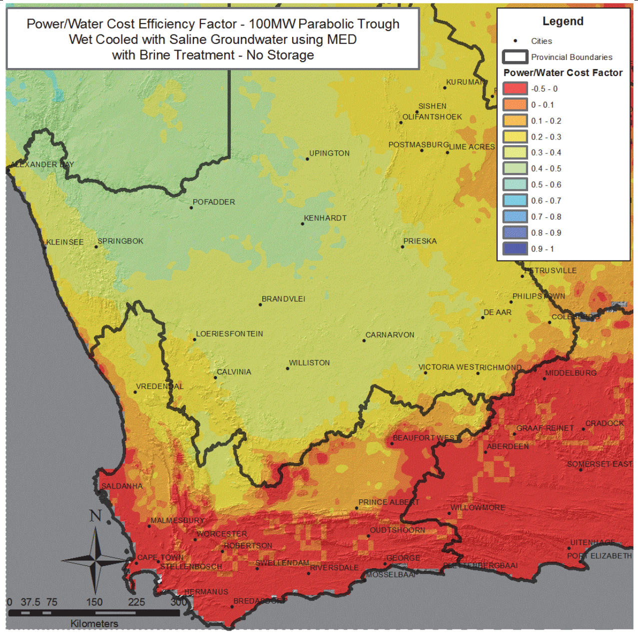




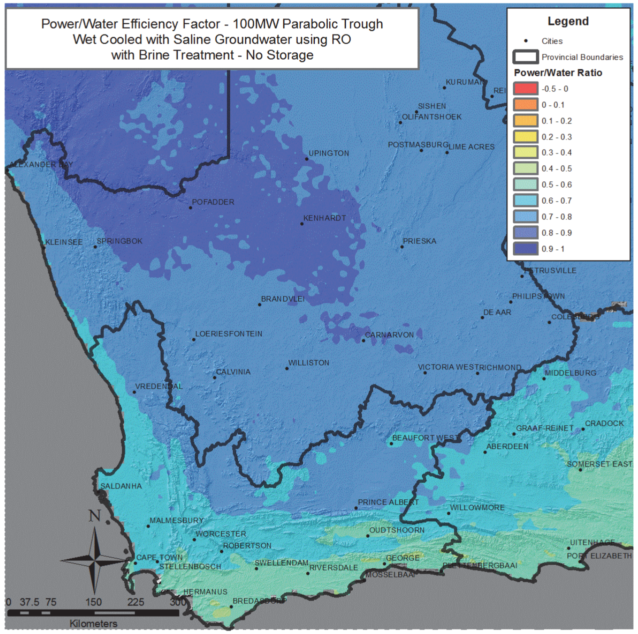
SCENARIO 6 – MED for town fresh water supply (wet cooled – saline water) – 0h storage

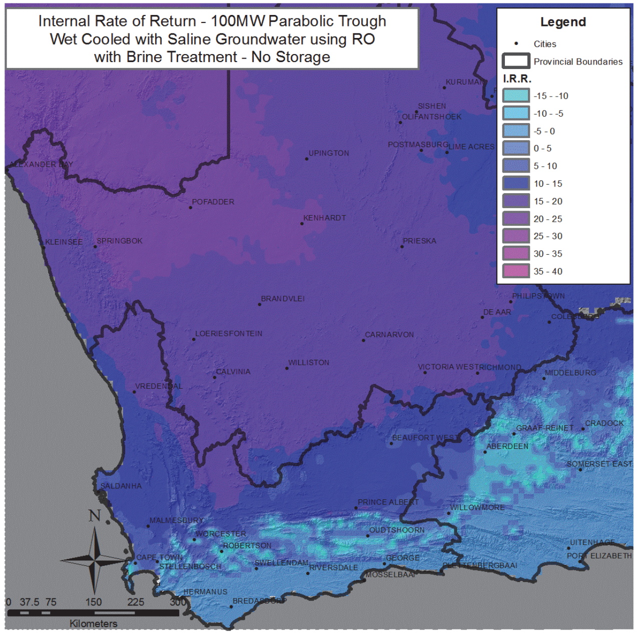


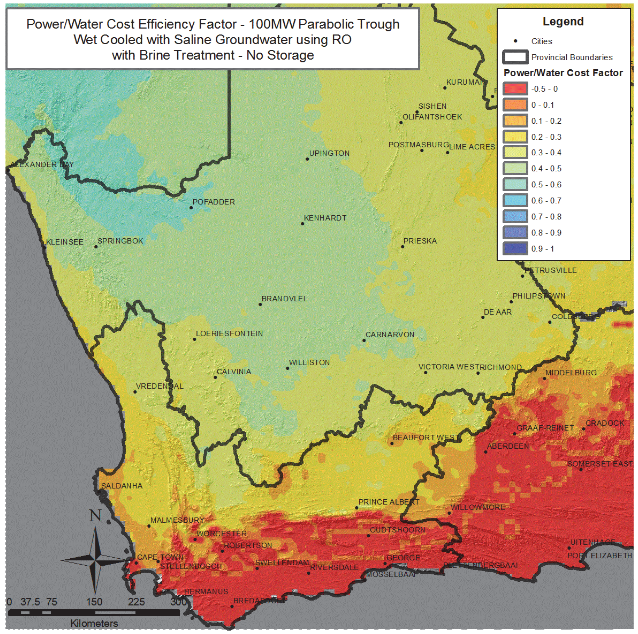




Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function
SCENARIO 7 – RO for town fresh water supply (wet cooled – saline water) – 0h storage		

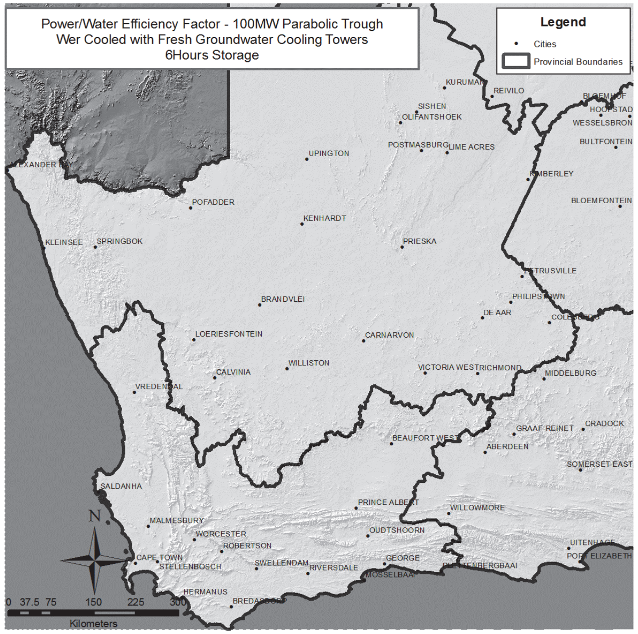


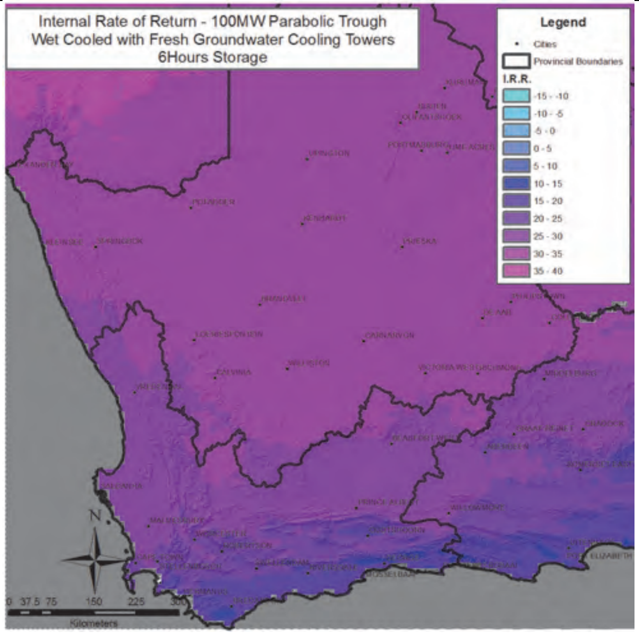


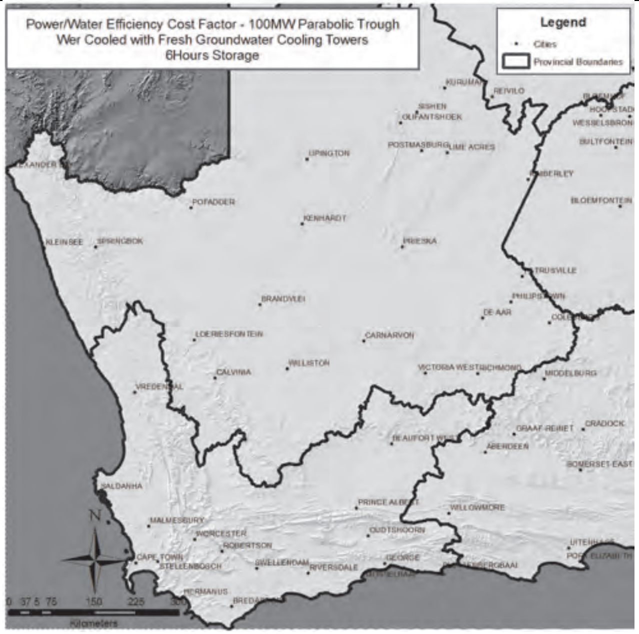


Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function

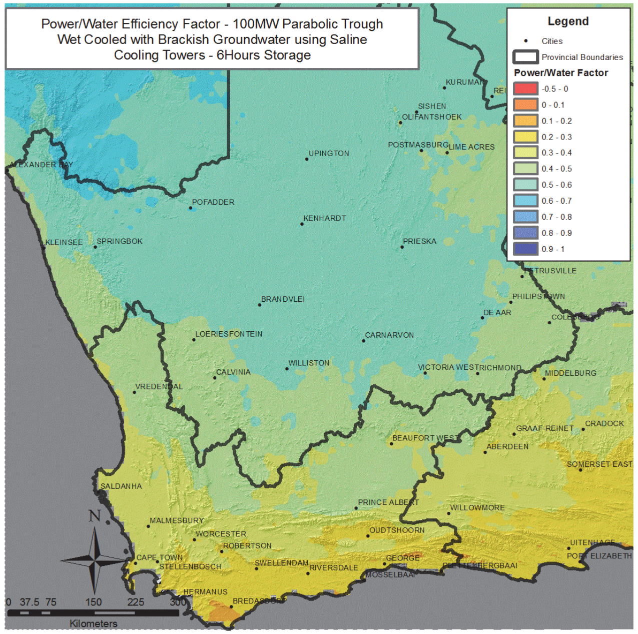
SCENARIO 8 – Wet cooled – fresh water – 6h storage

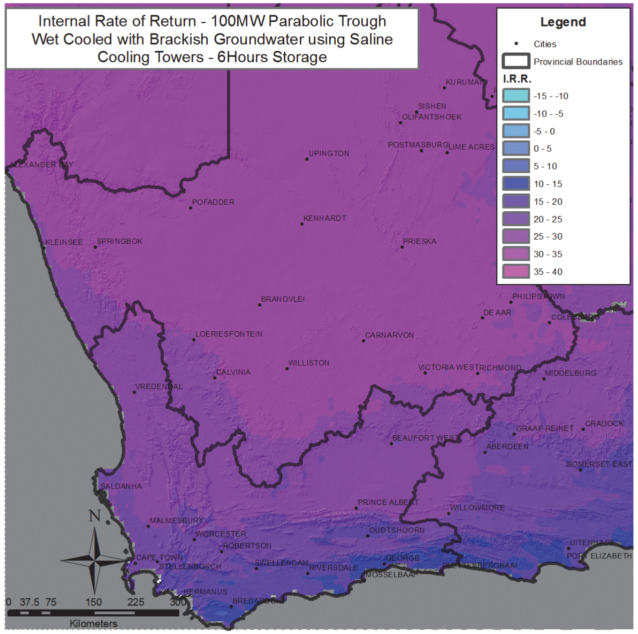


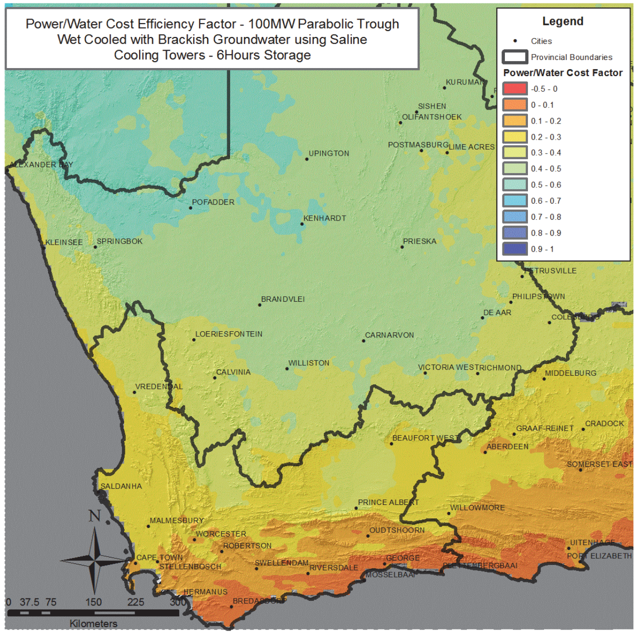




SCENARIO 9 – Wet cooled – brackish water – 6h storage

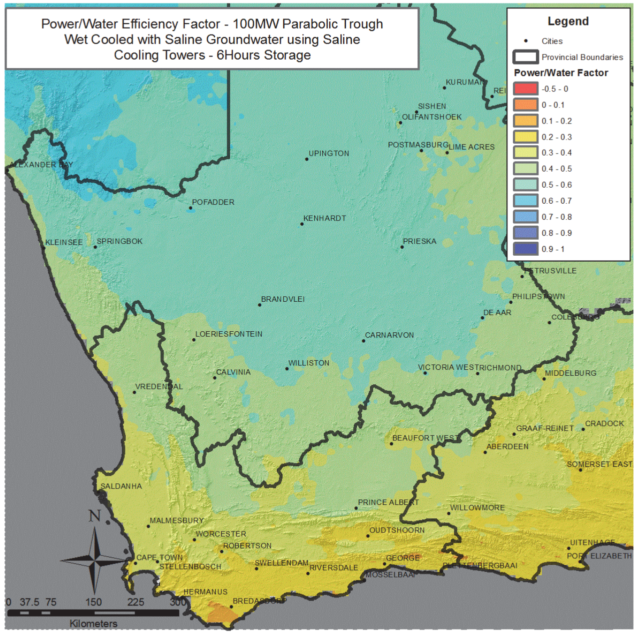


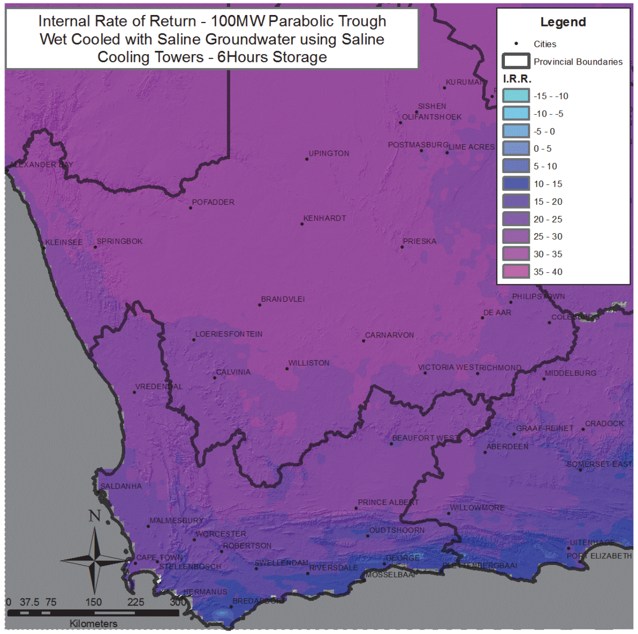


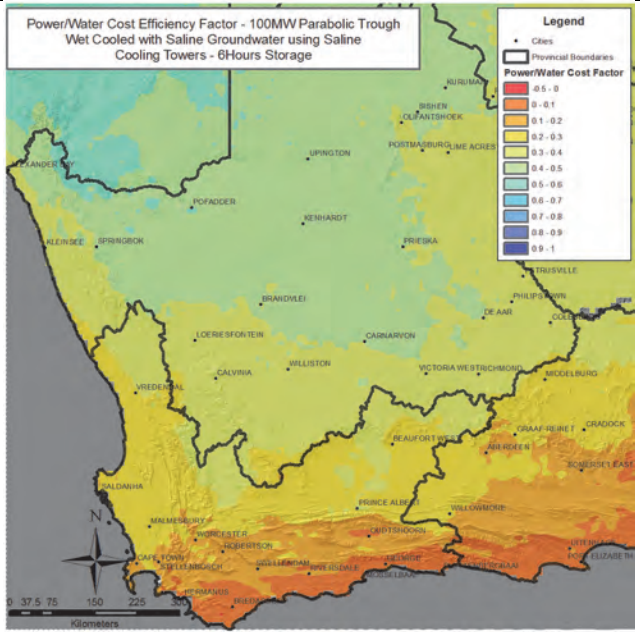


Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function

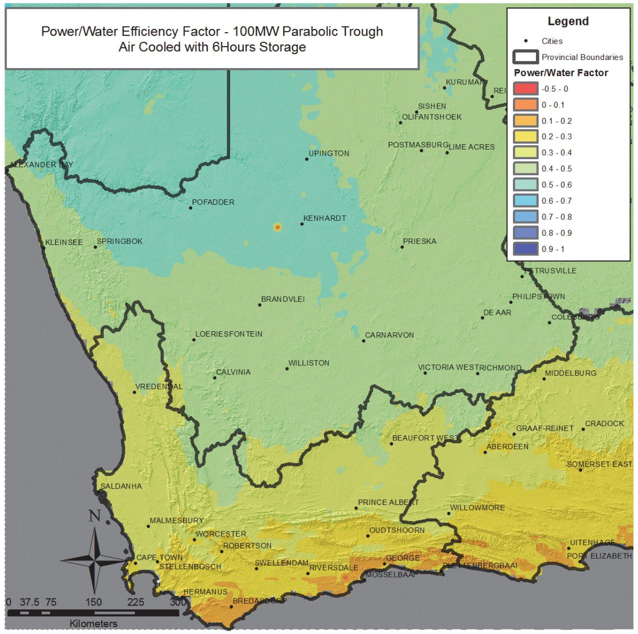
SCENARIO 10 – Wet cooled – saline water – 6h storage

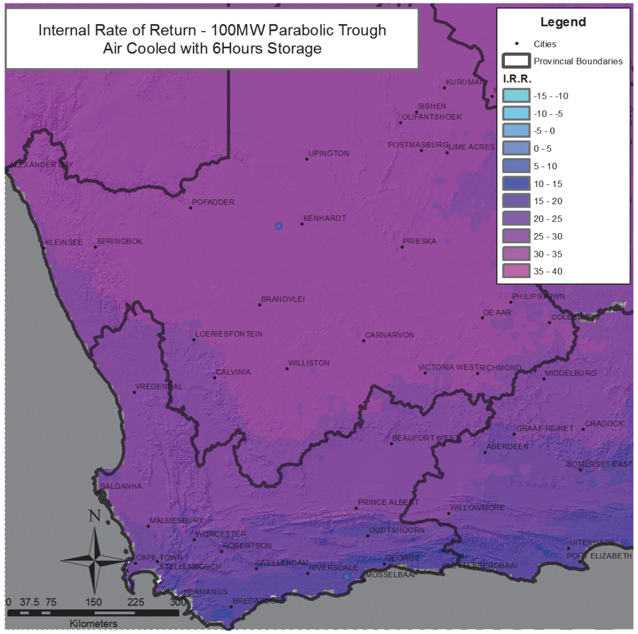


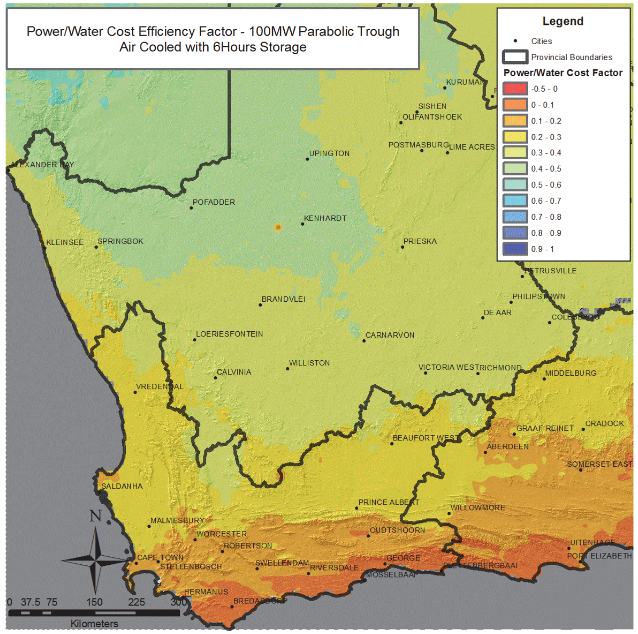


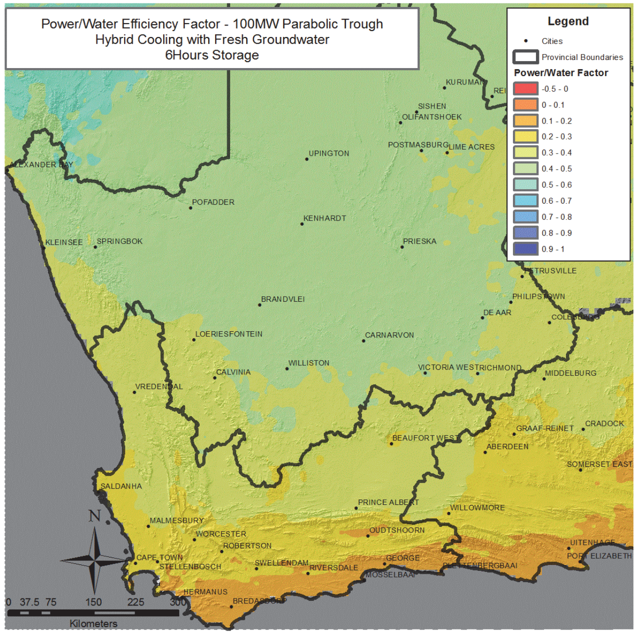
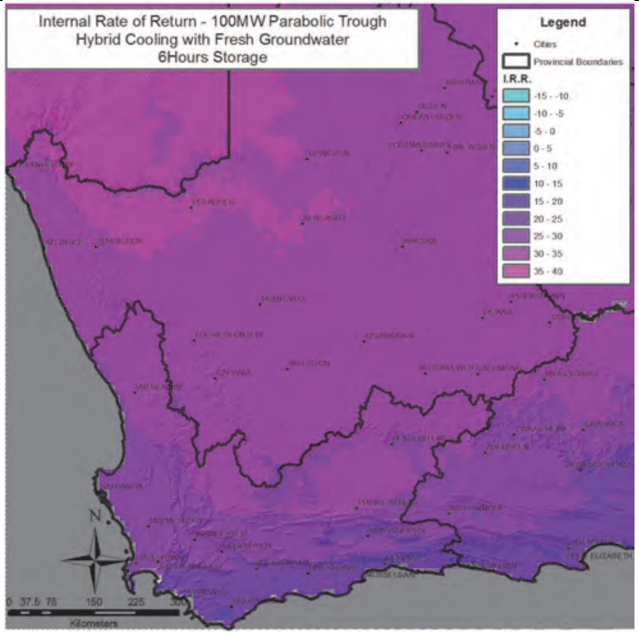
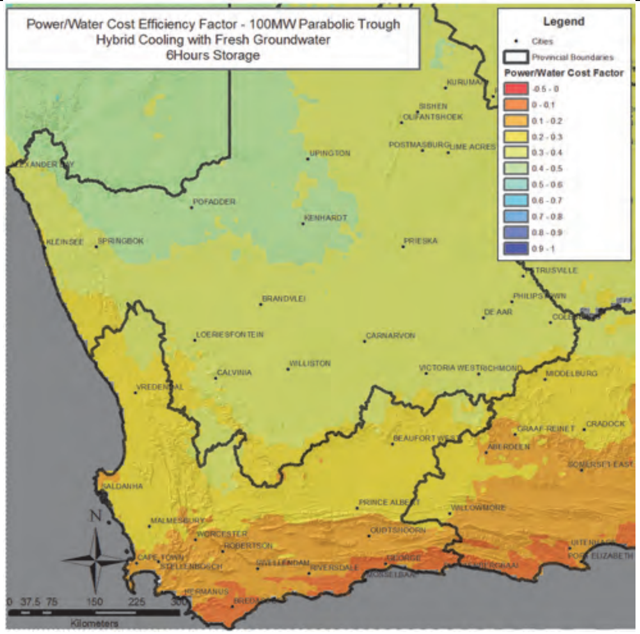
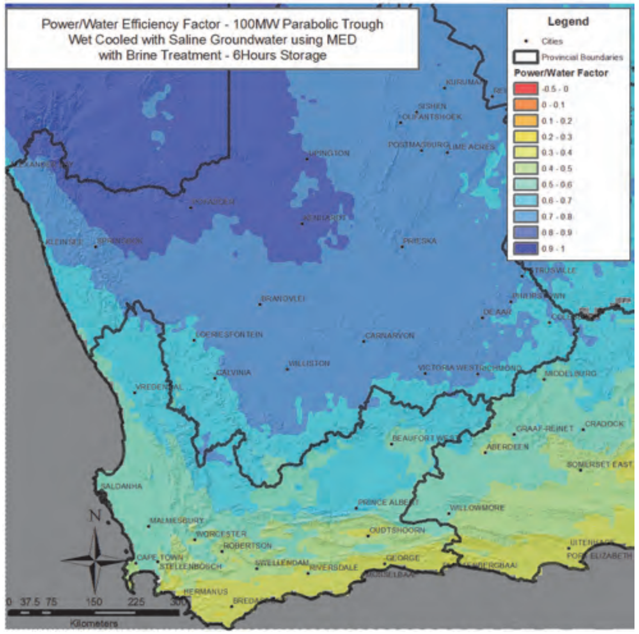
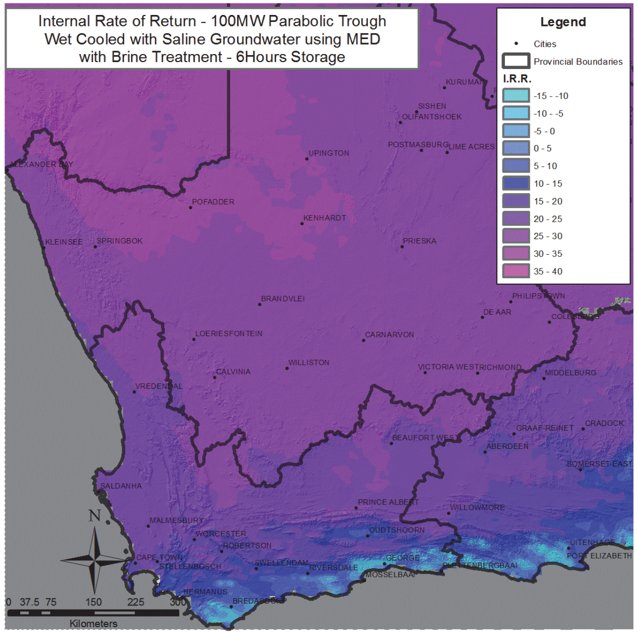
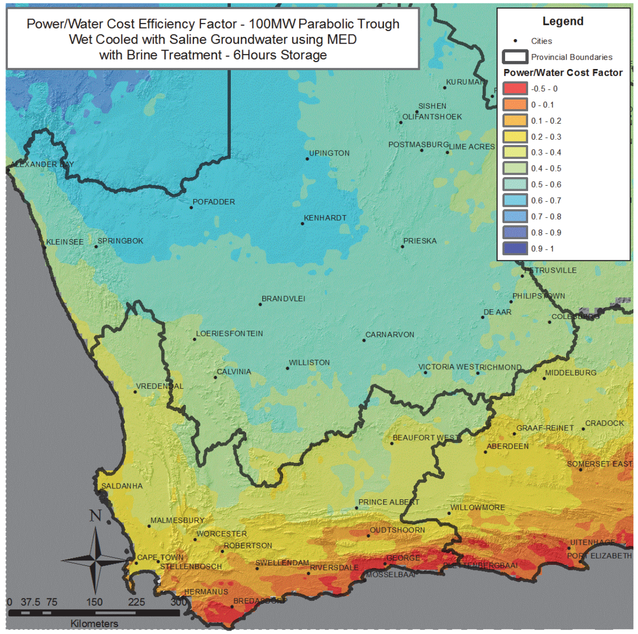


SCENARIO 11 – Air cooled – 6h storage







Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function
SCENARIO 12 – Hybrid cooling – fresh water/air – 6h storage		
		
SCENARIO 13 – MED for town fresh water supply (wet cooled – saline water) – 6h storage		
		

Power/Water Efficiency Function	IRR	Power/Water Efficiency Cost Function
SCENARIO 14 – RO for town fresh water supply (wet cooled – saline water) – 6h storage