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Exploring renewable energy powered reverse osmosis desalination plants in South Africa

A costing analysis of Reverse Osmosis desalination plants
powered by renewable energy and their potential for
South Africa

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A Dissertation submitted to the Energy Research Centre, University of Cape Town, in
partial fulfilment of the requirements for the degree of Masters in Energy and
Development Studies

November 2011

Acknowledgements

I would like to thank my supervisor, Kevin Bennett, for his guidance and support of my research, and to my colleagues, family and friends, especially Maureen Stein, Steve Kitley and Sally Rawson for their never-ending support.

Declaration

I know the meaning of plagiarism and declare that all the work in this paper, save for that properly acknowledged, is my own.

Signed: _____

David Kitley

University of Cape Town

Abstract

The desalination process requires large amounts of energy, either in the form of waste heat or grid electricity. If conventional grid electricity sources are used to power desalination plants, the burning of fossil fuels will contribute towards the release of greenhouse gasses. The consequence of this is that the production of desalinated water would adversely affect climate change if the end product allocation of greenhouse gasses was adopted. This, together with the effect of greenhouse gasses on the water cycle – where a changing climate can result in increased temperatures and/or decreased rainfall – could lead to severe drought and water shortages; the very problems that the desalination process was designed to address. In addition, the financial impact of rising fossil fuel costs, such as coal and diesel, will increase the cost of the electricity needed to run the aforementioned desalination plants.

For the above reasons, including societal pressures, there is a strong argument to use clean energy generation techniques to power desalination plants. Research and development, over the past decades, have assisted the scientific, engineering and development communities in optimising renewable energy and desalination technology combinations.

This dissertation aims to develop a model which quantifies the final unit cost of water based on South African renewable energy costs and Reverse Osmosis (RO) power requirements.

The research method adopted was largely exploratory and adapted using the extensive number of studies which have previously been conducted on renewable energy and desalination pairings to the South African context. The methodology tool applied to determine the final unit cost of water used to compare with current tariffs was the combination of Net Present Value (NPV) and Levelised Energy Costing (LEC) with specific energy requirement ratios.

The results revealed that for areas not connected to the electricity grid, it is feasible to invest in wind or solar powered Reverse Osmosis systems instead of a diesel powered generator. On a grid-connected basis, running a Reverse Osmosis plant using energy derived from supercritical coal is the cheapest option. However, the cost of using renewable energy, especially wind powered Reverse Osmosis systems in areas where

wind availability is in the order of 30% of its quoted capacity, is becoming more competitive. The findings illustrate costs are not yet competitive with South African municipal water costs; however it is perceived that municipal water costs do not reflect the true economic cost. On a regional evaluation the West Coast of South Africa appears to be the region most suitable for renewable energy powered desalination (RE-D) installations.

In conclusion the results have provided preliminary novel evidence of the costs incurred in combining renewable energy technologies with Reverse Osmosis desalination technology in order to produce potable water in the South African context.

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List of Abbreviations

ADURES	Autonomous Desalination Units Powered by Renewable Energy Sources
CESA	Consulting Engineers of South Africa
Capex	Capital Expenditure
CSIR	Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
DME	Department of Minerals and Energy
DOE	Department of Energy
DWAF	Department of Water and Forestry
GHG	Greenhouses Gas
IPP	Independent Power Producer
IRP	Integrated Resource Plan
KWh/MWh/GWh	Kilo - / Mega - / Giga Watt Hour
LEC	Levelised energy cost
NWA	National Water Act
NWRS	National Water Resource Strategy
m ³	Metres cubed or 1,000 litres
MW	Mega Watt
NERSA	National Energy Regulator of South Africa
NPV	Net present value
PPA	Power Purchase Agreement
PV	Photovoltaic
RDP	Reconstruction and Development Programme
RE	Renewable energy
RE-D	Renewable energy powered desalination plants
REFIT	Renewable Energy Feed-in Tariff
RO	Reverse Osmosis
SABRE-Gen	South African Bulk Renewable Energy Generation Project
SANERI	South African National Energy Research Institute
UNFCCC	United Nations Framework Convention on Climate Change
WMA	Water management area
UWC	Unit water cost

1. Introduction

1.1 Purpose of the research

The aim of this research was to develop an understanding, through quantitative and qualitative analysis, as to whether it is feasible, in South Africa, to produce potable water from desalination methods using renewable energy as a power source. To achieve this, two scenarios were evaluated, (1) a decentralised or “off-grid” scenario and (2) the effect of renewable energy technology investment costs over a period of 25 years in comparison to conventional energy sources. In addition, this research aimed to identify those coastal water management areas of the country that are water stressed and are characterised by suitable renewable energy potential to operate such systems.

1.2 Context

In her budget speech of 15 April, 2010, the then Minister of Water Affairs Buyelwa Sonjica, announced that in light of South Africa’s present water supply constraints that it will be necessary to use desalinated sea water to service “our water-scarce¹ country” (Service Publication, 2010). This bold statement has been supported by studies of the country’s water supply deficit, as well as the effects that climate change and variation in rainfall will have on the availability of water. To support this, Deputy Director-General of Water Affairs, Cornelius Ruiters, stated in his media statement released at the conference for the Implementation of Environmental Water Allocations (IEWA) in Port Elizabeth, that South Africa is looking to Desalination Technology to provide 8-10% of the national water supply by 2030 (Desalination currently contributes less than 1% of national supply) (Engineering News Online, 2010).

Although desalination may not be perceived as the most cost effective solution (Eltawil *et al.*, 2009), the evolution of desalination technologies has allowed the process to become more energy efficient and scalable. Therefore, as the price of municipal water increases and the cost of desalination infrastructure decreases, this option will become

¹RSA in terms of the UN definition is water stressed and on the border of being water scarce. The country’s water availability is 1,100m³ per person per annum, which falls below the water stressed mark of 1,700m³ per person per annum and just above the water scarce border of 1,000m³ per person per annum

economically competitive. As of 2010, the Government supplies the nation with 15 billion m³ of water per annum (South African Info Website, 2005), which puts estimates at the provision potential of potable water produced by desalination plants at around 1,500 million m³ per annum (or 460 million tons)². A concern raised is that the current budget does not allow for water infrastructure spending, as the immediate focus is on addressing the country's energy crisis. However, it has been further reported that this could create opportunities for involvement of Independent Water Providers or Public Private Partnerships (PPP) (Engineering News, 2010).

South Africa is regarded as a water-stressed country and studies completed by 2030 Water Resources Group (2010), McKinsey and Company (2010), Antony Turton (2010) and Mike Muller (2002); show that as early as the present decade, certain areas of the country will experience severe water shortages, increasing the risk of national shortage by the next decade. Of the available water supply in the form of surface and ground water, including water imports from across its borders, the demand is for approximately 95% (concluded in 2004) (South African Info Website, 2005). This does not allow much room for growth and is contrary to the country's aspirations of meeting its Millennium Development Goals of supplying water to the entire population, increasing the amount of land dedicated to agriculture and improving that which is already allocated, expanding the industrial and mining sectors and making supply available for the growing population and middle-class. To address these concerns, the Department of Water Affairs, cited above, has stipulated that the desalination of water will play an important role in the country's future, with the aim that the technology will contribute a minimum of 8-10% of the country's water supply by 2030. However, it has not detailed which areas of the country have been selected for the location of the plants and which desalination technology will be chosen.

In light of this supply-side strategy to mitigate the country's water stress through the use of desalination technologies, it is crucial to consider the energy implications of this decision. Desalination technologies are renowned for being expensive and for requiring large amounts of energy to power the respective plants, which is a concern considering the country's current situation of being energy stressed and the constant threat of load shedding, in addition to its aim of shifting its energy mix away from being fossil fuel dependent, towards contribution by renewable energies. It is estimated by the author that providing 10% of the country's projected water demand in 2030 by desalination

will require 0.5-1.5 GW worth of power capacity, assuming 1m³ requires between 3-9² kWh/m³.

To address the above-mentioned issues, this research will explore the possibility of South Africa installing renewable energy powered desalination technologies to mitigate its water and energy stress, in conjunction to avoiding the installation of conventional coal-fired power plants. This will be achieved by analysing the country's regional water supply versus demand forecasts, the country's regional renewable energy potential, an analysis of the renewable energy powered desalination plants that have been researched, tested and are in operation, and to financially evaluate two scenarios to understand if such systems are affordable in comparison to other energy intensive methods.

1.3 Problem statement

1.3.1 Main problem

The purpose of this research was to model the financial cost of the final unit cost of water using an array of renewable and conventional energy supply technologies, both on an off-grid and time scale, to identify which energy sources are most economical.

1.3.2 Sub-problem

The first sub-problem was to identify what the different types of desalination methods are, and which of these are most popular globally and in South Africa, and the reasons for this.

The second sub-problem was to understand what the different pairings of renewable energy and desalination technologies are, what the lessons learnt from operations has been, and to identify which of these pairings is the most economical and efficient.

The third sub-problem was to understand South Africa's renewable energy potential and which renewable energy sources are most favoured.

²The energy requirements are quoted from a senior manager in research and development from a seawater desalination plant manufacturer

The fourth sub-problem was to build a model based on the literature review, which links the suitable and relevant renewable energy and desalination technologies identified and quantify the equivalent unit water cost in comparison to current municipal supply tariffs.

1.4 Hypothesis

Considering the current water stresses that South Africa – both centrally and in remote regions – experiences, together with the promotion of a renewable energy sector to boost national energy supply, the aim of this research is to identify if it is economically feasible to invest in renewable energy powered desalination technologies as a means to increase potable water supply in South Africa, regardless of the size of the plant, and whether there is sufficient institutional structure and capabilities to support this. As such the two hypotheses for this dissertation are:

- i.) It is technically viable to use RE-D pairings to augment water supply in coastal WMAs experiencing water deficit,
- ii.) It is financially feasible to use RE-D pairings to augment water supply in WMAs experiencing water deficit.

1.5 Significance of the research

This research contributes to a very specific pairing of the country's renewable energy potential with the provision of potable water and the addressing of water scarcity. The results obtained will contribute to a better understanding of what new strategic opportunity exists for renewable energy and the developmental opportunity for communities, as an increase in potable water supply to regions previously stressed could drive agricultural development, in turn creating the opportunity for developmental and industrial activities. Furthermore, it will be an opportunity for the country to become less dependent on conventional fossil fuels while providing a necessity for society. And the skills created and the manufacturing of systems could

drive job creation and exporting revenues as the characteristics of energy and water scarcity are common traits experienced across Africa.

Finally, the research will also contribute to academia. Although much has been published on the subject of renewable energy powered desalination plants globally, this subject has not been explored in detail for South Africa. With the increase in demand for both water and energy, and the opportunity there is to harness South Africa's renewable energy potential, pairing renewable energy and desalination could provide the means to increase water supply whilst diversifying the country's energy mix and reducing its dependency on conventional fossil fuels.

1.6 Delimitations of the research

This research will look at renewable energy technologies, which include wind, solar and ocean energy, conventional energy technologies, which include diesel powered generators, conventional coal and nuclear energy, and Reverse Osmosis desalination technologies. Other renewable energy technologies, i.e. small-hydro and landfill gas, have not been considered due to their requirement for constant human management, as solar, wind and ocean energy are relatively self-sustainable. Similarly, other desalination technologies, i.e. multi-vapour compression, multi-effect distillation and multi-stage flash, were not considered for scenario modelling as research shows other technologies are not as energy efficient.

The research focuses on investment, fixed and variable costs as obtained from published literature and does not consider site-specific elements of additional infrastructure, e.g. additional piping and brine treatment technologies.

Finally, this research has been limited to the context of small and large sized desalination systems as categorised by the two models created.

1.7 Structure of report

The introduction and chapter 1 focuses on providing a high level description of the intention and purpose of this research and concludes by describing the situation the South African water sector finds itself in. Chapter 2 takes a look at the literature that is available on the global experience with conventional desalination technologies and exploring how, where and what renewable energy powered desalination technologies are being researched and utilised globally, and if they are suitable for use in South Africa. Chapter 3 unpacks the methodology used to analyse the financial aspects of RE-D combinations, the regional water deficits and the regional renewable energy potential. Following this, Chapter 4 and 5 details the results and discussion of the research, identifying which RE-D combinations are most suited to South Africa's regional renewable energy profile and levelised energy costs, and which RE-D combinations are most financially preferable. These results have been depicted from the perspective of levelised energy and final unit water costs. Chapter 6 includes a description of the key areas that the RE-D community need to address to promote the development of the systems while Chapter 7 and 8 focus on summarising the research and proposing new areas of research to assist in the development of these initial findings.

1.8 Situation analysis

The remainder of this chapter aims to provide the context of South Africa's current water situation. The focus is on water supply and demand forecasts, and touches on water treatment and quality, the free basic water policy, water pricing, infrastructure and institutional capabilities, and user profiles.

1.8.1 State of RSA water sector

Considering that South Africa is characterized as a semi-arid country with below-global average rainfall, as well as being a developing country, it has done well to ensure that few water shortages occur through the storing and transferring of sources between water catchment regions. However, it is widely documented that South African water allocation is reaching levels of unsustainable imbalance. The National Water Resource Research (NWRS), completed in 2004, utilizing data that was collected in 2000,

documented that there was an approximate total available yield of 13,991³ million m³ per annum, seen in Figure 2 and Table 1, for which demand existed for 95% or 13,280 m³ of this, see Table 2 (DWAF, 2004). In addition, 11 out of the 19 Water Management Areas (WMAs) were experiencing water deficits in 2004, and certain of the municipalities were resorting to providing water by road tanker due to groundwater exhaustion as a result of drought conditions (Otieno and Ochieng, 2004, Mukheibar, P., 2007).

This research has since been expanded by studies completed by leading researchers: Mike Muller, Antony Turton, UNEP, WWF and the 2030 Water Resources Group, who have all documented this threat of supply, highlighting technical improvements, increasing supply, political will and improving water productivity under economic activities, as feasible and necessary areas to focus on to resolve the probable water threat. Additional strain will be placed on the source of supply as demand-side growth is expected to increase as the government extends access to the entire population, improving the quality of water supply for household and sanitation purposes and increasing accessibility for the emerging farming sector. Furthermore, economic growth, population growth, urbanization and higher per capita incomes also increase consumption and demand (Segal, 2009).

Various estimates have been made as to when South Africa's water requirements will exceed water availability, with previous predictions of as early as 2000 by the Commission of Inquiry into Water Affairs in 1970, 2020 by the Department of Water Affairs and Forestry in 1986, between 2020 and 2030 by Odendaal in 1992, 2025 by Mike Muller in 2002 and the latest prediction of between 2020 and 2030 by the Water Resources Group in 2010. However, despite the variance, it appears that a water threat will be something that South Africa will face if it does not deal with the issues at hand. In response to these findings, a new Water Act was passed in 1998, but due to poor implementation of the integrated water resource management strategy by the Department of Water Affairs and Forestry, no visible improvements in tackling these issues have been seen.

³These figures refer to the institutional or water distribution sector managed by the Department of Water Affairs (DWAF) and does not include the total sources of supply that RSA receive through precipitation and run-off. This is due to the bulk of the water evaporating, being used by natural vegetation or remaining in the environment to augment surface water, groundwater and ecological reserves

Table 1 and 2 illustrate the current source and demand of available water supply. An estimated 77% of the country's water supply comes from rivers and dams, 14% from return flows of treated wastewater and 9% from groundwater.

Table 1: Source-wise water yield, South Africa, 2000 (Backeberg, 2005)

Sources	Million m ³ /yr	%
Surface Water	10,928	78.5
Groundwater	1,042	7.5
Usable Return Flow ⁴	1,941	14.0
From Irrigation	(672)	(4.8)
From Urban Sector	(1,015)	(7.3)
From Mining Sector	(254)	(1.9)
Total	13,911	100.0

Table 2: Sector-wise water requirements, South Africa, 2000 (Backeberg, 2005)

Sources	Million m ³ /yr	%
Irrigation	7,836	59.0
Urban	3,332	25.1
Rural	572	4.3
Mining and Bulk Industrial	756	5.7
Thermal Power Generation	296	2.2
Afforestation	488	3.7
Total	13,280 (95% of the supply)	100.0

The water that is available for use is sourced from both ground and surface water storage points, and consists of annual mean run-off due to precipitation, water importation and the storage of water in dams, rivers, lakes and water towers. It is estimated that the country receives a total run-off of 49.2 billion m³, of which an estimated 8% is lost due to evaporation and 6% to land-use activities. Around 10,200

⁴Return flows from irrigation of agriculture dry-land crops

million m³, or 20%, was abstracted for surface water use, leaving around 66% for natural river flow in the country's rivers (South African Info Website, 2005). It is estimated that the amount of surface water that is currently being used is around 15 billion m³ (WRG, 2010), decreasing the amount of water in rivers to 56%.

Water consisting of ground and surface water, can be loosely defined as a commodity, as the definition of a commodity is 'a resource that is traded', which in RSA occurs by the transferral of the resource across provincial boundaries through transmission infrastructure or rivers. Moreover, due to climate change and climate variability causing fluctuations to regional weather patterns, the predictability of rainfall or ground water renewal becomes a difficult task. Hence it could be deduced that water is a sensitive and limited resource, which affects the transferability or its tradable nature between provinces. This implies that the allocation of water needs to be managed in an efficient and economical manner. Under current circumstances however, it appears that this is not the case, with the allocation of large portions of water to irrigation and agriculture (the sector that contributes the least to national GDP, however provides the means to sustain a large proportion of the country's required food supply), as well as to providing equitable access to all in terms of the Free Basic Allowance policy. Figure 3, on page 19, illustrates the inter basin and cross border transfer of water that currently occurs.

Figure 1, on the following page, illustrates how the South African government has allocated water management to 19 water catchment regions, supported by 15 water boards and 169 water service providers. Additionally, these regions are further divided into a total of 283 different municipalities, which are individually responsible for managing their community's water. These 19 catchment regions, or WMAs, are responsible for managing their regions, and are responsible for drawing up a management strategy for both supply and demand pressures. At present, the water reconciliation strategies for supply and demand are being completed and are due in 2011, with the intention of making known a calculated environmental reserve or deficit. Figure 2 provides a map of the water supply versus demand in the different regions. This highlights the different region's individual stresses, with emphasis on the shortage that is observable in Gauteng, Western Cape and Kwazulu-Natal, which are South Africa's most populated provinces.

Figure 1: The 19 catchment areas as defined by the Department of Water and Forestry (1998)

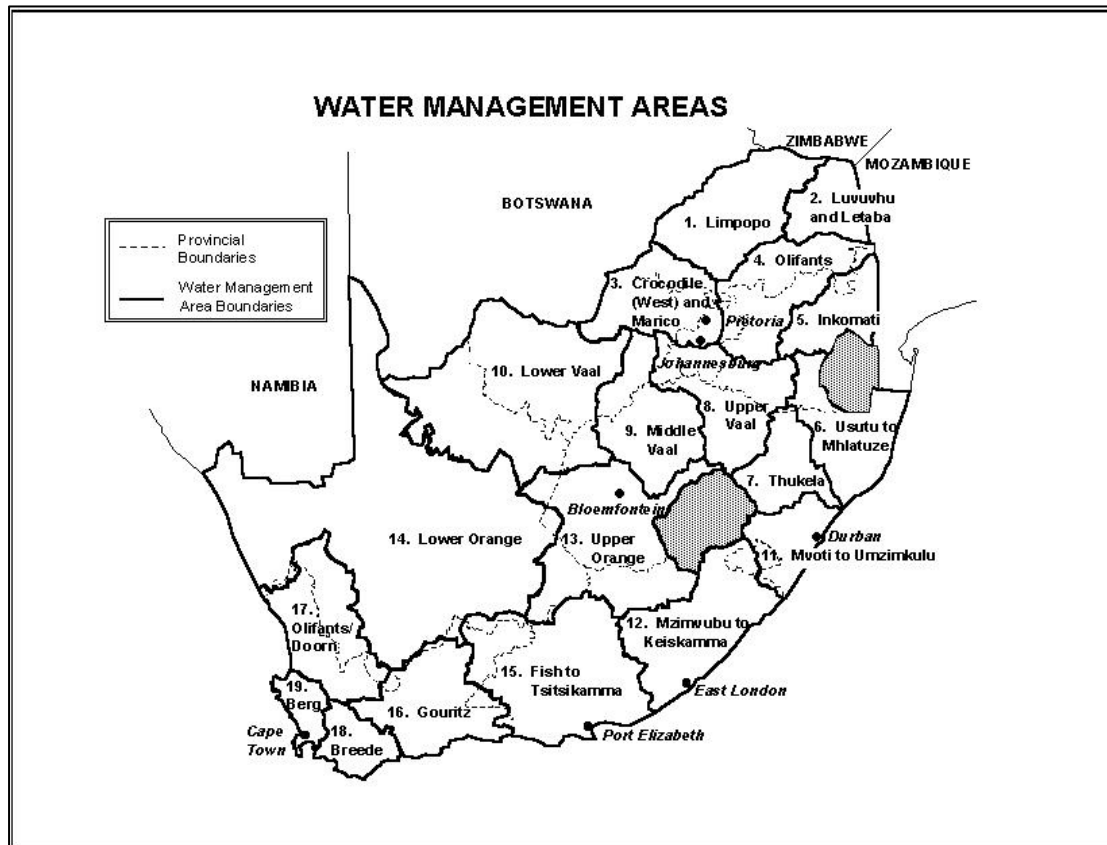


Figure 2: South Africa's water supply versus demand in 2000 (DWAf, 2010)

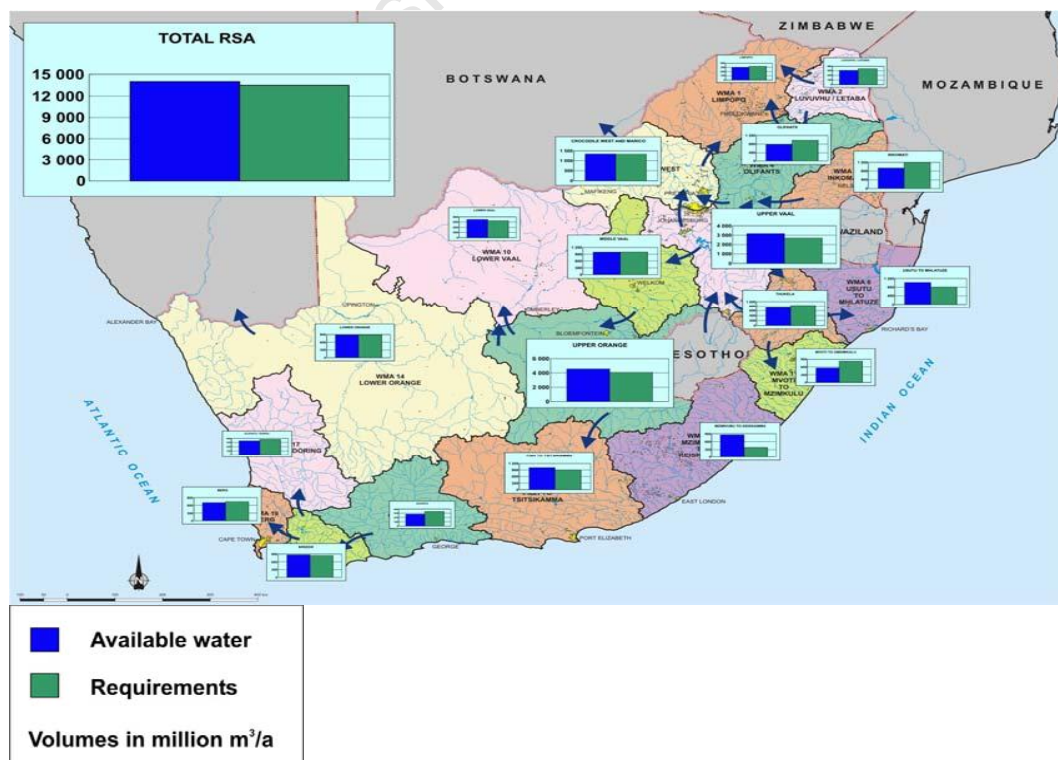
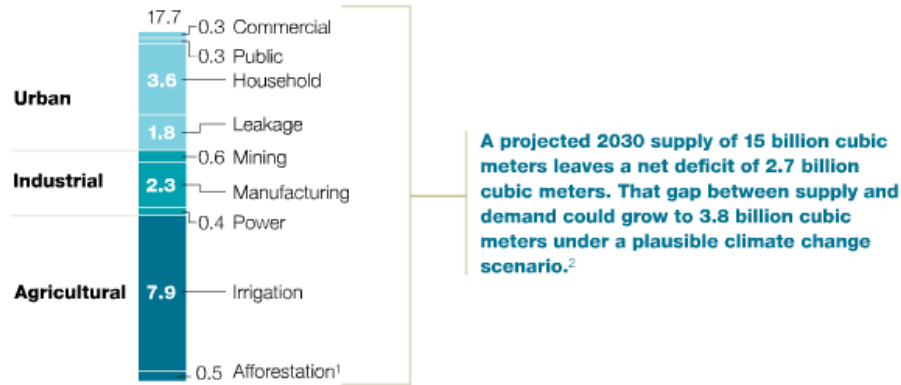


Figure 4: The 2030 water supply deficit (2030 WRG, 2010)

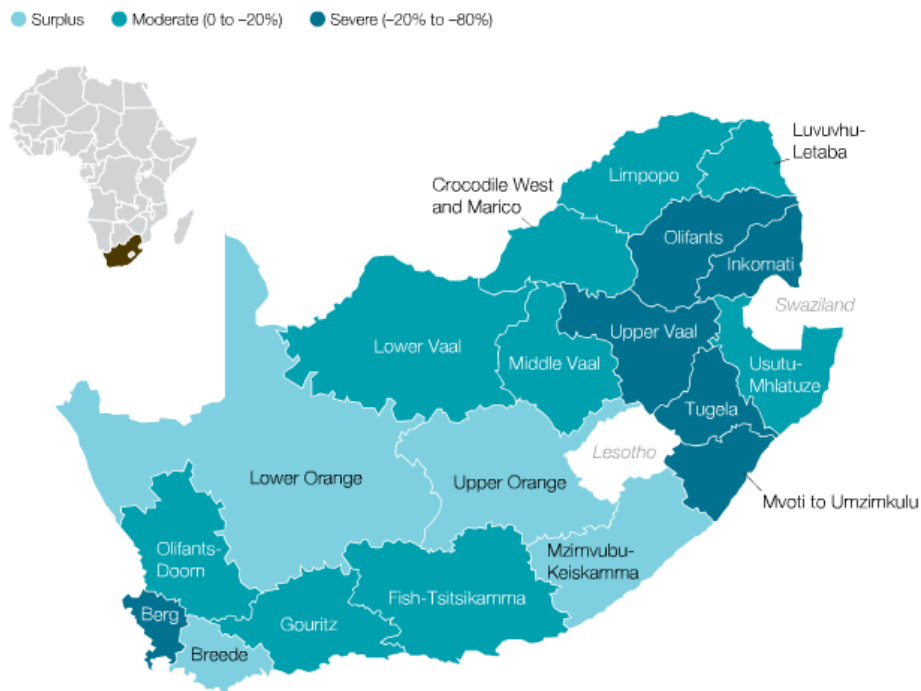
Estimated 2030 water demand, billion cubic meters



¹Afforestation is considered a demand, as it reduces the supply available for delivery to reservoirs and then to demand centers.
²Assumes yield of existing supply sources drops by 10%, effective rainfall drops by ~3%, and irrigation requirements increase by 10%, compared with today.

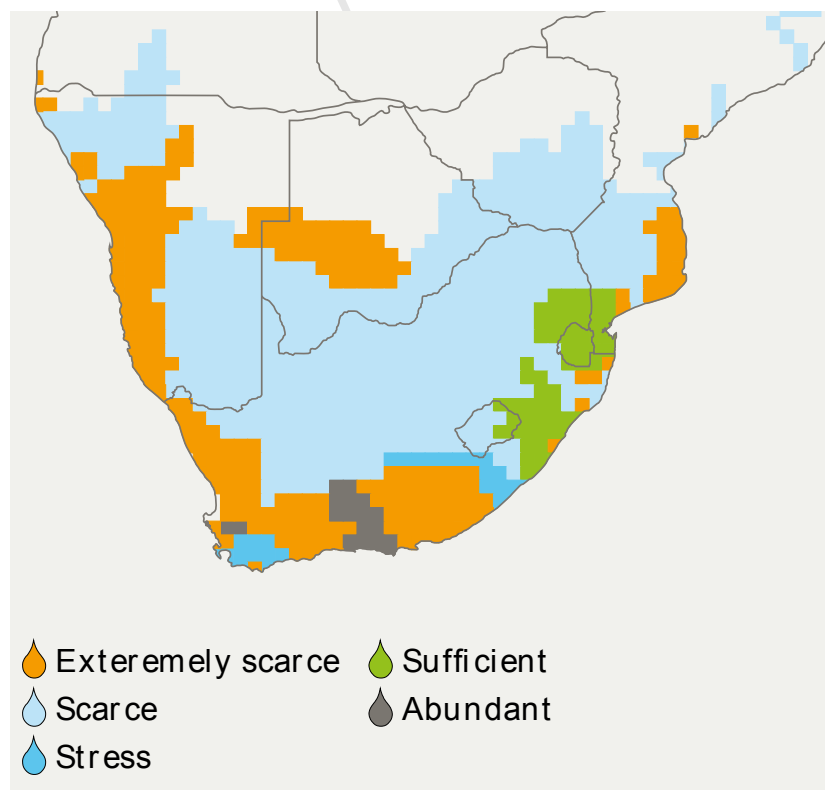
The report published by the 2030 WRG stated that their prediction for a water supply deficit was modelled conservatively according to current supply and demand variables, ignoring the possible effects that climate change and climate shifting may have on the country. Under a climate change scenario, a decrease in rainfall volumes and a subsequent increase in demand largely from the agricultural sector could increase the deficit to an overall 3.7 billion m³. The 2030 WRG research details those regions of the country that are likely to be affected by a surplus supply, moderate shortage and severe shortage, see Figure 3 (2030 WRG, 2010). Figure 4, taken from research completed by the WWF and SAB Miller, depicts similar water stress that has been projected by similar studies, and highlights the probable water stress along the coastal regions of the Western, Northern and Eastern Cape. From the two figures it is interesting to note the water resources available to the Northern Cape. Although the province hosts the Orange River and may have sufficient supply by capita, it does not have the infrastructure to freely distribute the resource to all in the province, and thus the “sufficient supply” description may in fact not be correct. This is depicted in Figure 4 where the coastal regions of the province are labelled as water scarce. An additional factor that contributes towards this scarcity is the harsh climatic conditions and strong solar irradiance that characterise the province.

Figure 5: The 2030 water supply deficit by water catchment region (2030 WRG, 2010)



¹Frozen irrigation levels and limited ability to increase rainfed land will drive an increase in virtual water trade between water-management areas and internationally with trading partners.

Figure 6: Annual water supply per person projected for 2025 (WWF and SAB Miller, 2010)



1.8.3 Water treatment and quality

Water quality is an additional stress affecting available water supply, as reports by the Department of Water Affairs and Forestry (DWAF) state that only 11% of the country's 283 municipalities have properly functioning water services that adhere to the required water standards. There is a continuous deterioration in the quality of water in rivers and dams, and the consequence is that in a growing number of locations the water quality is unfit for human consumption and is becoming more expensive due to the higher treatment costs required. In certain regions, in addition ecological damage is being caused (Segal, 2009).

Additionally, the debt owed to water boards is of sizable, as municipalities across the country owe water suppliers more than R1.2 billion (Water Rhapsody, 2010), of which more than half, is unsettled long-term debt. This highlights an issue that characterises municipalities, specifically their inability to collect water revenue, and the subsequent default of debt. This has further led to the lack of maintenance and investment in operations and infrastructure, which therefore yields the poor quality of the output. The most affected water service supplier is the Rand Water Board of Gauteng, which is owed R443.7 Million, largely due to poorer residents who inhabit the area which is further serviced by several municipalities. The inhabitants are known for illegal reconnection of disconnected services as well as tampering with pre-paid water meters. This affects the supplier's ability to operate as mandated, which is to collect all water in the area, purify it and deliver it where it is required. Reports by Service Publication Online are that the water situation in the country is worsening (Service Publication, 2010).

Several arguments have been raised as the reason for the poor state of water municipalities in the country, with the three most important being: the price of water is below economic cost and thus institutions have no way of being financial sustainable; there is a lack of skilled professionals to operate the infrastructure in place; and finally that the municipalities are incapable of over-seeing the responsibility required for managing these institutions.

1.8.4 The price of water

South African municipalities apply the block tariff pricing method to water tariffs. This aims to recover the revenue which covers the difference between the equitable share of government grants provided to them and the operation and maintenance costs incurred for the purchasing of raw water, infrastructure maintenance, quality enhancement and the delivery of the final water product to the users. The process of setting the appropriate tariff needs to take into consideration, such factors as social equity, financial sustainability and the recovery of costs, as well as the free water quota, water treatment and the uncontrolled volume of water that can be utilized. Thus, the applied framework to price setting needs to support the supply of water services and quantity to the poor, to discourage inefficient usage and to take into consideration the incremental cost required to increase and maintain the capacity of the water supply infrastructure (Gowlland-Gualtieri, 2007). Despite there being a pricing strategy in place, it is recorded that price information is spread via word of mouth with no central notice board giving the price to the public and this has led to price differentiation between buyers and sellers across the country (Grafton *et al.*, 2009; Niewoudt and Armitage, 2004).

Due to South Africa placing equity considerations as top priority through the NWA, 1998, and by making the right to water a constitutional right, the ability to ensure that there is some form of economic efficiency and sustainability with the recovery of adequate revenue seems a daunting task. Therefore, as recommendations are made for the water supply industry to become more economically efficient and transparent, sufficient regard needs to be given to the equity implications, and to understand that without the support and agreement of the impoverished and the political groups, a suitable pricing mechanism will be tough to implement (Grafton *et al.*, 2010).

Further confusion in tariff setting is that as the municipalities independently control their water tariff setting, prices differ and adjustment of prices year-on-year are at a different rate. However, these water tariffs are based upon the cost of the water that is supplied to municipalities by their water boards. In 2010, it was estimated that water boards across the country would be increasing their tariffs by between 6.2% and 43% (Water Rhapsody, 2010).

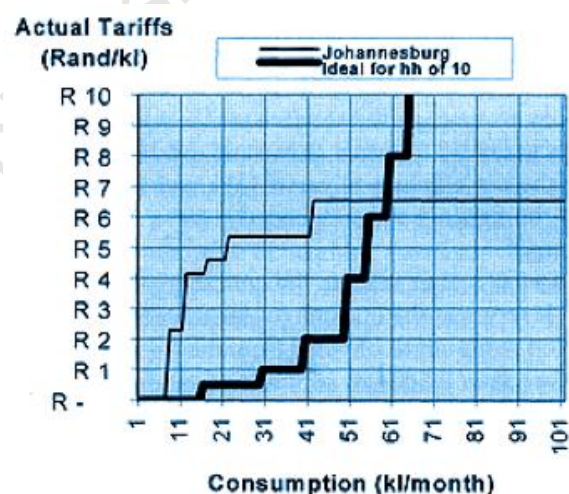
An extract of current prices, 2010, reported by different water boards for bulk water supply to municipalities are:

- Umgeni Water – R3.47 per kilolitre (increased by 6.2%);
- Namakwa – R9.11 per kilolitre (increased by 43%); and
- Rand Water – R3.97 per kilolitre (increased by 14.1%)

The above increases will have a dramatic effect on the costs that municipalities will pass on to households through block tariff price settings.

The subsidization of water and the FBW has a definite lifespan, and the consideration of a full cost pricing strategy will need to be addressed in the future. This is necessary as parallels may be drawn between the problems that caused the electricity crisis and those that may compound and precipitate a possible water crisis. The pricing strategy and tariff implemented will need to include considerations such as the need for investment in water infrastructure, encouragement of efficient usage and a policy that forces a ‘polluter pays principle’ in relation to waste discharge. These elements, coupled with an enforceable and transparent water policy, will significantly impact on the ability to better manage available water resources, for both economic and social good.

Figure 7: Water pricing strategies, Johannesburg (2001) vs. ideal tariff charges (Bond, 2010)



1.8.5 Water management and infrastructure

It is reported that the water infrastructure and maintenance backlog is large. The Department of Water Affairs released an estimate that no more than 20% of the necessary expenditure for maintenance has been made in the last 10-15 years (Segal, 2009).

In 2010, the then Minister of the Department of Water Affairs and Forestry, Buyelwa Sonjica, reportedly stated in her post-budget speech that the allocation of finances to her department was insufficient to avoid a water catastrophe in the country in the future. Furthermore she was recorded as saying *“Over R100 Billion is required in the next three years to erase the backlog in infrastructure maintenance and to construct new dams, with a further R60 Billion necessary to fix water services, which includes the treatment of sewage and the provision of safe drinking water.”* Of the required amount, the department only received R26.7 Billion to use until the 2012/13-budget year.

Considering that large water schemes can take up to 20 years to implement, possibilities of reusing treated effluent ground water and desalination technologies are only at early stages of planning. The issue of supply stress will be further exacerbated if there is not a consolidated effort by the Department of Water Affairs and their respective Water Catchment regions, to better manage both water supply and demand systems (Segal, 2009).

1.8.6 Domestic, Industrial and Agricultural requirements

The current available and accessible fresh water supply in South Africa is estimated (2010) at 15 billion m³ per annum and is reported as seriously constrained. The 2030 Water Resources Group (2030 WRG, 2010) cited the constraints to be due to low rainfall, limited underground fresh water stores, and a dependence on water transfers and run-off across provinces as well as the Lesotho and Mozambique border. In addition, they highlighted the shortcomings of over allocation to the agricultural sector, key industrial activities such as mining and power generation, and the country's expanding urban population.

According to 2005 data, agricultural, industrial and urban demands accounted for 8.4 billion m³ (62%), 1.5 billion m³ (11%) and 3.5 billion m³ (27%) respectively, and comprises more than 95% of what is currently referred to as available and reliable fresh water supply. Of this, 15% is sourced as groundwater (Potgieter, 2010). Groundwater is used in the agriculture sector, by 300 towns and over 65% of the country's rural population (2030 WRG, 2010).

An example of apparent misallocation of resources is the irrigation and agriculture sector that currently consumes approximately 64% of the country's available water supply. In addition, this sector uses sources of ground water that have not been taken into consideration, while contributing only an estimated 5% towards the nation's economic wealth. Furthermore, the average price charged to the agricultural sector is approximately R0.023 per m³, in 2000 Rand terms, whereas the average price paid in the trade and services sector is R12.00 per m³ and R1.19 per m³ in the domestic sector (Potgieter, 2010; Statistics SA, 2006). This clearly shows market imbalance, price inefficiency and a misallocation of resources that is not financially sustainable. However, this must be considered in context, as the benefits of the agriculture sector do spill over to other sectors in backward linkages with input supplies and service provision, and forward linkages through processing and marketing. Accumulatively this can provide an approximate benefit of 30% of the national GDP, rather than its real benefit of only 5% as originally envisioned (Backeberg, 2002). The elasticity of water, as well as its connection with agriculture and food supply, its requirement for human survival, and its necessity for industry indicates that if there is an increase in overall water prices, there will be a domino effect on prices of all output goods, that has water as an input factor. This could dramatically affect RSA's inflation rate.

The above argument raises the issue that the national water supply and demand needs to be understood holistically within a system, with better management across all provincial borders required, plus consideration of the characteristics of each province on both a regional and national perspective to be valued in isolation as well as overall.

2. Review

2.1 Conventional desalination plants

The focus of this chapter is to examine past experiences and the current trends in desalination technologies installed globally and in South Africa, the lessons learnt and the challenges that have been identified internationally when coupling desalination methods with renewable energy technologies. The review will identify the suitability of these pairings to South Africa and explore which pairings are better matched. Empirical data will be collected for use in the evaluation of the economics of desalination technologies and their coupling with renewable energy sources for comparison with conventional water supply techniques in South Africa.

2.1.1 The purpose of desalination plants

About three quarters of the earth's surface is covered by water, however only about 3% of this water is potable. Of this available potable water, 25% of the world's population does not have access to sufficient volumes, and approximately 80 countries face severe water deficits (Karagiannis *et al.*, 2007). Water scarcity is a well-researched subject, as most continents, nations and regions have suffered, at some time from a lack of an easily accessible, potable water supply. Desalination provides the answer that can address situations where insufficient water supply is available with the location of these regions either near the ocean or a source of brackish water. Desalination refers to the removal of dissolved salts from a water source - seawater or brackish - in order to produce water that is fit for human consumption or industrial use; this can be achieved either via thermal or membrane methods.

Desalination processes were first recorded in the 1930s, when California, a thriving state in the United States of America, was devastated by a drought that severely affected the water supply to the region. It was during this time that desalination was explored as a solution to water shortage and climate shifting, and by the 1940s, the USA was monitoring its water supplies and the means that could be exhausted in order to sustain a growing demand. Desalination was again explored in the 1950s, post-World War II, as countries began to recover and develop at a rapid pace, exhausting and putting strain on available water supplies. During this same period, countries in the Middle East adopted

the development that had been achieved by the West, and installed several desalination plants to assist in their development and to reduce the volumes of water that were being imported across borders (Delyannis *et al.*, 2010).

2.1.2 Desalination plant examples

There are two methods of desalination in operation: the thermal distillation (or thermal method) which uses heat to drive water phase change, simulating the natural evaporation and precipitation process common to the water cycle, and the membrane method which uses semi-permeable membranes to separate the salt solute from the potable product (Eltawil *et al.*, 2009). Membrane methods were not fully developed in the early exploration phase of desalination plants, and therefore thermal methods dominated the historical market as government engineers globally set about researching and developing different technologies to convert accessible sea-water into potable water. The distillation processes were widely adopted with the Multi-Effect Distillation (MED) and Multi-Effect Flash (MSF) processes being the most popular. Other processes that were explored during this time were: multi-vapour compression (MVC), thermal vapour compression (TVC), electro-dialysis (EDR) and water freezing. All these processes fell under the thermal method category and a main characteristic was the use of large amounts of energy, unless additional forms of energy, such as waste heat, could be used.

Only in the 1960s was demineralization by a semi-permeable membrane developed, which was then further developed in the early 1970s into the Reverse Osmosis method that is popular today (Delyannis *et al.*, 2010).

Through research and development, technologies have improved in both performance and size, resulting in the decrease in cost of equipment and materials, and the decrease in operating expenses through the further incorporation of energy and heat recovery systems. Hence the energy requirement has reduced through the development of improved systems. Additional factors that affect the cost include: the financial cost of the plant chosen, the cost of installation, the feed water quality or salinity levels, the size of the plant and the desired quantity of potable water, plus the energy infrastructure and electricity costs (Eltawil *et al.*, 2009). These all need to be considered within the context of the accessibility to a raw water source.

Figure 8: Global installed desalting capacity by process (Eltawil *et al.*, 2009)

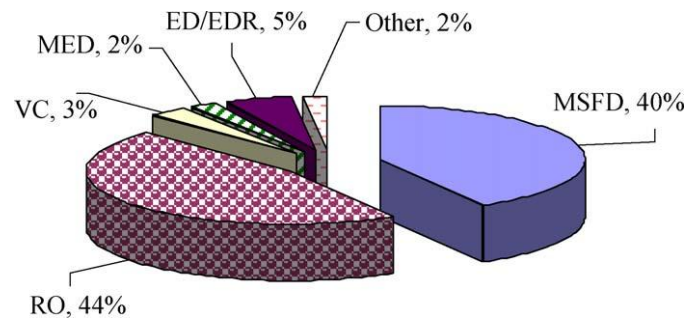


Figure 8 above, illustrates the global installed proportion of plants, where Multi-Stage Flash (MSF) and Reverse Osmosis (RO) processes, with 40% and 44% of the market respectively, are the dominant installed desalination plants. MSF processes are widely installed in the Middle East because of the abundance of liquid fuels and the cheaper energy costs. It is widely predicted that membrane processes will take market share from thermal desalination methods, as currently 59% of new build capacity is membrane based (Eltawil *et al.*, 2009). Much of the popularity of the membrane methods is due to their ability to produce large-scale water volumes. For example, the 45 Million m³ Capacity plants in Swakopmund, Namibia, and the 330 Million litres per day plant in Askelton, Israel, are both RO methods. These plants are large in scale and are able to assist with the provision of an essential resource for all domestic, industrial and agricultural users. This ability was previously limited to the thermal methods that dominated the large-scale production market.

All desalination technologies and methods, with their dependence on (amongst others) energy, cleaning solvents, the intake of sea water and the output of brine concentrate, will have a negative impact on the surrounding environmental systems, whether be it on land or through the return of the brine by-product into the ocean. Table 3 below, extracted from the Desalination guide for South African municipal engineers (2006), and gives an idea of the risks that each technology brings to the region where it is installed (du Plessis *et al.*, 2006).

Table 3: Potential environmental impacts of desalination processes (du Plessis *et al.*, 2006)

Desalination Technology	ENVIRONMENTAL IMPACT						
	Noise	Heat	Brine	Visual	Gas	Cleaning Solvents	Energy
MSF	Low Risk	High Risk	High Risk	Low Risk	Low Risk	High Risk	High Risk
MED	Low Risk	High Risk	High Risk	Low Risk	Low Risk	High Risk	High Risk
VC	Low Risk	High Risk	High Risk	Low Risk	Low Risk	High Risk	High Risk
RO	High Risk	No Risk	High Risk	Low Risk	No Risk	High Risk	High Risk
NF/UF	No Risk	No Risk	High Risk	Low Risk	No Risk	High Risk	High Risk
EDR	No Risk	No Risk	High Risk	Low Risk	Low Risk	High Risk	High Risk
Solar Distillation	No Risk	No Risk	High Risk	Low Risk	No Risk	Low Risk	No Risk

Notes: All Brackwater desalination options will have a risk of over exploitation of the water resources. Environmental aspects only refer to operational aspects. Construction will have a number of different possible environmental risks.

High Risk 
 Low Risk 
 No Risk 

As illustrated above in table 3, the process with the least effect on the environment is Solar Distillation, a method of utilizing solar thermal energy to convert seawater into potable water. The disposal of brine, as seen in the table above, is a major issue, as the brine by-product reaches on average a concentration of 1.7 times that of the seawater originally used and may also contain traces of heavy metals or chemical solvents. The preferred treatment is to pump the brine solution back into the sea; however site-specific limitations like currents and wave action have an impact on the dispersion of the brine. The brine concentrate, due to its high salt content, is denser than seawater thus sinking on entering the sea if not dispersed quickly. This potentially will affect all marine life that it comes into contact with. Other methods of treating the brine by-product include harvesting the salt or dispersing the brine via the dunes, however the latter method is not recommended as flora in dunes is highly sensitive and the increase in salt content could have a detrimental effect. Unfortunately, due to the corrosive effect of seawater, the chemical reaction with heavy metals and the resulting traces of heavy metals in the discharge is inevitable; further development is being carried out to identify the ideal materials to reduce these traces in the discharge process (du Plessis *et al.*, 2006).

A characteristic of all desalination technologies is that they are expensive and require initial capital investment, and a constant supply of energy. The investment costs for small-scale initiatives are especially expensive as they do not benefit from the economies of scale that large-scale projects have. For most plants already in operation, energy is supplied using conventional fossil fuels. The use of fossil fuels causes additional damage to the environment, mainly through the release of damaging greenhouse gasses and excess heat, a problem that could be addressed through the use of renewable energy technologies.

2.1.3 Desalination development in South Africa

The desalination industry in South Africa is divided between public and privately run operations. There are 13 public sea-water desalination plants currently in operation, with the latest installation being in Sedgefield on the Garden Route. See the complete list in Table 4. Several privately run plants are also in operation and are used to treat brackish water for industrial use or to address the poor quality of water that is the result of mining practices, e.g. Eskom across its power stations, Sasol in Secunda and Emalahleni Water Reclamation Project in Witbank (McGrath, 2010). The total number of privately operated desalination plants is unknown, but it is speculated that there are several units installed on farms and in privately run businesses.

Table 4: Public desalination plants in South Africa (du Plessis *et al.*, 2006)

Desalination Plant	Owner/Water Authority	Supply	Capacity (m ³ /h)/Plant Age	Number of persons supplied	Raw Water
Sedgefield	Gouritz Municipality		62.5/1	-	-
Robben Island	Cape Metropolitan Council		20/8 years	-	-
Bushman's River Mouth	Albany Water Board		71/8	20,000	35,000
Rietpoort	West Coast District Municipality		1.8/-	1,000	2,500
Kheis	Kamiesberg Municipality		1.6/6	450	5,000 - 15,000
Lepelfontein	Kamiesberg Municipality		1.6/6	370	5,000 - 15,000
Klipfontein	Kamiesberg Municipality		1.6/6	469	5,000 - 15,000
Spoegrivier	Kamiesberg Municipality		1.6/6	457	5,000 - 15,000
Soebatsfontein	Kamiesberg Municipality		1.6/6	241	5,000 - 15,000
Bitterfontein	West Coast District Municipality		12 (upgraded to 38)/13 years	5,000	5,000
Plettenberg Bay	Bitou Municipality		83/1	-	-
Mossel Bay	Mossel Bay Municipality		200*/1	-	-
Knysna	Knysna Municipality		83/1	-	-

* Mossel Bay is presently constructing the largest desalination plant in South Africa today, a 15 Million Litre a day plant, with the first 5 Million Litres phase completed, and the remaining capacity to be completed in 2011 (Engineering News, 2010).

The latest installation, the 1.5 mega litres per day Reverse Osmosis plant installed at a cost of R16 million in Sedgefield is already in operation and filling the regions once dry reservoirs. The installation of this plant has been surrounded with controversy. Firstly, as the plant was built during the 2008/9 water crisis in response to the region's emergency, and secondly, as the plant has yet - as of January 2011 -to receive government and environmental approval. The possibility of fines, expenses relating to Environmental Impact Assessments and additional unknown costs could result in significant increases to the total cost of the plant. The plant is only utilized when

required, specifically during the summer months when tourists increase the demand for water in the town (Nay, 2010), with estimates of approximately R3/m³. However the response from the community is positive as the infrastructure provides security to the region as well as agricultural opportunities.

Additional plants have been planned along the Garden Route, specifically for the regions of George, Bitou, Plettenberg Bay and Knysna, as well as for Cape Town and Port Elizabeth. It is envisioned that Cape Town will experience a water shortage in the next four years and will need to utilize water demand management or desalination technology for relief. Currently, the Kenton-on-Sea desalination plant is in the process of refurbishment and the size will be increased to a capacity of 1,800 m³ per day (Service Publication, 2010).

With South Africa benefiting from international research and development, improvements in technology have meant that potable water can be produced at an average of R3/m³, quoted as the cost for investment and operation for the new Sedgefield plant by the technology providers Grahamtex Systems (McGrath, 2010). DWAF estimates the cost of desalination, including both capital redemption and operational costs in the region of between R5 and R8 per m³ (du Plessis *et al.*, 2006), differing according to East and West coast respectively. In comparison, the cost of conventional treatment can range between R1 and R3.50 per m³ (ignoring the raw cost of water) at present, meaning that potable water from desalination is competitive with traditional municipal water in certain instances. See Table 5 for a comparison of these costs as calculated by the City of Cape Town.

Table 5: Water costs for desalination and conventional plants⁵ (du Plessis *et al.*, 2006)

Treatment System		Water production cost (R/kl)	Notes
Conventional water treatment	Amatola Water (For 14 water treatment plants)	3.39	Cost includes purchase of raw water.
	Rand Water (For 6 large water treatment plants, treating a total of 5 260 MI/d)	2.53	Conventional water treatment plants. Cost includes purchase of raw water.
	City of Cape Town (various plants)	1.05 – 1.25	Including raw water cost which includes the new Berg Water project and excludes bulk management and conveyance.
	Midvaal (250 MI/d treatment plant)	2.52	Treatment plant includes ozonation and dissolved air flotation for treating eutrophied water. Cost includes R 1.52/kl for purchase of raw water, excluding capital redemption (2004).
	Withoogte (72 MI/d treatment plant)	1.04	Conventional water treatment plant. Cost includes purchase of raw water. Only small portion of capital redemption remains.
Desalination plants	Bitterfontein (12 m ³ /h RO groundwater desalination plant)	7.81	Relative high cost for management functions and transport due to remote location of the RO plant.
	Boesmanskloof (45 m ³ /h RO seawater desalination plant)	2.26	Cost includes electricity, labour, membrane replacement (every 5 years) and pump maintenance, but excludes capital redemption.
	Costing model (15 m ³ /h RO groundwater desalination plant)	5.30 – 9.40	Range is for low TDS (2 000 mg/l)(lower cost) and high TDS (12 000 mg/l)(higher cost)
	Costing model (5 MI/d RO groundwater desalination plant)	2.40 – 4.90	Range is for low TDS (2 000 mg/l)(lower cost) and high TDS (12 000 mg/l)(higher cost)
	Costing model (5 MI/d RO seawater desalination plant)	5.80 – 8.30	Range is for East Coast water (lowest cost), South Coast water and West Coast water (highest cost)

In addition to the competitive costs for potable water, desalination plants are further favoured due to their ability to be scaled-up in size if required. Furthermore, with its modular ability, plants can be built in stages according to the limited finances available to municipalities. However, public outcry over water price increases and the environmental impact of the brine effluent discharged from desalination plants has acted as local deterrents against the uptake and promotion of the technology (SA Delivery Online, 2010).

With regard to technology, South African engineers favour the membrane method of Reverse Osmosis above other options. The reason for this as provided in the

⁵The information provided in the table relates to 2006 costs and does not take the recent quotes of the Sedgefield desalination plant into consideration

Desalination guide for South African Municipal Engineers, 2006, is that thermal methods require either large amounts of waste heat or cheap fuel in order to generate the heat that is necessary to assist the thermal process (du Plessis *et al.*, 2006). Although RSA was historically known for its relatively low electricity costs, excessive waste heat is not easily accessible and is not cheap to produce. There is a probability that in due time with the expansion in generation capacity from nuclear energy, excessive heat, which is a by-product of the energy production process could be utilised by the thermal methods of desalination. The proposed location of a nuclear plant is alongside the ocean, thus it makes logical sense to couple the nuclear plant with an appropriate desalination technology. Furthermore, through the use of concentrated solar power, the heat generated can be used to vapourize, distil or heat sea-water, instead of generating electricity.

An additional factor for South Africans to consider is the rising costs of electricity as charged by Eskom and municipalities. Electricity expenses can increase to more than 50% of the total operating costs for producing potable water using the thermal distillation methods. In comparison, the membrane method uses less electricity and thus may be a cheaper process for running a desalination plant (Eltawil *et al.*, 2009; du Plessis *et al.*, 2006). This rationale is supported by the most recent installations of desalination plants globally favour Reverse Osmosis membrane technology, particularly: a detailed feasibility research completed by NamWater for a RO plant at Swakopmund; an in-depth analysis by the municipality of Perth, Australia; a RO plant is being considered in Sydney, Australia; the largest desalination plant in the world has recently been installed in Ashkelon, Israel and all the existing plants in South Africa (du Plessis *et al.*, 2006).

2.2 RE-D pairings

As stated previously, the desalination process requires large amounts of energy, either in the form of waste heat or grid electricity. If conventional grid electricity sources are used to power desalination plants, the burning of fossil fuels will contribute towards the release of greenhouse gasses, so the production of desalinated water will adversely affect climate change if the end product allocation of greenhouse gasses is adopted. This, together with the effect of greenhouse gasses on the water cycle – where a changing climate can result in increased temperatures and/or decreased rainfall – can lead to

severe drought and water shortages, the very problems that the desalination process has been designed to address. In addition, the financial impact of rising fossil fuel costs – such as coal and diesel – will increase the cost of the electricity needed to run the plants.

For the above reasons, as well as the fact that society is evolving to become more environmentally conscious, it is necessary to use clean energy generation technologies to meet *all*, or at least a portion of, the power that desalination plants require. Research and Development conducted over the past decades have assisted the scientific, engineering and development communities in optimising renewable energy and desalination technology combinations. The focus here has been on harnessing the potential that certain by-products of renewable energy technologies – namely thermal energy, electricity and shaft power – can bring to assist with the powering of these technologies.

In this chapter, an introduction to the most widely used and popular combinations of renewable energy powered desalination methods will be provided, grouped by the renewable energy type. This work comes from an assortment of studies, with the most important being the ProDes Project, which is based on the work of the project ADURES (Autonomous Desalination Units powered by Renewable Energy Sources), an updated collection of information on installed renewable energy desalination (RE-D) plants completed between 2009 and 2010. Between 1974 and 2009, an estimated 131 RE-D combinations have been installed, some as pilot installations that are no longer operational, but others are still providing drinking water to communities. Figure 9 illustrates the most popular RE-D combinations, showing that Photovoltaic and Reverse Osmosis, comprising 32% of the total installed combinations, is the most popular pairing, with wind and RO next with 19% and Solar MED with 16%. This is understandable considering that solar energy, in the form of PV, is a well-known technology type and has been in existence for some time. The technology is continuously evolving with improvement in efficiency and costs being the highlights to date. Solar radiation compared with wind energy is more common within areas of water supply deficits, making it a more suitable mitigatory solution. In a similar vein, desalination by Reverse Osmosis is the technology of choice, as shown earlier. A lot is known about the technology and its progression in energy efficiency, and thus as a desalination technology choice it is a suitable match (PRODES, 2009).

The remaining pairings can be seen in figure 10, where engineers - through research and development, understanding the ability and limitations of the technologies, and through testing on pilot sites - have combined renewable sources with desalination units. The suitability of combining a renewable energy source with a desalination plant is dependent on both the energy requirements of the desalination technology and the ability of the energy source.

Figure 9: RE-D rankings according to accumulative installation (ProDes, 2009)

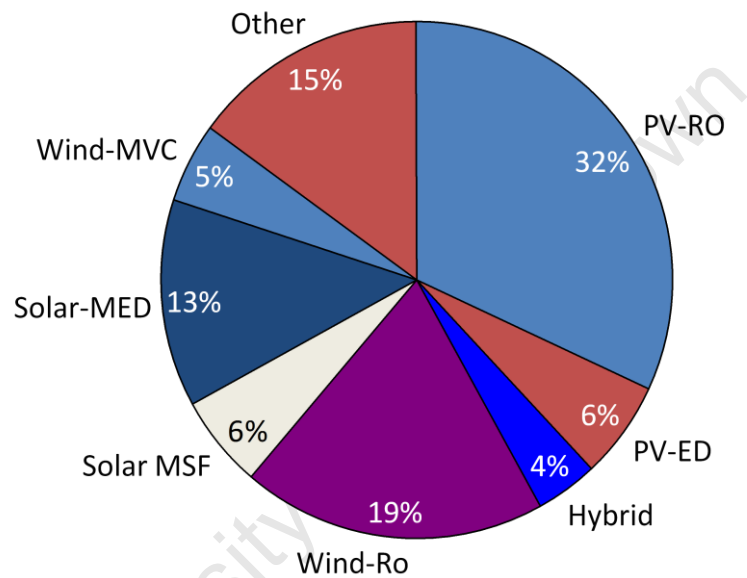
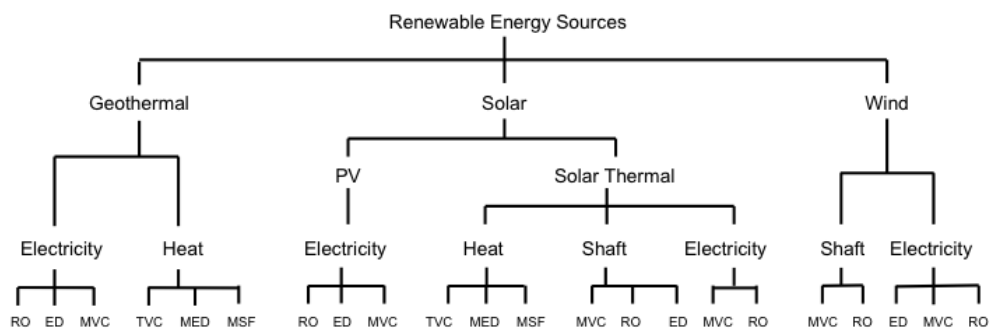


Figure 10: RE Sources and Desalination technology combinations (Inco Programme, 2005)



New combinations such as solar freezing, forward osmosis and vacuum distillation which are all interesting concepts have been left out of the research scope, whereas geothermal energy, a form of energy not common in South Africa, has been included due to its similarity as a source of energy from waste heat, from either nuclear or CSP energy.

2.2.1 Overview

Renewable energy represents the best energy source for desalination plants in areas that are arid or have windy climates, and where conventional energy supply and water infrastructure is not available. The benefit of both technologies is that renewable energy provides energy diversification and decentralisation where the economics of extending the grid infrastructure are not feasible, with a similar argument for desalination plants along the coast or inland. The convergence of economics as renewable energy costs decrease and fossil fuel prices increase, with the additional pressure of pricing in the environmental effects caused by fossil fuels, means that in due time, renewable energy costs could be equal to if not cheaper than conventional fuels (Eltawil *et al.*, 2009).

The market split, as can be seen in Figure 9 above and below in Table 6, is dominated by Solar Photovoltaic (PV) and thermal energy technologies, with 43% and 27% respectively, being accumulatively 70% of the RE technologies installed. The membrane method of Reverse Osmosis is the dominant desalination technology with 62% of the market, as seen in table 7.

Table 6: RE sources for desalination technologies (Papadakis *et al.*, 2007)

Renewable Energy Type	Market Share %
Solar PV	43
Solar Thermal	27
Wind	20
Hybrid	10

Table 7: Desalination processes used in conjunction with RE (Papadakis *et al.*, 2007)

Desalination Technology	Market Share %
Reverse Osmosis	62
Electro-dialysis	5
Multi-Stage Flash	10
Multi-Effect Distillation	14
Vapour Compression	5
Other	5
Total	100.0

There are clear advantages for the installation of renewable energy desalination systems, which at present contribute only 0.02% of the global installed desalination capacity. There are four main reasons for the low level of implementation (adapted from Eltawil *et al.*, 2009):

- i.) Availability – the compatibility of sufficient renewable energy sources and the occurrence of water stress in the same geographical location;
- ii.) Costs – even though costs are decreasing, initial capital installation costs are still expensive and are hampering the commercialization of the system;
- iii.) Technologies – the ideal combination of renewable energy source and desalination technology is not yet known, as the optimum combination is dependent on a number of factors, especially the desired volume of output; and
- iv.) Sustainability – in most cases, the maturity of the desired technologies do not match the low level infrastructures that can characterise the geographical regions experiencing water stress, as current reports show that operations generally fail due to the lack of reliable technical support.

Thus, matching renewable energy sources with desalination plants requires a number of important, local factors to be considered, such as:

- Geographical conditions;
- Topography of the identified site;
- Capacity and type of energy available and the cost;
- Availability of local infrastructures (electricity and water) and skills;
- Renewable energy possibilities;
- Desired plant size and volume output required; and
- The feed water salinity and temperature (Eltawil *et al.*, 2009).

The below table, Table 8, provides a comparison on the combinations of renewable energy sources with desalination technologies, and the output that is most likely to be achieved. It is interesting to note that renewable energy powered Reverse Osmosis plants are not able to provide large scale water quantities, compared with MED and MSF methods, yet RO plants using conventional energy are producing the greatest quantities of water when compared per unit.

Table 8: Recommended RES-Desalination combinations by volume (Inco Programme, 2005)

Water output	Water input	System Size	Small (1-50 m ³ /d)	Medium (50-250 m ³ /d)	Large (>250 m ³ /d)
Potable	Brackish Water	Conventional Energy + RO, ED	*	*	*
Distillate		Solar Distillation	*		
Potable		PV - RO	*		
		PV - ED	*		
		Wind - RO	*	*	
		Wind - ED	*	*	
Potable	Sea Water	Conventional Energy + RO, ED, MSF, VC, MED	*	*	*
Distillate		Solar Distillation	*		
Potable		PV - RO	*		
		PV - ED	*		
		Wind - RO	*	*	
		Wind - ED	*	*	
		Wind - VC		*	*
		Distillate	Solar Thermal - MED		*
Solar Thermal - MSF					*
Geothermal - MED				*	*
Geothermal - MSF					*

In the most recent international desalination studies, which have analysed energy requirements and output costs for membrane methods, one gets a clear understanding of the operational expenses that are expected if the direct energy requirement and the

source and cost of that energy is known. This concept will be applied in the methodology as the experience from international projects, where energy requirements are known, will be applied to current South African energy costs, forecasts and renewable energy comparisons. Tables 9, provides the energy requirements of the most popular desalination and renewable energy combinations.

Table 9: Percentage distribution of cost factors for Reverse Osmosis (Eltawil *et al.*, 2009)

	Brackish water (%)	Seawater (%)
Fixed costs	54	37
Electric power	11	44
Labor	9	4
Membrane-replacement	7	5
Maintenance and parts	9	7
Consumables (chemicals)	10	3

2.2.2 Solar Thermal Energy

Solar energy, in the form of heat from the sun, has been harnessed by humans in the form of photovoltaic panels and solar thermal collectors. This development has its foundation in lessons learnt from the environment, where solar energy is used, amongst others, to drive the process of photosynthesis and the water cycle. Humans, due to our dependence on water as a source of life, have succeeded in duplicating the water cycle by harnessing solar energy in either directly - in the case of using solar stills - or indirectly by using solar thermal collectors connected to desalination plants (PRODES, 2009).

i. Solar Stills/Solar Distillation (SD)

The solar still is a low-tech method to distil⁶ water that is powered by the heat of the sun. The method is old in concept and is not extremely popular due to the requirement of large areas of land to produce a relatively small volume of potable water, and is not as successful with the more saline water input (PRODES, 2009). This is a concern for coastal regions on the west of South Africa as the cold Atlantic Ocean is known for its

⁶The evaporation and subsequent collection of a liquid by condensation as a means of purification

'salty' or saline waters. Solar stills are popular in the Middle East where well-designed units produce between 1.5 and 4 litres per m² per day.

The 'greenhouse' design of a solar still allows for simple operation and minimal maintenance. The process is as follows: The transparent exterior of a solar still (a triangular shaped tube) allows short-wave solar radiation to pass through and the heat is then absorbed by a black surface that is in contact with the saline water. Due to the contact with the black surface, the water is heated which brings upon evaporation, beginning the process of distillation. The transparent covering prevents the water vapour from evaporating, causing the vapour to condense on its surface because of the difference in temperatures between the interior and exterior. The cool air of the exterior decreases the temperature of the surface on which the vapour condenses, causing the vapour to turn into droplets, running down the surface to be collected in a groove at the base of the still (PRODES, 2009).

Methods to increase the productivity of stills include altering the configurations by adding multiple basins that have two or more compartments. This allows for the recovery of latent heat that is transferred to warm up the water in an upper compartment. Further improvements in productivity can be achieved by including a heat exchanger powered by a flat plate solar collector. An example of this has been seen in the Solar-Institut Julich in Gran Canaria where a heat recovery system was included with multiple effect basin stills. Recordings show a production of 15-18 litres of water per m² per day, a conservative increase of 350% due to the addition of a heat recovery system. One of the biggest solar still plants installed is on the island of Patmos in Greece. The plant covers an area of 8,640 m², and desalinates seawater (low saline quality) at a rate of 26 m³ per day (or 3 litres per m² per day) (PRODES, 2009).

The potential for this technology is to identify improvements in absorber materials and at cheaper costs. Its opportunities for use seem limited to situations where small amounts of water are required, and appears suitable for self-sustaining domestic or small agricultural use.

ii. Multiple Effect Humidification (MEH)

The graduation from solar stills is the improved efficiency of the Multiple Effect Humidification method. The MEH system uses the heat from highly efficient solar

thermal collectors, where multiple evaporation and condensation cycles occur inside isolated, steam-tight thermal containers, to separate water vapour and concentrated salt solutions. The improved process of regaining energy used for initial evaporation is used in subsequent cycles of evaporation and condensation. This recycling reduces the total amount of thermal energy required for the desalination process and increases the overall productivity rate. An installation in Jeddah, Saudi Arabia, shows that a MEH coupled with Solar PV using brackish water can produce 20-30 litres per m² per day on average (PRODES, 2009).

iii. Membrane distillation (MD)

Membrane distillation combines the thermal distillation basics of the solar stills and MEH methods where the thermal energy increases the vapour pressure on one side of a membrane, with a selective membrane separation process which acts as a valve opening when the vapour pressure accumulated is sufficient to permeate the membrane. The membrane only allows vapour to permeate it, and not water, thus it is effective in separating the distillate from the remaining solution. The system is able to be stand-alone and can operate using either solar or waste heat. The material used for the membrane is less sensitive to that used for the Reverse Osmosis membranes and more favourable towards intermittent energy supply, resulting in a decrease of incidents where bio fouling and scaling occur. In addition it does not need to be fixed to any structure, making it movable (PRODES, 2009).

The largest MD systems reported by PRODES (2009) are found in Singapore and Netherlands, where using flat plate type modules, between 50-80 m³ per day can be generated.

iv. Multiple Effect Distillation (MED)

The MED process has been in existence since the late 1950s and is an evolution of the original solar still system. The MED system occurs in a series of vessels where evaporation and condensation occur at reduced pressures. The reduction in vessel pressures simultaneously decreases the boiling point of water, allowing for a self-sustaining heat recovery and transfer system. This process will continue for as many vessels as there are connected, but studies show that the efficiency gain is limited to

between 15-20 vessels, however development in process configuration could extend the amount of vessels connected and increase productivity (PRODES, 2009).

An example of this system exists in Almeira, Spain, where a pilot solar, seawater sourced MED system using 14 vessels, is used to generate power using the solar thermal energy method, specifically Compound Parabolic Collectors (CPC). The capacity of the plant was 72m³ per day and was located on 500m² of land, effectively 144 litres per m² per day. The system is not movable due to the structure of the solar collectors, and the operation and maintenance is deemed to be highly reliable with no problems observed during tests (PRODES, 2009).

2.2.3 Concentrated Solar Power

The previous sub-chapter describes systems that are relatively small in scale. On the contrary, the possibilities that Concentrated Solar Power (CSP) and its ability to generate energy on the Megawatt (MW) scale open up the opportunity for larger quantities of potable water generating potential. The four main CSP technology types are: central receiver, parabolic trough, parabolic dish and linear Fresnel, all of which function using reflective glass mirrors that track the daily position of the sun to attain the desired concentration ratio. The tracking mirrors divert solar energy to a concentrated source where it is transferred to a power cycle. The pressure generated from high-pressure steam is directed to a turbine that drives a conventional power cycle able to be used for power production. Globally, a total of 180 MW of CSP is currently installed, with 1,500 MW in the pipeline. Energy technology projections propose that CSP should contribute 14% of the global electricity demand by 2025 and 57% by 2050 at an estimated cost of 8-15⁷ eurocents per kWh (Greenpeace International, 2011). South Africa is proposing CSP to contribute a minimum of 100 MW in the next two years through Eskom's Upington project, based in the Northern Cape.

Because of CSP's ability to generate both electricity and heat, several configurations are possible, specifically: Multi-stage flash and MED are able to utilize the heat from the steam generated and Reverse Osmosis units powered by the electricity generated.

⁷ Equivalent of R0.80 – R1.50 in 2010 terms (EURZAR exchange rate is R10)

A disadvantage in the design of CSP technologies is that they require large amounts of fresh water themselves to sustain operation, specifically cooling and cleaning the mirrors, with the result that by coupling desalination units, a portion of the output will be used by the technology to continue operations. This pairing will assist with the technology becoming more self-sustainable. A design to assist this necessity is the inclusion of an MED system, where the waste heat in the form of steam can be the drive to facilitate distillation. Whether the purpose of the CSP is to drive a desalination plant or to generate electricity, this system will assist in reducing the operational costs of running a CSP plant. PSA CIEMAT, the Spanish Ministry of Science and Technology are researching this concept and as yet have not released the results from pilot projects (PRODES, 2009).

i. Multi Stage Flash (MSF)

The Multi Stage Flash (MSF) method has been in operation since the 1950s and is the process that incorporates the evaporation and condensation of water and water vapour through several chambers. Similar to the MED method, the MSF process of progressively moving through the chambers occurs at a diminishing pressure point. The distinguishing aspect is that the feed water enters the first chamber at a temperature above all previous methods, at 120 degrees centigrade, due to the steam extracted under high pressure from the CSP turbine (PRODES, 2009).

The term 'flash' is derived from the effect that the steam has on the saline solution which when coming into contact with another, the steam causes the saline water to immediately evaporate in a 'flash' like fashion. The steam continuously feeds subsequent chambers, resulting in further 'flashing' as the pressure of the chambers becomes progressively lower. Due to the heat exchanger tubes that pass through each chamber with cool water, the chambers are cooled and condensation occurs, allowing for the potable product water to feed into the next chamber, becoming progressively purer as it moves through the process. Some plants have between 15 and 25 chambers, and the quality of the feed water will determine whether the final product is fed through the process once or twice (PRODES, 2009).

PRODES reports that during the 1980s the testing of MSF methods began and several pilot combinations were commissioned. Surprisingly little knowledge of the results is

available in the public arena outside of the speculation that this combination could have the potential of producing over 5,000 m³ per day (PRODES, 2009).

2.2.4 Solar Photovoltaic

i. Photovoltaic driven Reverse Osmosis (PV RO)

The method of combining solar photovoltaic (PV) fields with a Reverse Osmosis (RO) plant is similar to the previous MSP-CSP combination where electricity is the primary energy source driving the system. The design of the system is such that the PV fields will generate electricity, requiring a DC/AC converter to convert the power generated into a usable form. The RO membrane used differs from the membrane used in the MD method as salt water rather than vapour is pressurised against a membrane, allowing water to pass and preventing any salt particles from permeating the barrier. The success of pilot studies has resulted in the commissioning of systems as stand-alone structures in rural areas in developing countries, e.g. Tunisia, Morocco and other Mediterranean countries. However the negatives of the RO method - and in particular, the diminishing effect that intermittent energy has on the membrane useful life - prevents the system from being self-sustainable, as a suitable amount of training is required to carry out maintenance. A solution to the intermittent energy is to have PV systems supported by battery systems to assist with continuous energy provision once the sun has set. An additional hurdle is the large amount of space required for PV fields, and the scaling necessary to generate a sufficient quantity of power (PRODES, 2009).

The relative maturity of the individual technologies and the quality and reliability of the end product have propelled this pairing into popularity. Its ability to operate as a stand-alone system allows for it to be favoured as a means of providing potable water to hard-to-reach communities in developing countries, regardless of its ability to compete economically with other more conventional methods of water provision. With the progression of solar PV research and development and the ability to improve the efficiency in energy conversion with the improvement that configuration management can have, the economic limitations of the pairing is expected to decrease over the coming years (rather than decades)(PRODES, 2009).

ii. Photovoltaic driven Electrodialysis (PV EDR)

The process of electrodialysis is used to transport salt ions from one solution through an ion-exchange membrane to another solution under the influence of an applied electric potential difference. The chemical makeup of seawater is such that it contains salt ions that are either of a positive or negative charge. The membranes used are of an equivalent charge, meaning that they will only allow specific cations or anions to transfer through them. Applied to the process of desalination, differently charged membranes are installed alternately. This process aids with the process of transferring only fresh water through the membrane and containing the salt water. The benefit of the EDR system is that no inverter is needed, reducing the amount of energy that is lost through conversion (PRODES, 2009).

PRODES cites that few examples of the PV EDR pairing exist due to the limitation on the scaling of the required EDR units; thus only pilot plants for research and development purposes are in operation. In addition, the process of EDR is such that only brackish or low saline quality can be used as a source of feed water, inhibiting the sea-water sources that characterise the coastal regions of South Africa. However, this may be a viable technology for off-grid areas inland.

2.2.5 Wind Energy

When compared to solar energy, far fewer wind energy pairings with desalination plants are in existence. However, for those wind energy desalination pairings that are in operation, the area characteristics are remote, windy areas, specifically islands. Where the coupling of wind energy and desalination units has been trialed, the desalination technology of choice has either been powered by electricity or by the mechanical energy generated by the turbines.

i. Wind-driven Reverse Osmosis (Wind RO)

Where wind energy is converted into electrical energy to power desalination plants, buffer and battery packs are necessary to address the issue of power supply stability. The pairing of wind energy and RO is similar to that of solar RO, where the electrical energy is used to power the RO plant. The fluctuating range of power generated by wind turbines requires a smoothing mechanism or control system that balances the amount

of power supplied to power the RO plant and transfers the excess power to a powering system that will charge the supporting battery packs.

The Canary Islands tested a seawater RO plant (8 x 25 m³ per day) with 2 stand-alone wind turbines (230 kW), the results of which showed a product of 8 m³ per hour, whilst using a double control system that assisted with the load management of the wind generators to continuously balance the flow of power (PRODES, 2009).

2.2.6 Geothermal

Geothermal energy was described at the beginning of this chapter as an energy source which was not readily available in South Africa, however useful due to its characteristics being similar to excess or latent heat given off by industrial activities or nuclear power plants. Geothermal energy exists in different forms, either in the form of heat or steam, or as thermal energy which can be converted into shaft power or electricity.

The first desalination plant powered by geothermal energy was constructed in the USA in 1972, and since then several more have been commissioned specifically in Tunisia, France and in Greece. In 1990 a sea water MED powered by geothermal energy at a temperature of 61 degrees centigrade was commissioned for the Kimolos Island in Greece. Results show that the plant produces 80 m³ per day (PRODES, 2009).

Considering the potential that geothermal energy offers, thermal distillation techniques have been identified as the method of choice for future geothermal desalination plants (PRODES, 2009). The relevance of this in the South African context is that in the event that waste heat is being generated in coastal regions or areas with a brackish water supply, thermal distillation methods should be considered as a means to utilize the waste heat and generate a by-product of value.

2.2.7 Ocean Power

- i. Wave driven RO and MVC

The combination of ocean power through wave or tidal movements is the most logical pairing with desalination plants as the source of both energy and water are available in abundance and at the same location. However, technologies have not been developed and are still in their prototype phase. The details of the prototypes are based on RO as the desalination technology of choice, as wave power can either generate electricity or be used directly by the action of the waves where seawater becomes pressurized. A MVC prototype has been proposed but as yet no pilot plant has been commissioned (PRODES, 2009).

PRODES assume it is probable that potable water from wave driven RO systems can produce 500-5000 m³ per day, based on the potential of wave energy technologies designed for electricity production, and are able to service municipal, industrial and agricultural scale water production.

2.3 RE-D lessons from international experience

In this section the barriers that challenge the development of RE-D technologies will be discussed, however, only with relevance to RE-D and not to renewable energy or desalination technologies independently.

2.3.1 Technological

i. System reliability and cost

As desalination technologies have developed, so too has the size of design. The focus of the design has centered on large-scale plants and moved away from small-scale units. RE-D systems are generally geared towards the latter and thus require different configurations, e.g. small-capacity pumps and control systems for decentralized operations, suitable pre- and post-treatment of water, energy recovery and storage systems, and a suitable method to dispose of brine, both for inland and coastal installations. Due to the above additions, RE-D is more costly than grid-connected or fossil-fuel run desalination plant equivalents (PRODES, 2009).

ii. Variability of energy supply

A characteristic of renewable energy supply is the intermittency of the supply as generation is entirely weather dependent, e.g. wind speed, solar radiation and solar duration. This is in contrast to desalination technologies that are based on the constant supply and availability of an energy source. Thus a situation develops where there is a mismatch between the demand and supply of RE-D systems. This will have an effect on the maintenance and operations, as it may occur that a situation of under-utilization of capacity arises. This may result in instances of fouling for the likes of RO systems where a membrane may require replacement due to underuse, driving up the operational costs. Additional ramifications from variable supply include scaling, where microbial and other biological contamination occurs (Eltawil *et al.*, 2007 and PRODES, 2009).

To address this, PRODES suggests that a form of energy storage or smoothing needs to be used, i.e. a battery pack to store excess electricity generated, or for thermal methods, where some form of thermal fluid be used for heat storage. In addition, the coupling of RE-D systems with electricity grid or fossil-fuel run generators could assist with providing the constant supply of energy required.

2.3.2 Economic

i. Market and risk uncertainty

There are few commercially operated RE-D systems, and little is known about the full cost of RE-D pairings. As such, known returns on investment are not available, requiring predictions and probabilities to estimate figures. Due to this there are large numbers of unknowns, bringing with it a high-risk rating. Furthermore, an area's suitability to RE-D systems needs to be evaluated in its entirety. It is not sufficient to draw top-down conclusions for the allocation of RE-D pairings from the fact that an investment in desalination plants is required and that there is a sufficient renewable energy potential. A bottom-up approach of understanding the skills and requirements of a community and the infrastructure is in place to ensure that both maintenance and management can

take place, should also be carried out. Without this, any progress made in reducing the use of fossil fuels will be nullified if engineers or management staff are required to travel far distances to monitor and maintain the system (PRODES, 2009).

ii. Pricing structures

Access to water is considered a human right in South Africa. Consequently the cost of producing water fit for consumption, either by desalination or otherwise, is often not equivalent to the tariff that end consumers pay for the amount they use. The situation in South Africa is that the charge paid for the amount used is grossly less than the economic cost due to subsidies. Subsidies are provided to municipalities by the government to assist in reducing the amount that end users pay, however this results in a lack of understanding and transparency for water as a resource and social good by the end consumer. In addition, municipalities are not in a position to manage the infrastructure required to ensure service delivery. This limits the possible development of RE-D systems because relative to subsidized water supplied, RE-D water costs on a comparable basis are too expensive. The analysis of this research will take a look at the current subsidized cost of water, and compare it to an estimate of true economic cost.

The investment costs and cash flow implications of RE-D systems upfront may seem unfavourable, regardless of whether the operational and maintenance costs are lower. This could dissuade investment and development in RE-D systems. For example, a household may earn enough to purchase bottled water daily, however does not have sufficient savings to invest in a RE-D system that could save the household money in the long run. An incentive of financial support could remedy this situation of high initial investment costs, with micro-financing or other rental agreements assisting these households. However the financial support given in situations like the above are generally from RSA Non-governmental organizations and as yet there are no policies in place to promote this support.

iii. Lack of funding for demonstration plants.

Because of the abovementioned facts, there has been minimal interest from investors to enter the RE-D market. This has hampered the development of the systems, which in turn has prevented the growth of pairings. This vicious cycle will continue until sufficient development funding is provided to further develop the industry. In addition,

the areas suitable for the installation of these pairings are often small communities away from the public eye and as such these niche markets do not have the capabilities to invest in the required technology, while the greater communities capable of investing are often not aware of the need (PRODES, 2009).

2.3.3 Institutional and social

i. Lack of training and infrastructure

Due to the few installations globally, there is limited practical experience in working with these pairings. Consequently there are few trained professionals who are capable of operating and maintaining the RE-D systems. Furthermore, the spare parts necessary to run these systems may not be easily available, which increases the risk of providing a reliable resource to users (an issue which would certainly influence the mind-set towards the technologies).

In addition, these systems cannot be purchased off the shelf, requiring separate service providers to provide the renewable energy and the desalination services. This results in additional costs with less guarantees available, and certainly more project management required to manage the interfaces between the service providers (PRODES, 2009).

ii. Negative perceptions

Despite the fact that the public knows the benefit and usefulness of both renewable energy and desalination technologies, global acceptance is slow due to the perceptions that they are uneconomical and environmentally damaging. Examples of this are: desalination plants are known to be energy intensive, thus the use of RE-D may still be misconstrued to be energy intensive and environmentally damaging regardless of whether clean energy is being used; and potable water produced by desalination plants may be perceived to be not fit for human consumption based on cultural or personal opinions, rather than fact (PRODES, 2009).

Taste is also a concern that pilot studies have shown to be an issue. The taste of potable water from desalination plant differs to that from a tap due to different cleaning agents and chemicals used. This can be overcome, by blending or adapting the potable water produced and a similar taste can be achieved (PRODES, 2009).

Finally, due to the mismanagement and failing of plants, certain consumers have been conditioned to believe that desalination plants are unreliable. In addition, a lack of education on the technology used - both for desalination plants and renewable energy technologies - creates a misunderstanding of the capabilities and expectations of the system's potential (PRODES, 2009). The consequence of this is that communities or municipalities give little support, preventing buy-in by those investors and people required to ensure that these projects are sustainable.

Applying these barriers in the context of South Africa, where social upliftment, and renewable energy initiatives are slow to be accepted by communities, the lack of education provided during the implementation phase and the lack of financial sustainability is often seen as the cause (due to a lack of development financing or no contribution made from the end consumers). From the perspective of financial sustainability, it is essential to establish some form of payment for the service provided, in order to ensure assets function as designed, and are maintained.

2.4 Limitations of literature

Based on the findings that the economic cost of water is not represented in the tariff that is set by WMAs, opinion on what an appropriate tariff should be, was obtained by a leading water professional⁸. Therefore, when comparing desalination and RE-D costs with municipal water tariffs, the estimated figure for water supply and a comparable figure of R10.50 per m³ will be used. This amount has been quoted by a water official as a suitable estimate that reflects the true economic cost of water and incorporates the appropriate costs required to provide potable water to the end consumer, including an element of cross-subsidisation for the free allocation of water to the poor. However, an additional opinion was not obtained and thus this figure is biased and potentially untrue. An economic study on water pricing in South Africa with a focus on the Agricultural Sector was being completed at the time of writing up this research. Factors that are considered in this tariff include infrastructure maintenance and development, the treating of raw water, water official's salaries, new build financing and a return on asset amount - exact figures and cost splits were unobtainable.

⁸Interview with analyst from Trans-Caledon Tunnel Authority

Access to detailed and recent information was limited for all data used in the analysis. The main limitations are highlighted below:

- Cost data for RE-D pairings is not available for all combinations and all the input variable details are not known;
- The economic cost of water in RSA is not reflected in the tariffs charged by WMAs, an estimate was used for comparison purposes as described; and
- Updated water supply and demand figures for WMAs are not available publicly thus the last public information has been used for analysis, this is 10 years old;

2.5 The relevant characteristics of RSA to support RE-D

South Africa is fortunate in its supply of both solar and wind energy with predictions that when combined, wind and solar energy could provide a minimum cumulative potential of 5,100 MW, by 2019 (Eskom, 2010), an estimated 10% of total energy capacity. Additionally, the locations of these renewable energy resources are in regions of the country where water stress also occurs, particularly along the coastlines of the Western and Eastern Cape. This suggests the integration with desalination plants is possible if the economics prove feasible.

With its vast coastline, South Africa has three different feed water qualities, specifically: the colder West Coast, the warmer South Coast, and the warmest East Coast. It is known that the colder the water, the higher the concentration of salt, which affects the investment costs of a plant as more filtration is required to produce the desired water volume and quality (du Plessis *et al.*, 2006). There is thus a clear trend in decreasing investment costs with warmer, less saline, feed waters.

2.5.1 Increasing demand for potable water

As detailed in the introduction, South Africa's water demand is expected to increase at a compounded average growth rate of 1.1 % between 2010 and 2030, reaching 17.7 billion m³ by 2030 (2030 WRG, 2010), leaving a greater than 2.7 billion m³ shortfall based on supply currently available. This projection paints a gloomy picture for the

prospects of meeting national and regional water demand. Suggested reasons for the greater than expected deficit include:

- The predicted impact that global warming and climate change will have on the weather patterns of the country. Perceived effects are that there will be less rainfall across the country, especially in the western regions, and crops will require more irrigation, decreasing the total supply available by an estimated figure of 1.1 billion m³ (2030 WRG, 2010); and
- A large increase in demand due to an increase in population, a growing middle-class and an increase in urban household and municipal demand. This will increase household and municipal allocation to 34% of total demand, with agriculture decreasing and industry increasing in consumption to 46% and 19% respectively (2030 WRG, 2010).

2.5.2 Renewable energy potential

The South African government, through its White Paper on Energy (1998) actively declared the pursuit of energy security via energy diversification. In this paper, it was acknowledged that renewable energy technologies are the least-cost energy alternative in many circumstances, especially if social and environmental costs are included in the evaluation of conventional forms of coal-sourced energy. Furthermore, these technologies provide for local economic development, job creation, climate change mitigation as well as achieving the country's energy policy objectives. The White Paper on Renewable Energy, 2003, established a renewable energy target of 10,000 GWh by 2013, incorporating both electricity generating and non-electricity generating technologies such as solar water heaters and biofuels. This equates to approximately 4% of the projected electricity demand in 2013 (DME, 2003). To date, this target does not look as if it will be achieved, and government is currently reassessing it.

In response to this, the Integrated Resource Plan (IRP) released in 2011 stipulates that it is the new goal of government to incorporate a cumulative amount of 17.8 GW of energy from renewable sources into the energy portfolio by 2030. Structures put in place to promote this include the Renewable Energy Feed-In Tariff (REFIT), which has been designed to give financial incentive to private investors and project developers.

However at the time of writing, the likelihood of the REFIT being scrapped to be replaced by a bidding process was highly likely, whereby the REFIT tariffs initially expressed would serve as a ceiling for independent power producers. The chosen technologies, as stated in the IRP, are solar PV (8.4 GW), CSP (1 GW) and Wind (8.4 GW). This places the opportunity that exists for renewable energy and the market capacity that has been proposed into perspective.

The following section looks at the solar and wind energy potential of South Africa. It will not touch on wave or ocean energy potential; however ocean energy will be included for modelling purposes. South Africa is blessed with a long coastline, with abundant sunshine and wind, three important ingredients highlighted in this research.

i. Wind Energy potential

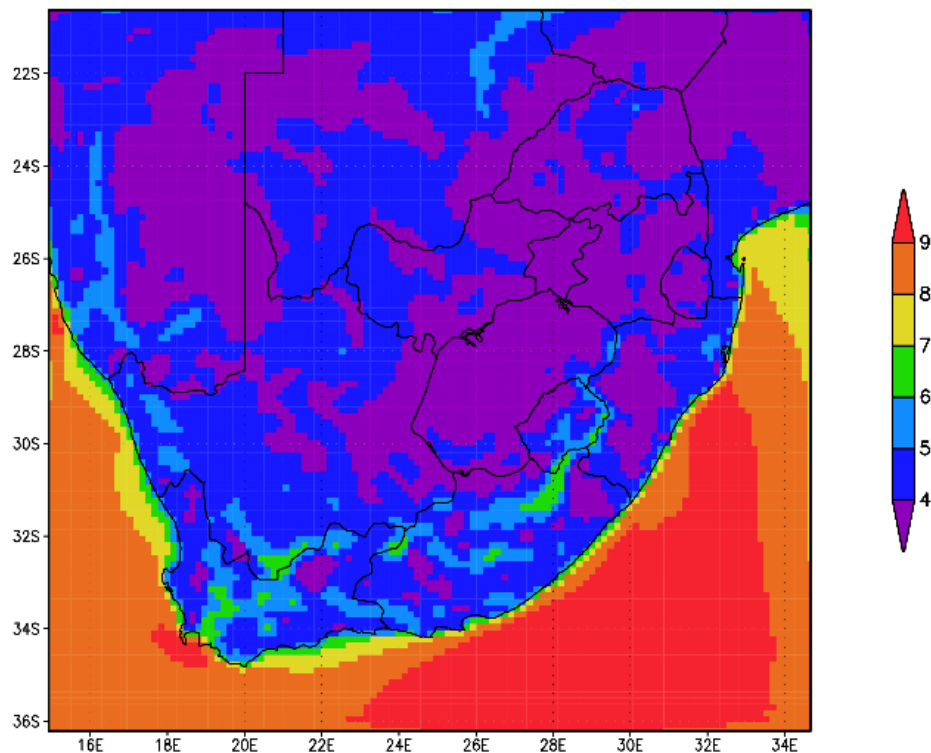
To date, there are three wind resource prospecting studies that have been completed in South Africa, with a revised wind resource assessment being carried out for the Department of Energy by the South African National Energy Research Institute (SANERI) in conjunction with partners. Although this research reveals different findings, they all show there is great potential for wind turbine installations across the country. The three wind resource assessments are the Diab Wind Atlas of South Africa (1995), the Eskom SABRE-Gen project (2001) and the Hagemann Mesoscale Wind Atlas of South Africa (2008). The latest, Hagemann's Mesoscale will be discussed below:

Hagemann Wind Atlas of South Africa (2008)

In light of the results, and with queries as to the accuracy of the Diab and Eskom assessments, it was found that the measuring masts from these studies were too close to buildings and other obstacles. Moreover, due to the low height at which measurements were taken (Waller, 2010; Banks and Schaffler, 2006), it was felt that a revised assessment was necessary. Kilian Hagemann's Mesoscale Wind Atlas of South Africa, Figure 11, modelled wind speeds across the country at 10m above ground level and used Geographic Information Systems (GIS) scenario analysing to assess the feasibility of different wind power penetration levels (Waller, 2010; Hagemann, 2010). This GIS-based scenario analysis considered proximity to existing infrastructure, assumed height of wind monitoring and minimum capacity factors. The results showed that in three different scenarios (conservative, moderate and optimistic) there was the potential for

20 TWh/year (6,000 MW), 80 TWh/year (26,000 MW) and 157 TWh/year (56,000 MW) respectively. The Wind Atlas shown in Figure 11 provides a map of the annual average wind speeds at 10m above ground level in South Africa. It proposes areas within the Western Cape, Northern Cape and Eastern Cape as having the most wind generating potential, making mention of the potential that is available along the coast line and offshore (Waller, 2010).

Figure 11: Average annual wind speeds at 10m above ground in m/s (Hagemann, 2008)



There are variances, ranging from 7.9TWh per year (3000 MW) to 157 TWh per year (56,000 MW) between the abovementioned studies, and it is difficult to accurately determine the finite potential of wind availability across South Africa. The revised fourth assessment, currently being completed, will provide clearer insight into South Africa's significant wind potential in specific regions, particularly the Western Cape, Eastern Cape, Northern Cape, and Kwazulu-Natal, which will not pose a technical constraint to possible projects, provided that successful independent studies are carried out in these regions. Despite these findings, currently there exists in operation only 10.4 MW of wind energy in the country, however with a further 8,000 MW under varying stages of development (Feasibility, Development, Pre-Construction, Construction or Commercial

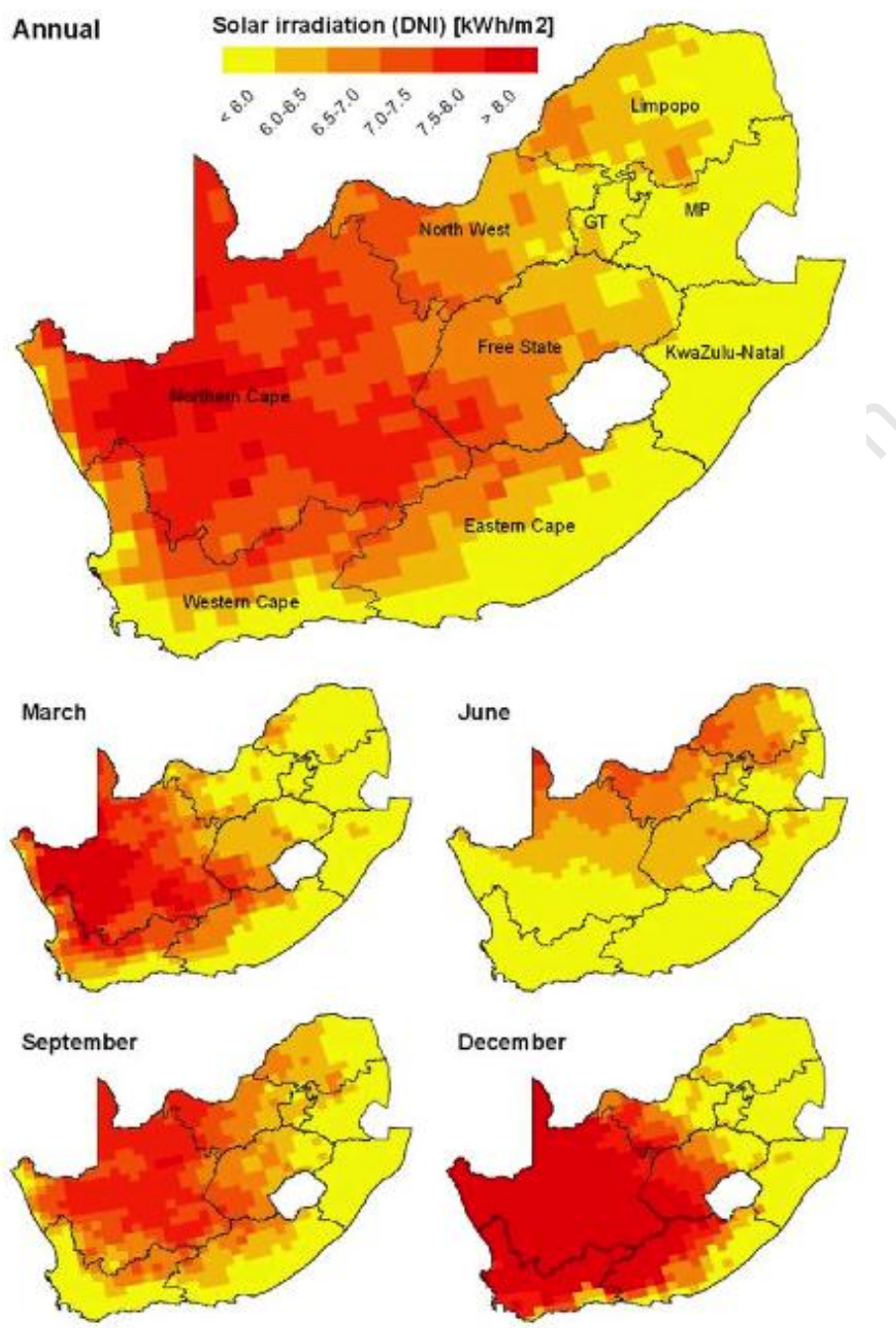
Operations stage) (Waller, 2010), there is a growing realization of the potential for this source of energy.

ii. Solar Energy potential

South Africa is blessed with an estimated 2,500 hours of sunshine on an annual basis (Edkins *et al.*, 2010) - twice that of Europe - and daily solar irradiance varies between 4.5 and 6.5 kWh per m² or 16 and 23 MJ per m². This makes RSA one of the better climates across the globe for the collection of solar energy, either via panels or through solar thermal technology. In this research, the two technology types, Solar Photovoltaics (PV) and Solar Thermal Technology, will be the focus of the solar energy potential research as both can be coupled as power and thermal sources for desalination technologies.

Thomas Fluri, in his research of the potential of concentrated solar power in South Africa (2009), identified that with South Africa's strong direct normal irradiance (DNI), see figure 12, there is potential to install a cumulative capacity of 547.6 GW of Concentrated Solar Power (CSP) across South Africa, especially in the Northern Cape (510 GW), Free-State (25 GW), Western Cape (10 GW) and Eastern Cape (1 GW) (Fluri, 2009). Also shown is the solar potential that exists in the country, which is not limited to Solar Thermal or PV technologies. To date, Eskom has made provision for a possible 325 MW (Fluri, 2009) and the IRP for 600 MW (IRP, 2011) from solar energy technologies. Figure 12 illustrates where the solar potential exists across the country.

Figure 12: The average daily DNI for South Africa for the whole year and for the months of March, June, September and December (SWERA, 2008)



Solar Thermal Technologies

Through the use of lenses and mirrors, solar thermal technologies concentrate sunlight from a large collection surface area to a small area. This concentrated energy drives a turbine, usually steam-based - that is connected to an electrical generator. There are four forms of concentration, namely: parabolic trough, dish Stirling engines, concentrating linear Fresnel reflector and the solar power towers. Each of these forms are capable of producing high temperatures and high thermodynamic efficiencies, and although they are expensive, through technology learning and improvements in research and development, i.e. in their ability to track the sun's movements, these technologies are becoming more cost effective and efficient in their conversion ability and efficiency. However, this technology type is known to consume large volumes of water during the energy generation process through the process of wet cooling (Wikipedia: Solar Thermal Technology, 2010), allowing an opportunity to consider dry cooling methods. This factor needs to be considered when identifying the ideal location for technology installation, suggesting that coastal regions are possibly more suitable locations due to the large volumes of water that are available.

South Africa is currently planning to build a large CSP plant in the Northern Cape. The estimated capacity of the plant is 100 MW, utilizing the central receiver method, and will also include 8 hours of energy storage capacity. As suggested through the REFIT, the ceiling tariff that IPPs would likely receive through the new bidding process, of R2.34 per kWh produced; there is sufficient incentive for project developers to invest in this type of project, despite the large investment required.

Solar Photovoltaics (PV)

In contrast to the thermal technologies, solar PV converts solar radiation directly into electricity through the use of semi-conductors, either thin-film solar cells or crystalline silicon modules, and is known to be the fastest growing power-generation technology in the world (Wikipedia: Solar Photovoltaics, 2010). The characteristic of this technology that has driven its global popularity is its scalability. This diversity and flexibility bodes well for its use for power technologies in areas that are not connected to the centralised electricity grid. Furthermore, with the addition of the REFIT suggestion of R3.94, the upper-most tariff possible under the new bidding process for IPPs, for an installation

that is greater than 1 MW in generation capacity, will assist with breaching the high cost hurdle that has prevented its mass installation nation-wide.

2.5.3 Summary of key points

After considering the information in this chapter, as well as the facts and arguments in the preceding sections, a concluding argument is presented: SA should consider exploring the concept of pairing renewable energy with desalination plants, either directly as shown in the RE-D section, or indirectly through promoting the off-take of renewable energy electricity generated coupled with the smoothing of conventional energy. The literature review has shown that specific pairings are more suitable for different desired volumes, which is useful when one considers the purpose these technologies can be used for, e.g. to supply a family, self-sustaining farm, industry or an entire municipality. Understanding the current state of the country's water supply, the demand profiles, the failing infrastructure, poor maintenance and worsening quality of treated water, poses no confidence that the situation, if extrapolated, will improve. This perception welcomes the need for desalination to augment available supply. However desalination should only be considered if renewable energy as a power source is used, in order to avoid exacerbating the dependency on fossil fuels and 'unclean' grid electricity. In addition, addressing the need for water prices to be increased to assist municipalities to recover more revenue to finance the required improvements, favours the argument for RE-D and desalination plants, as costs will become even more competitive.

There are several barriers as identified by international case studies that would affect an industry such as this one progressing in South Africa. The country is known for its poor service delivery, high unemployment rate and lack of skilled workers. This, in combination with the negative perceptions for socially focused renewable energy projects, highlights the problems associated with the sustainability of these technologies. These barriers will be addressed in the analysis discussion where a strategy to ensure sustainability - based on international experiences - will be proposed.

The next section includes the analysis of cost data where the pairings of RE-D, desalination and conventional water systems will be compared, identifying the

scenarios that the favoured RE-D and Desalination option will be affordable, and in which regions of the country these options would be more suited.

3. Research Methodology

The research aim is to ascertain whether it is financially feasible to use renewable energy to power a reverse osmosis desalination plant, in comparison to using conventional methods of diesel or grid electricity. The methodology applied is of a mixed method approach, in that both qualitative and quantitative data were incorporated.

The quantitative analysis evaluated two areas: the off-grid scenario and large scale grid connected. The off-grid scenario incorporated using Net Present Value (NPV) analysis between Wind, Solar PV and a Diesel powered generator, and large scale, comparing unit water costs produced by Reverse Osmosis using Levelised Electricity Costs (LEC), from 2009 – 2033, for a variety of clean energy sources. This information was used to determine the end cost of water per unit using an adapted unit water cost model. The qualitative analysis evaluated the South Africa renewable energy potential and water supply deficit identifying those areas ideally situated to generate renewable energy and those that were characterised as water scarce (see figure 2 for more details). The Reverse Osmosis technology has been used as the desalination technology due to its popularity in South Africa and globally, and due to it being highly energy efficient in comparison to other desalination technologies available.

The purpose of breaking the quantitative analysis into two steps was to create an understanding of two opposite water supply circumstances. The one being those small towns located along coastal areas that are not serviced by constantly available electricity (or where energy is supplied through the use of diesel generators), fresh water and sanitation. And the other for large municipalities, cities and industry where water supply is not as freely available as before and energy prices are increasing in comparison to renewable energy quotations.

The research was largely exploratory as although extensive studies have been conducted on various elements of Desalination, Renewable Energy and RE-D, no previous research was found relating to RE-D in South Africa. The research method used to attain the results will facilitate the process of creating a wider view of the possibility of RE-D development in the country and supporting a deeper understanding of the subject.

3.1 Research methodology

The methodology applied to determine the financial viability of RE-D was a combination of NPV, LEC and Unit Water Cost analysis. Furthermore, the process of overlapping specific maps to identify ideal regions for RE-D locations was applied. The tools used to evaluate the feasibility of the technologies have been explained below.

Net Present Value (NPV)

NPV is a financial tool that uses the time value of money to appraise long-term projects and is used in the project finance world. It is defined as the sum of the present values of the individual cash flows, both incoming and outgoing. Its wide use across industries make it an appropriate tool to use, considering the research aim of evaluating costs of different technology options (Wikipedia: Net Present Value, 2011).

For the purpose of this research, only outgoing cash flows have been considered due to the research aim of evaluating the cost of technologies. The rate used to discount the cash flows to the present value is a key variable to the process, in addition to the costs used. A company's weighted average cost of capital is often used, or in the case of energy finance in South Africa, NERSA guidelines can be used for simulation purposes. A higher discount rate is often used, or a premium is included, to take into account risk or unknown factors like additional costs (Wikipedia: Net Present Value, 2011).

Further, the cost of lending extracted from the NERSA guidelines was used, in addition to a higher rate, as using two different rates will better reflect comparing decisions under different scenarios. The rates did not include a premium for opportunity cost as the investment in energy and water was considered a crucial factor to the country's development and thus the money invested should not be compared with alternative investment opportunities.

Levelised Energy Costs (LEC)

The LEC method is the most common methodology used internationally for the comparison of energy generation costs from different technologies (Marquard *et al.*,

2008). The method provides a good indication of cost comparisons, as it takes into consideration finance charges, pay back periods, and an average of the expected investment, fixed and operational costs per kW or kWh over the lifetime of the project. LEC is equivalent to the average price, consumers would have to pay to exactly repay the investor capital and operational and maintenance costs with a rate of return equal to the discount rate (Edkins *et al.*, 2007).

There are two approaches to utilizing the LEC method: either the IEA method that '*sums the costs incurred by the plant in each year, discounts these, and divides these by the discounted electricity output for each year*' (Marquard *et al.*, 2008), or the Annuity Method, used by Marquard *et al.* in their research. The annuity method has been chosen for this research due to the cost assumptions that have been made and with the intention of identifying the expected decreasing trend in renewable energy LECs over time through technology learning.

The annuity method focuses on analysing the cost stream, which consists of discounting annual costs and then levelling these into equal annual payments, and dividing this by the annual electricity output. The cost stream is comprised of capital, fixed operating costs, variable operating costs and fuel costs. For the purpose of Marquard *et al.*'s research, fuel costs were taken as zero for the renewable energy costs, and were internally considered in the price forecasts for grid electricity tariffs.

The LEC methodology is highly dependent on the discount rate that is used, thus a similar approach of using two rates has been applied as mentioned in the NPV method described earlier.

The LEC methodology has several shortfalls; in particular, it does not take all the costs into consideration for specific projects, e.g. grid connection or transmission investment costs, but this can be accounted for by increasing figures by premiums to factor in the unknown. This has not been considered in this research as the costs obtained have been considered reliable and transparent due to their use in South African renewable energy calculations, e.g. Marquard *et al.*, 2008, and free from significant errors and assumptions.

Unit water cost (UWC)

The Unit Water Cost (UWC) evaluation has been calculated using information gathered from operational desalination units and research publications where expenses and cost allocation on a cost per unit basis is known. The energy requirements and costs of these plants will be isolated and adjusted using the results from the NPV and LEC models. A problem identified is that any errors incurred during the modelling will be carried through, and the modelling will assume that all RE-D environmental characteristics are similar to that of the Desalination data used.

A drawback to using the NPV, LEC and Unit Water Cost as methodology tools is that as they are simulation techniques they may result in possible simulation errors occurring. A further disadvantage is that simulation itself is not reality and therefore not a concrete basis for on-going inference of results and the models should be updated periodically.

3.2 Research design

The research was initiated by conducting an extensive literature review. This detailed the different pairings of RE-D which have previously been evaluated as well as the financial conclusions reported for various combinations. This identified those renewable energies that have been sufficiently researched and whose costs are known in the South African context. The pairings in combination with understanding the country's renewable energy potential were used as a starting point for developing the NPV and LEC models. These were then expanded by linking the results with energy requirements for desalination plants in the process of calculating the expected end cost of water per m³.

Once constructed, the final cost of water per m³ was derived to be used to compare with water supplied by municipalities. The energy requirements were adjusted, using a sensitivity analysis, to quantify the effect that this may have on the end cost of water and this range was compared to current costs paid by municipalities for their water supply. The derived outcomes were then analysed and assessed against the literature information that exists.

3.3 Data collection

The method of data collection was predominantly archival with the source being documentary and therefore secondary (Groenewald, 1986). The literature was reviewed with five objectives in mind.

The first objective aimed to establish and determine what different installed combinations of RE-D are currently in operation. The second was to ascertain which renewable energy technologies are favoured in South Africa. From this, two renewable energy technologies and one conventional technology were identified on the small, decentralised energy scale, and four renewable and two conventional technologies for the large electricity generation scale evaluation over time, and a reverse osmosis desalination plant. These were identified to create the primary model used as the starting point for the NPV, LEC and Unit Water Cost comparisons.

Thirdly, the aim was to establish the portion of total unit water cost produced by RE-D which is attributable to energy expenses and how the energy requirements fluctuated across studies, affecting the multiplier effect used to calculate the final unit cost of water. The fourth objective was to identify the water cost for WMA's and municipalities across South Africa to ascertain the current expenditure for water supply. This information was used as the benchmark to compare the final unit cost of water from the tested RE-D systems modelled. Finally the impact of those coastal WMA's currently experiencing and predicted to experience water deficits were identified to be compared with maps depicting the country's renewable energy potential. This determined which areas of the country were most suited to the installation of these systems.

3.3.1 Desalination, RE-D and water cost data

The RSA costing information for Desalination comes from the Desalination guide for South African municipal engineers (du Plessis *et al.*, 2006) and from public news reports related to the latest installations for Sedgefield and Mossel Bay. The analysis was limited to using the Reverse Osmosis technology due to the energy efficiency and cost in comparison to the other technologies identified through the literature review. In addition, all new build plans for desalination in the country and globally favour the use

of Reverse Osmosis plants. The regional water tariffs were extracted from the Nation Water Accounts from Statistics South Africa (2000), and an inflationary figure was applied to this for comparison purposes. The RE-D cost data was extracted from the ProDes research on the Roadmap for RE-D, 2009. The RE-D figures were quoted in Euro and thus were adjusted to a South African Rand figure for comparison purposes. Renewable energy costs were collected from a number of sources, specifically Edkins, Marquard and Winkler's South Africa's renewable energy policy roadmap (2010), Greenpeace International (2011) and Gilau and Small's paper on designing cost effect SWRO systems under optimal energy options (2007).

As a result of South Africa being known for its solar irradiation and windy cities, in conjunction with the relative maturity and development of these technologies (research that has been published), the data collection was limited to these two renewable energy potentials for the off-grid scenario, and compared with diesel powered generators. Whereas for large-scale analysis, Ocean and CSP energy was considered, in addition to Solar PV and Wind, due to its relative development and it's speculated investment and fixed costs.

3.3.2 South Africa's WMA profile

Due to the unavailability of recent WMA supply and demand details in the public domain, figures from the National Water Resource Strategy (NWRS), 2004, were used to identify those areas of the country which had insufficient supply to meet the regions demands. This information relates back to 10 years ago, 2000, thus it is fair to assume that the situation since then has further deteriorated due to the intervening lack of water infrastructure investment (See figure 2 for further details).

3.3.3 South Africa's RE potential profile

The renewable energy sources have been limited to solar and wind energy due to their relative maturity in comparison to others. The latest maps were obtained for each energy source, specifically: Hagemann Mesoscale Wind Atlas of South Africa, 2008, and SWERA's map of national solar irradiation potential, 2008.

Ocean energy has been included for analysis principles however its known potential in South Africa as yet has not been mapped to the same extent as has been done for solar and wind energy. Therefore it is not possible to use ocean energy as a filter to identify a region most suitable for RE-D installation. Areas like harbours and ports, and other natural areas that capture tidal and wave fluctuations could be suitable for the use of this technology.

3.4 Data analysis and data interpretation

The data collected was modelled using excel functions. Exhibits from the model have been included in the Appendix. Linear extrapolation and discounted cashflows manipulated the processed data to provide further insight into the unit cost of electricity, and subsequently water. The results of the NPV, LEC and UWC testing will be interpreted taking into account the literature that exists. Three tests were completed to identify the feasibility opportunity for RE-D systems.

3.4.1 Test 1: Off-grid scenario

The purpose of Test 1 is to compare the cost of electricity and the subsequent cost of a unit of water produced from a RO plant powered by wind, solar PV and a diesel generator on a small scale, simulating the energy options a community not connected to the grid has when considering augmenting water supply by desalination.

The basics of this test have been extracted from Gilau and Small's study on Designing cost-effect seawater Reverse Osmosis systems (2007), where they identified the requirements of powering a RO plant that produced 35m³ per day to provide sufficient water for 108 households. The study was completed for a community located in Eritrea that had good wind (6.8 m/s) and solar conditions (6.8kWh/m²), and where the community was not connected to the central electricity grid. These conditions are equivalent to those experienced on the West Coast of South Africa (see figure 11) and from the perspective of understanding the cost of electricity and water for areas not connected to central grids. Therefore, this study was identified as a suitable source of information for the required system sizes. The costs for the system were updated using Marquard *et al.*'s (2010) data.

For the analysis, it is assumed that the RO system can be powered by a 17 kW base load. In order to achieve this: a 30kW stand-alone wind turbine, a 17 kW stand-alone PV power system (without tracking) and a 50 kW diesel powered generator have been considered. The costs and availability factors have been included in Table 10. The costs for the diesel generator have been extracted from the study by Gilau and Small and adjusted for exchange rate and inflationary effects. The analysis considers a wind and solar power system without battery storage. Additionally, the cost of diesel is assumed to increase according to a flat rate of 6% annually. The purpose of this is to simulate the increasing cost of diesel and the threat that diesel could become as a limited resource.

According to the literature reviewed, energy requirements range from 2 - 30kWh/m³ and can contribute between 40 and 80% of the total overall UWC. It was assumed for this study that energy contributed 44% (Eltawil *et al.*, 2007) of the overall UWC due to South African waters being considered some of the densest with salt and other particles in comparison to the waters of Europe. The effect of this is that other costs like membrane replacement and maintenance will add to the expense of running the desalination plant.

Table 10: Electricity plant characteristics and cost assumptions for RSA (Marquard et al., 2010)

Energy technology	Plant life	Efficiency	Availability	Investment Costs (R/kW)	Fixed Costs (R/kW)	Variable Costs (R/MWh)	Learning ratios	Source
Wind	20	100%	23%	16 424	253	-	19%	Marquard
Solar PV	15	100%	27%	50 042	97	-	20%	Marquard
CSP	30	100%	55%	56 218	474	-	15%	Marquard
Ocean	20	100%	55%	51 233	200	-	20%*	Green-peace international
Nuclear	40	31%	83%	37 445	751	4	0%	Marquard
Super-critical Coal	50	40%	86%	25 000	230	29	0%	Marquard

* The learning ratio of 20% has been assumed for ocean energy based on improvements in technology expected, as comparable with Solar PV.

The following equations were used in the analysis of calculating NPV, LEC and Unit Water Costs:

$$NPV = C_i \times \{1/(1+i)^n\} \quad (1)$$

$$\text{Energy produced} = \text{Hours in a day} \times \text{Days in a year} \times \text{Efficiency} \times \text{Installed Power} \quad (2)$$

$$C = \frac{r(NPV)}{1 - (1 + r)^{-n}}$$

$$\text{Equivalent Annuity cash flow adjusted} \quad (3)$$

$$\text{LEC} = \text{Equivalent annuity cash flow} / \text{Energy produced} \quad (4)$$

$$\text{UWC} = \text{LEC} / \text{Portion of UWC allocated to Energy cost} \quad (5)$$

Where:

NPV: Net present value

C: Equivalent annual annuity cash flow which is the factor by which the NPVs are adjusted for the different durations (R)

C_i: Initial capital cost (R)

I: Discount rate - which is 6% according to Nersa guidelines and 10% for comparable purposes

N: Project lifetime (years)

LEC: Levelised energy cost (R/kWh)

UWC: Unit water cost (R/m³)

It was assumed that the PV and diesel generator system would operate for only 8 hours per day throughout the year. The operation and maintenance cost of the diesel generator is R13/hour, with the diesel cost roughly R8.50 per litre (2009 RSA diesel price). The life time of the generator is estimated at 20,000 hours.

3.4.2 Test 2: Expected water costs from RE-D (2009-33)

The purpose of Test 2 is to compare the cost of renewable and conventional energy sources over time and the effect this will have on the final UWC as produced by RO desalination plant.

The LEC calculations are based on the annuity method as explained in Marquard *et al.* (2008). Not all the technologies evaluated in this original study were simulated, only those considered as self-sustainable, i.e. wind and solar, plus the additional technology of Ocean energy, which was not included. The renewable options were simulated against the conventional energy options of supercritical coal and nuclear energy production. No additional costs, e.g. carbon tax or other environmental costs, were included for the

latter conventional technologies as the government of South Africa have not determined which form of costing they will use to factor in these effects.

The LEC costs included technology learning rates as used in Marquard *et al.*'s study to take into consideration the effect that economies of scale and research and development will have on the cost of technology between 2009 and 2033. These years were used to understand the possible cost landscape over the next 25 years. The technology learning rates have been included in table 10. These are included to take into consideration the improvement in technology performance and reduction in costs expected. Additionally, the availability factors have been adapted from Marquard *et al.* initial study. The impact of inflation was ignored for all calculations.

The LEC did not consider other complex costs of plant installation in electricity systems, such as connection to the grid. The LEC costs were used as input to identify the final UWC.

The UWC is dependent on the energy requirements of the Reverse Osmosis plant, the maintenance expenses to run the plant and the cost of input energy to power the desalination plant. For this analysis, the maintenance expenses were assumed constant at R4.48/m³ or 56% of R8/m³ as broken down by the South African Municipal Desalination Guide (du Plessis *et al.*, 2006). As such the variable cost has been the amount of energy required and the remaining 44% of the cost.

The following equations were used in the analysis of calculating NPV, LEC and Unit Water Costs:

$$\text{LEC} = (\text{AC (capital cost)} + \text{fixed cost}) \times 1000 / (365 \times 24) \times \text{CF} + \text{variable cost} \quad (1)$$

$$\text{UWC} = \text{LEC} / \text{Portion of UWC allocated to Energy cost} \quad (2)$$

Where:

AC: Annualising fraction, -PMT in Excel

CF: Conversion or availability factors

3.4.3 Test 3: Suitable regions in RSA

The purpose of Test 3 is to identify coastal regions of South Africa experiencing a water deficit, and to understand if these regions have sufficient renewable energy sources that could be used to generate sufficient power to provide the required energy source for desalination plants.

A simple analysis of the demand and supply of water available per WMA was completed to determine those regions experiencing water deficit. The renewable energy maps for wind and solar were also used to identify if these regions were characterised with sufficient renewable energy potential.

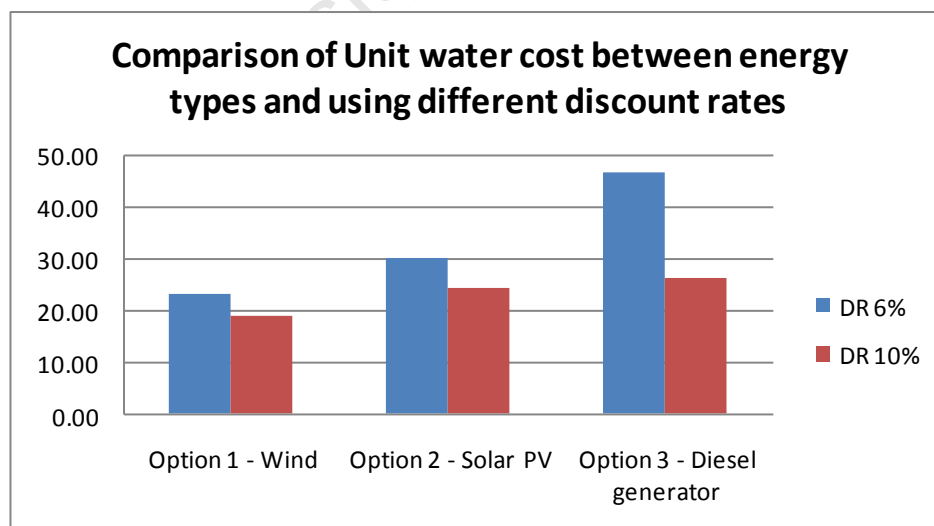
University of Cape Town

4. Results

4.1 Results of Test 1: Off-grid scenario

The results of comparing UWC for a Reverse Osmosis plant powered by solar PV, wind turbine or a diesel powered generator at a 6% discount rate, illustrate that pairings with both renewable energy options are cheaper than the diesel powered generator. This comparison was done using the equivalent annuity factor to adjust the durations to be equally comparable. Figure 13 illustrates the final UWC per energy source scenarios modelled for this test as adjusted using the equivalent annuity method. Under the scenario of a higher discount rate, 10%, the cost of water for all pairings decreases, but the cost for water generated by diesel generator and solar PV become more comparable at R24/m³. This is due to the higher discount applied to the annual expenses of the diesel generator. As shown in Figure 13, wind RO pairing is the cheapest of the options at R23/m³ compared to R30/m³ and R46/m³ for Solar PV RO and Diesel-powered RO respectively.

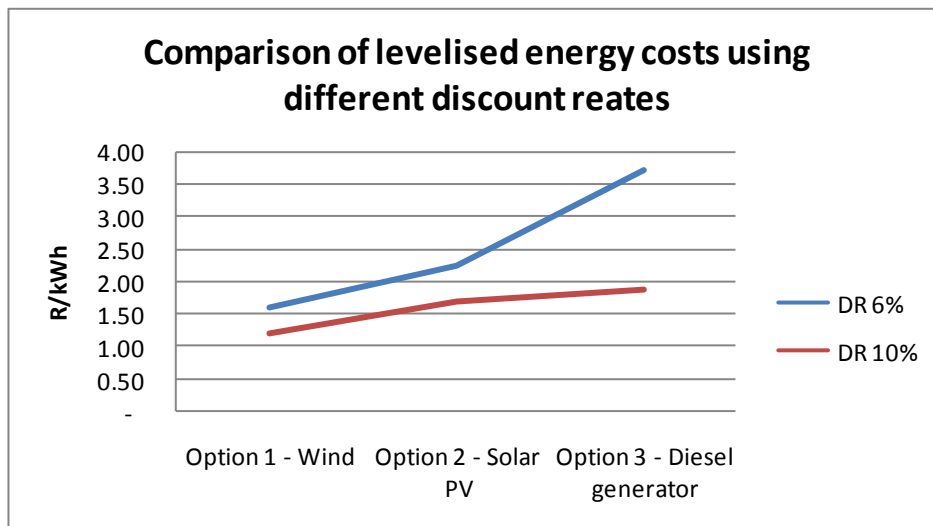
Figure 13: Comparison of UWC for different energy sources assuming different discount rates



Comparing the cost of electricity using wind, solar PV and a diesel generator, the cost for the wind system is the cheapest at R1.60/kWh. According to the simulated results, the

diesel generator option is the most expensive at R3.71/kWh. Under the scenario of a 10% discount rate these figures decrease to R1.21/kWh and R1.88/kWh respectively, as illustrated in Figure 14.

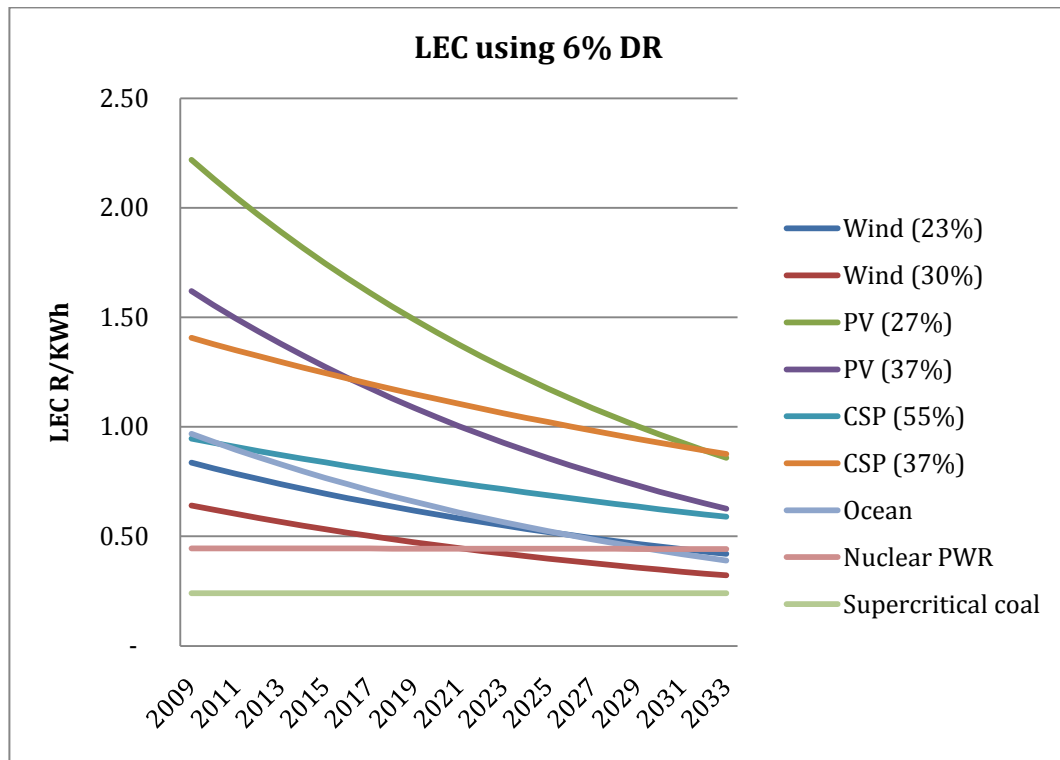
Figure 14: Comparison of levelised energy costs assuming different discount rates



4.2 Results of Test 2: Expected water costs from RE-D (2009-33)

Comparing the modelled levelised cost of electricity over the period of 2009 to 2033, it is expected that economy of scales and research and development will play an important role in reducing the cost of renewable energy. Under the scenarios of 6% discount rate, the cost of electricity from supercritical coal is cheaper than all other technology options modelled, at around R0.40/kWh. See figure 15 below. However, under the scenario of a 10% discount rate, the cost of wind energy, assuming 30% availability, is comparable and becomes more affordable than supercritical coal from the beginning of 2020.

Figure 15: Estimated cost reductions for renewable and conventional energy technology



The results from using the levelised costs calculated as input data for the UWC model, figure 16 below, illustrate the expected final cost of producing potable water using a Reverse Osmosis desalination method and show that using the cheapest form of energy, i.e. supercritical coal, results in water costing R7.63/m³. However comparing the calculated water prices between 2009 and 2033, wind powered RO plants become comparable to use with supercritical coal from 2025.

Using the scenario of a 10% discount rate, figure 17, costs for water become more competitive with grid-powered desalination costs. The higher discount rate results in a higher overall cost of water, UWC for supercritical coal which increases to R10.74/m³; however, and with the annuity method of calculating costs, the pairings with renewable energy sources become more affordable. Wind energy, at an availability factor of 30%, becomes competitive with supercritical coal from 2020, and ocean energy becomes competitive with nuclear energy from 2016.

Figure 16: Estimated UWC based on LEC results at 6% discount rate

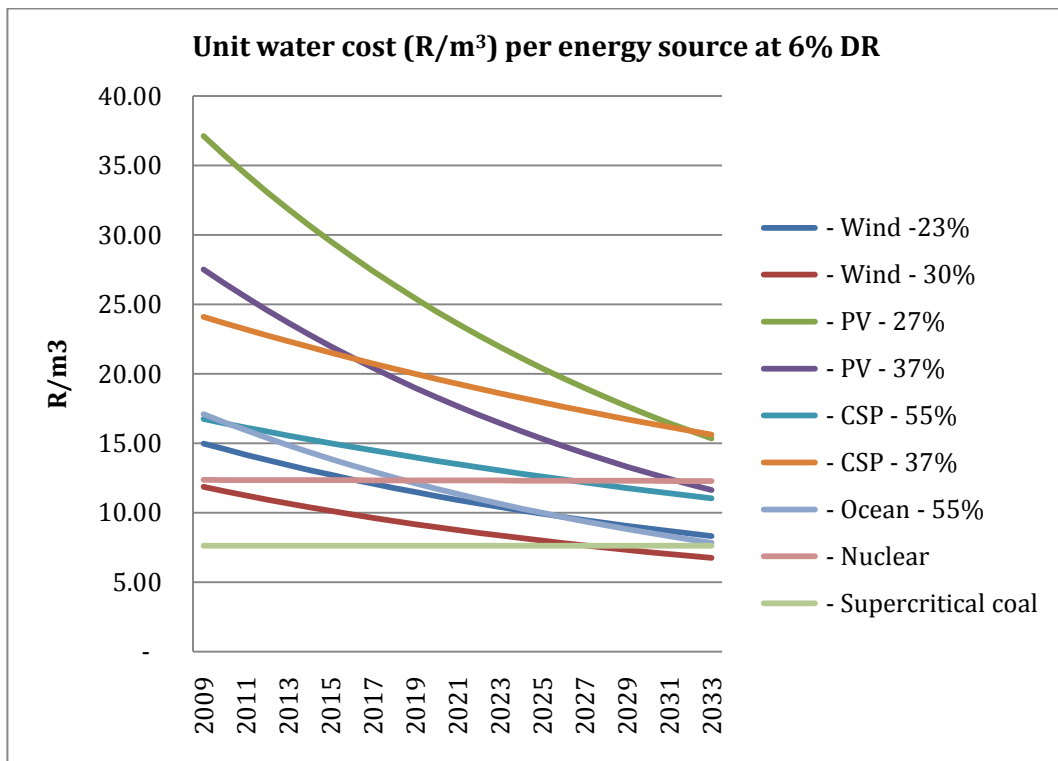
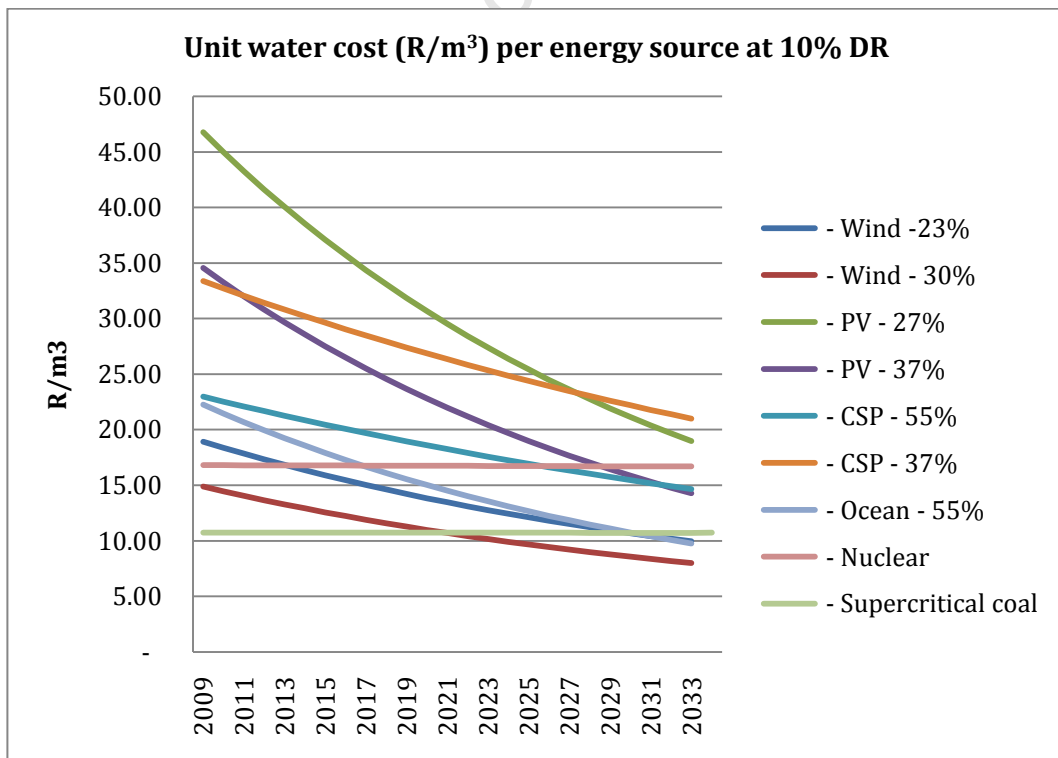


Figure 17: Estimated UWC based on LEC results at 10% discount rate



4.3 Results of Test 3: Suitable regions in RSA

The analysis shows that out of the 19 WMAs, there are a total of 12 experiencing water deficit. Of significance is the Lower Orange WMA where due to river losses, a large volume of water is required to be pumped into the region. Figure 18 below illustrates this deficit compared to over-supply for the respective WMAs.

Figure 18: Estimated water situation (deficit or excess capacity) per WMA

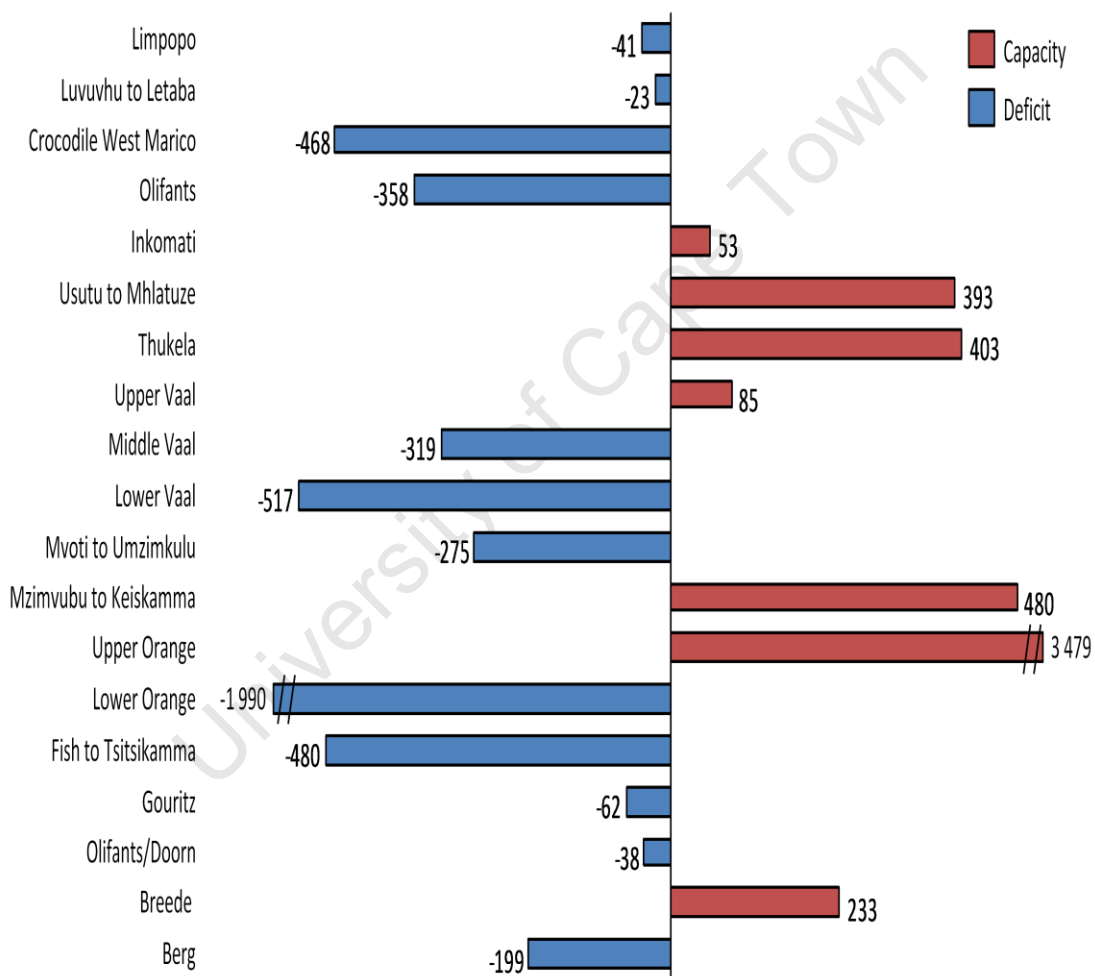


Figure 19 below illustrates that 7 out of 9 coastal WMAs are experiencing a deficit and desalination plants already in operation have been labelled to illustrate what WMAs

have done in the recent years to augment supply. Refer back to Table 5 on page 34 for the details relating to each plant.

Figure 19: WMA regions experiencing deficit and the location of public desalination plants

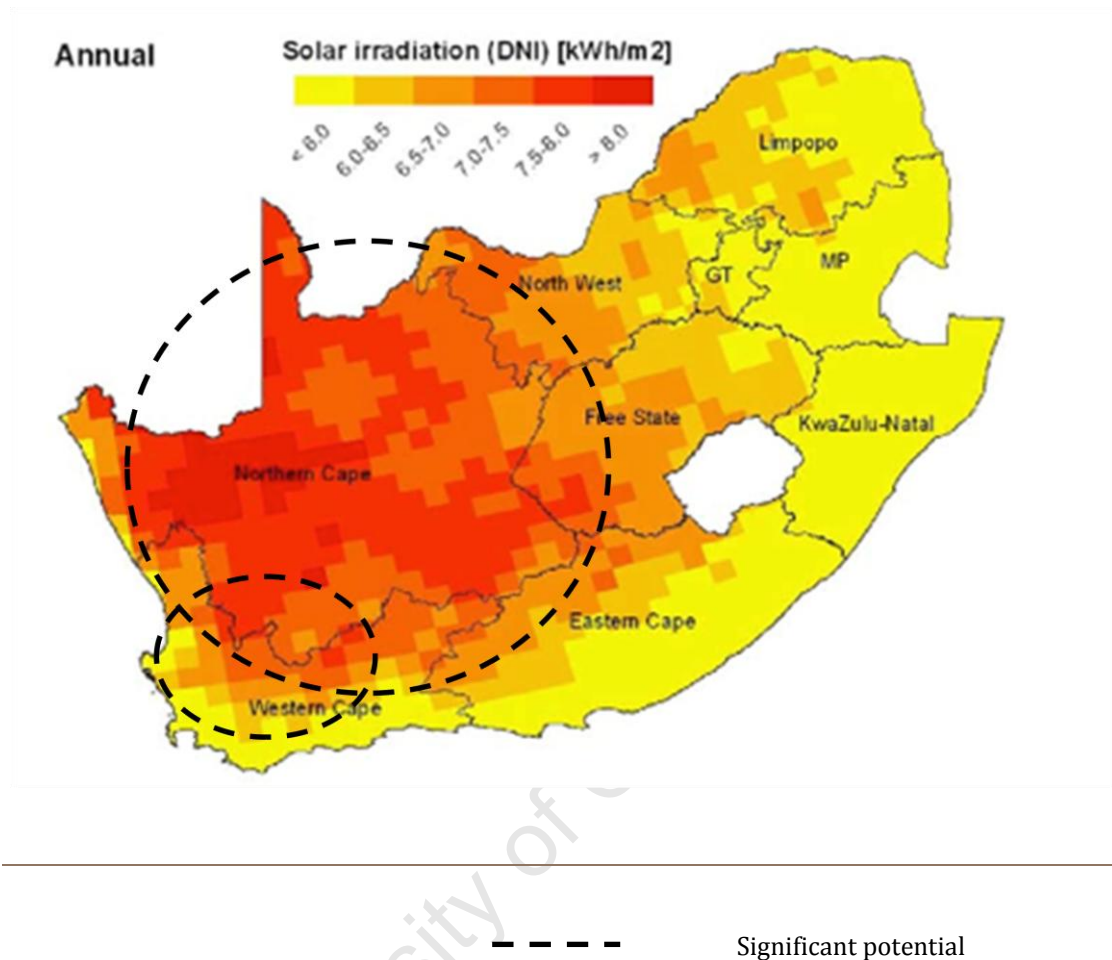


- - - Coastal WMAs experiencing deficit
- ★ Desalination plants in operation

4.3.1 Solar potential

From figure 20 below, it is clear that the Northern Cape is the most suitable for any form of solar energy, particularly CSP. However from the SWERA atlas it has been shown that West coast regions and regions slightly inland also have significant solar potential at above 6 kWh/m². The solar irradiance potential spreads further east into the central region of the country however solar irradiance is not as strong on the East Coast as it is on the West.

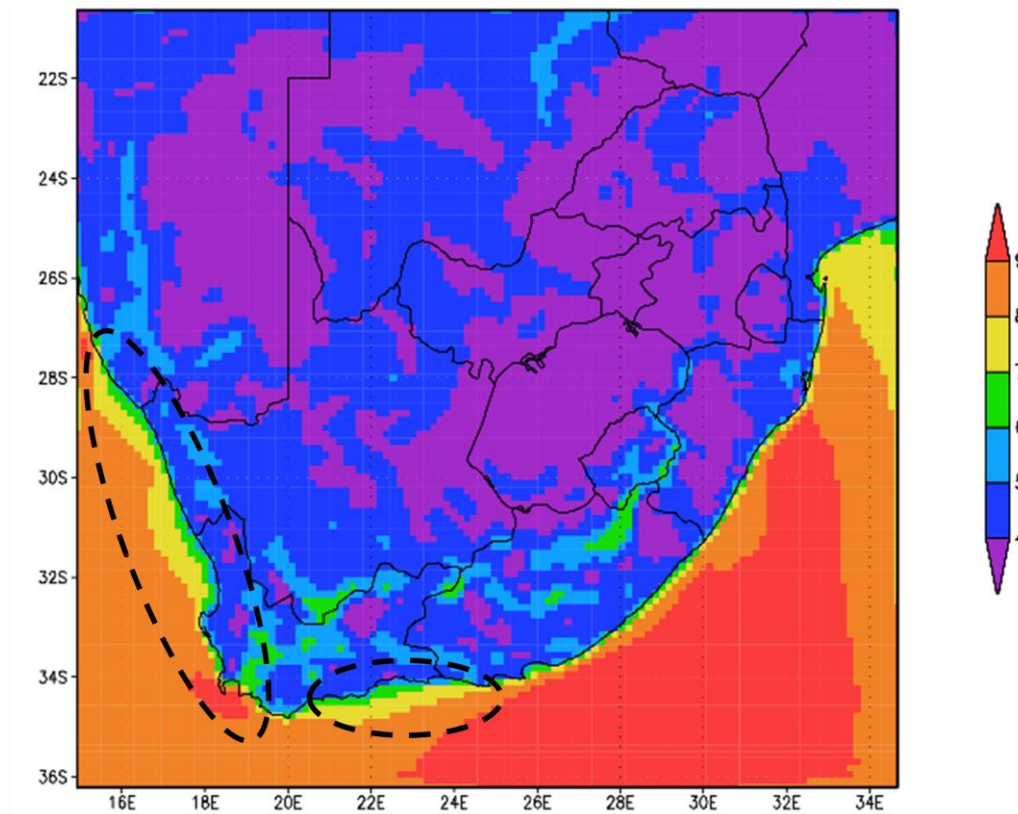
Figure 20: The average daily DNI for South Africa per annum (SWERA, 2008)



4.3.2 Coastal wind potential

Figure 21 below, adapted from Hagemann, illustrates the wind energy potential across the country. The map highlights the Western Cape, Eastern Cape, Northern Cape, and Kwazulu-Natal as those provinces that have the greatest potential. Hagemann found that the largest potential is along the Western and Southern Coasts as indicated by the black dotted circles.

Figure 21: Average annual wind speeds at 10m above ground in m/s (Hagemann, 2008)



----- Significant potential

4.4 Validity and reliability

In order to ensure the research was accurate, meaningful and credible (Leedy and Ormrod, 2005) the following checks were put in place.

4.4.1 External validity

External validity refers to the general applicability of the results of the study (Neuendorf, 2002) and ties in closely with the delimitations mentioned in Chapter 1. Owing to the extensive literature review which was conducted, the results obtained were expected to be appropriate and relevant to the purpose of this study, as well as reproducible and replicable.

4.4.2 Internal validity

Internal validity refers to the extent to which the researcher will be able to draw accurate conclusions from the study with particular reference to the possibility that the research results could have come about for reasons not explored in the study.

An extensive literature review was conducted in order to obtain an adequate and complete representation of the technologies which were being investigated. This created a strong internal validity for the research as the results were generated from previously identified input data, as outlined in the literature and defined by the principle problem statement. In addition to this, input, suggestions and feedback were obtained from various individuals, with both industry knowledge and practical experience pertinent to the research question further reinforced the internal validity. Finally in modeling the respective costs, different scenarios were constructed to determine the application and validity of the results initially obtained.

4.4.3 Reliability

Reliability relates to the consistency of the results within the study, and the accuracy and precision of the measurement procedure (Neuendorf, 2002). The probability of another researcher concluding the same results in terms of NPV, LEC and unit water cost analysis would depend to a large extent on the input data which is utilised. In light of the literature reviewed and the financial tools chosen, the conclusions derived would most likely be consistent with the findings of repeated research.

5. Discussion

5.1 Test 1: Off-grid scenario

5.1.1 Energy Options

Based on the renewable energy potential within South Africa and the results from Test 1, both wind and solar PV energy sources are feasible when compared to a diesel powered generator. According to the model, at a discount rate of 6%, the solar PV energy system is more expensive than the wind powered system, with costs of R2.23/kWh and R1.60/kWh respectively. However the results of the sensitivity analysis show that at a higher discount rate, the use of the diesel powered generator becomes more competitive with solar PV at R25/m³. In both scenarios, wind power is cheaper than the PV power; however in terms of reliability it is assumed that PV will be more reliable than wind - due to sunshine being more easily predictable than wind (Gilau and Small, 2007). Therefore, it is easier to predict the operation of a PV powered RO system than a wind powered system.

A limitation of the model is that it does not consider the use of batteries, the aspect of travel for maintenance and the extended life on diesel generators. This is an important consideration, as the use of batteries will assist in storing the excess energy generated, which can then be used during times when the renewable energy source is not available, i.e. after daylight hours or when the wind is not blowing. The storage options such as batteries though expected to drive the investment costs up, would however provide the benefit of both more energy and end water which is likely to nullify this increase in investment through additional revenue streams.

Also, areas that are not connected to the central grid and require diesel generators are often some distance from any large city. Considering that South Africa's main cities all have ports and airports, the supplies will arrive here, if the solar panels and wind turbines are manufactured overseas. If the location of installation is not close to freight stops, and if the area does not have the sufficient skills to attend to the maintenance of the system, qualified personnel would be required to travel to these areas, which requires diesel or petrol powered vehicles. This use of transport exposes maintenance costs to a similar factor of inflation expected for the rise in diesel prices due to security of supply and an increase in demand. However the rise is not expected to be as high. An

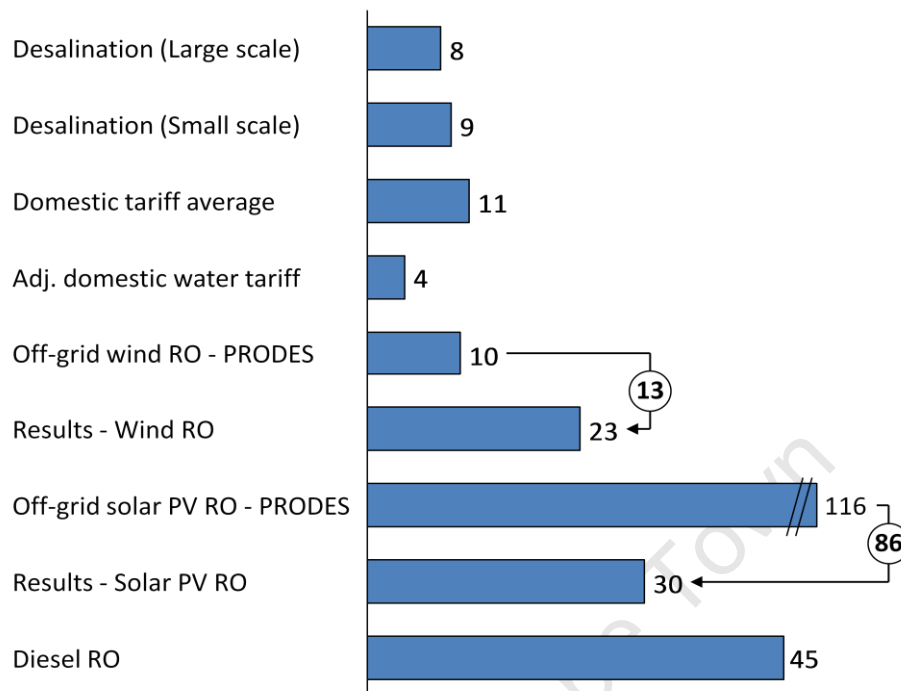
element which was not considered, however, that may have an impact on the results and the variable costs of renewable energy technology expenses.

Finally, the model assumes that the useful life of a diesel generator is 20,000 hours, or 7 years if the generator is used for 8 hours per day. In Africa, assets are sometimes used over and above their useful life limits and thus their investment costs are expected to decrease over time as more value is generated. However, due to the running costs of fuel acquisition driving the overall cost of the final product, expected end product costs are not expected to reduce over time.

5.1.2 Water Cost

The Desalination Guide for Municipal Engineers calculates a water cost of R8 per m³ using a small-scale RO system (du Plessis *et al.*, 2006), thus the energy portion of the cost equates to R3.52 (a factor of 6.8 or 6.8 kWh/m³ if the electricity price paid by operators is R0.40/kWh). This is in line with quotes received from water consultants in RSA who quoted an energy range of between 3 – 9 kWh/m³. Using this information as a guide, a UWC cost of R23.21 and R30.18 per m³ is expected for wind and solar powered RO systems respectively, using the equity annuity calculation method. Compared to international studies completed by ProDes, it appears to be more feasible to invest in Solar PV RO systems, whereas wind RO systems appear to be more expensive, as shown in Figure 23 below.

Figure 22: Comparison of UWC from a variety of sources (R/m³)



A comparison of tariffs paid by municipalities for water supplied, an average of R4/m³, shows that RE-D costs are still expensive; however the cost comparisons of renewable energy against diesel illustrate that renewable powered desalination systems are cheaper for decentralised regions. The true cost of water is not reflected by the amount of R4/m³ as stated above, and a figure of R10.50/m³ is more representative. Even if this amount is used, the RE-D systems modelled are still not competitive.

5.2 Test 2: Expected Water Costs (2009-33)

5.2.1 Energy options

Due to the learning rates used in the calculations, the result is a reduction in the LEC's as seen by the downward sloping trend curve for all renewable energy technologies. Interesting to note is that ocean energy and CSP, with an availability of 55%, become competitive with nuclear energy from 2030 at R0.55/kWh.

In contrast to the reduction in renewable energy costs, the cost trends for nuclear and supercritical coal are flat due to the 0% learning rate expected. According to research completed by Marquard *et al.* (2010) and Greenpeace International (2011) the costs for supercritical coal may in fact increase due to additional technology required for desulphurisation, and other measures to capture the environmentally damaging gasses released. In the event that carbon capture or carbon tax becomes the norm, the price of supercritical coal energy is expected to increase, ensuring that renewable energy options become comparable.

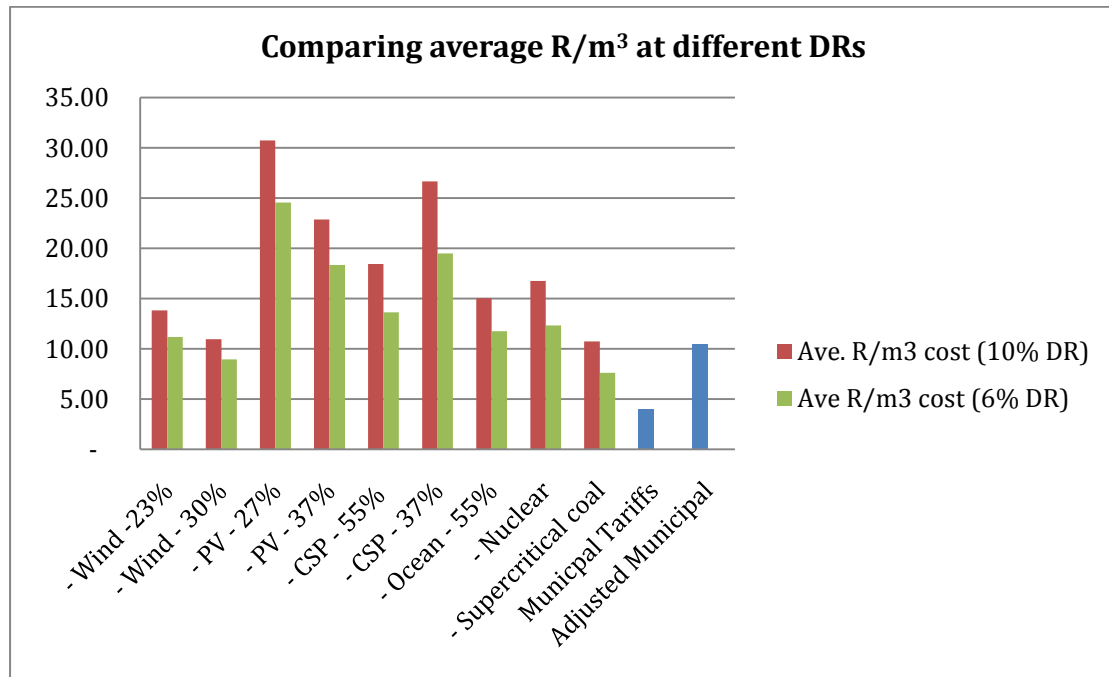
Furthermore, suggested tariffs (REFIT) available for IPPs through bidding, and other financial support mechanisms for renewable energy investment have not been considered. These support mechanisms will assist renewable energy power producers to recoup the large investment as a single buyer of electricity will pay more for energy produced from cleaner sources. To date these mechanisms and incentives have not been finalised but will have a positive impact on investors in renewable energy.

5.2.2 Water cost

The results show that at a 10% discount rate, the cost of wind-RO (availability of 23%) in comparison to coal-RO becomes cheaper than coal in 2030 at R9.40/m³. However if there is wind availability of 30% or if a storage system is used, this could improve (ignoring investment costs), and the costs become more competitive from as early as 2021 at R7.80/m³.

Figure 21, below, illustrates the average for the UWC over the period of 2009 – 33. From this the feasibility of wind can be observed in relation to coal, CSP, ocean energy and nuclear energy.

Figure 23: Average UWC per energy source over the period of 2009 - 33



Similar to Test 1 a more realistic water cost of R10.50/m³ indicates that RE-D and desalination methods will become more competitive.

REFIT and renewable energy incentive schemes will reduce the estimated price of RE-D water produced so as to become more competitive with conventional desalination plants.

5.2.3 Recommended pairings suited to RSA

Based on the findings and RE potential of the country, specifically known solar and wind potential, there are three options for RE-D pairings: Solar PV-RO, Wind-RO and Ocean-RO.

The above combinations have proven to be competitive with municipal water for both Test 1 and Test 2.

5.3 Test 3: Suitable regions in RSA

Test 3 highlighted those regions most suitable for RE-D installation. A characteristic of the South African coastline is that there is strong irradiance and in most regions a moderate to strong source of wind. A highlight of the findings is that there appears to be no major WMA's that do not have a source of wind or solar that cannot be exploited; however the West Coast of the country appears to have a stronger degree of availability in comparison to the East coast. The Eastern seaboard should not be ignored as the irradiation experienced is still sufficient to warrant exploration of solar energy use, however an updated study on the solar irradiation potential of this region, and the whole of the country, specifically focusing on coastal regions, should be completed to understand its true potential.

5.4 Conclusion

In summary, the findings from test 1 and 2 illustrate that the UWC for potable water produced by RE-D systems is comparable with conventional forms of energy and water provision.

6. Recommendations for enabling RE-D in RSA

The results show that in certain instances, RE-D systems are becoming more financially competitive, especially in small-scale investment for decentralised, coastal areas. However, the large capital investment required for RE-D systems is usually the first hurdle that investors and developers trip over. In light of this, and the barriers identified from international literature in chapter 2.3, an opportunity exists for the system's success, if there is a strong strategy that addresses the three main negative points of the RE-D systems. These are: To improve reliability and reduce the costs, to address the variability of energy supply and to coordinate energy and water policies. These aspects are discussed below.

6.1 Improve the reliability and reduce the costs

The development of the RE-D systems and the research thus far completed has been due to numerous academic institutions and small developers. However it is of the opinion of ProDes that these pockets of Intellectual Property should cooperate in order to achieve greater opportunities and to share technology insight. In addition, by combining forces, the footprint of the industry will appear bigger with a united front instead of fragmented, as it is currently with several small operators.

By coordinating efforts, research and development can focus on the respective components characterizing desalination and renewable energy technologies, including the robust components which are necessary for stand-alone operations in harsh environments (ProDes, 2009). Additional focus points to improve reliability are:

- Adaptation of high pressure pumps and energy recovery systems to improve energy efficiency in smaller plants,
- Robust and suitable battery systems to store additional energy generated and to increase the duration of energy provision,
- Improved seawater-resistant material,
- Self-sustaining and more environmentally friendly pre- and post-treatment technologies, and

- Automated control systems able to optimize the performance of both renewable energy and desalination systems and to minimize the maintenance required.

By addressing these common needs, the RE-D industry will move closer to developing standardised, reliable and robust systems with guaranteed performances (ProDes, 2009).

6.2 Addressing the variability of energy supply

It is well documented that renewable energy sources provide intermittent power and that membrane methods of desalination are expected to foul and deteriorate at a higher than normal rate because of this. Several options exist to address this problem.

One approach could be to provide energy through hybrid systems, where conventional and renewable energy sources are combined to provide a supply of energy that is more constant. Examples include:

- Wind turbine with solar PV,
- Solar PV or wind turbine with connection to the central electricity grid,
- Solar PV or wind turbine with a diesel powered generator,

In addition, according to the latest RSA Integrated Resource Plan (2010), the expected contribution by renewable energy increased to 29.8% of the total capacity by 2030 (IRP, 2010). As the electricity capacity becomes less dependent on conventional energy, or as more electricity is generated by renewable energy technologies, desalination operators could purchase electricity directly from IPPs, using the transmission and distribution network as a vehicle for delivery, paying the higher expected tariffs for this cleaner energy source.

6.3 Promotion and coordination of energy and water policies

The relationship between electricity and water is such that they should not be considered independently. Water is the source of steam to generate electricity and a form of cooling in most coal-fired power stations, and electricity is used to pump large

volumes of water across the country. However, it is far too common that the management structures of energy and water are separated. A stronger cooperation between both sectors should be encouraged and supported in both non-governmental and governmental institutions (ProDes, 2009).

South Africa is making progress in this field as the latest IRP and energy strategy studies accept that new, supercritical coal fired power plants linked with dry-cooling systems require far less water. Furthermore, the new build plan, which focuses on the promotion of nuclear, supercritical coal and renewable energy technologies, will require less water than historical energy generating technologies.

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7. Conclusions

This research produced important findings which will create a basis on which RE-D in South Africa can be further explored. From the literature reviewed, suitable pairings as well as the characteristics of these pairings were identified, and only those relevant to South Africa were considered. Elements identified for pairings include: wind, solar and ocean renewable energy sources, combined with the Reverse Osmosis desalination method. Three tests were completed for this research, and the results are summarised below:

A NPV and Equivalent Annuity Factor model was used to calculate the final unit water cost on an off-grid basis when evaluating which energy source (solar PV, wind or a diesel powered generator) would be more economical when paired with a Reverse Osmosis plant to produce potable water for a region not connected to the electricity grid. The outcome was that both solar PV and wind energy are cheaper than that of using the diesel generator.

A similar methodology was used to model the Levelised Energy Costs, evolving over a period of 25 years, for a selection of renewable and conventional energy sources. The results were used to simulate the energy required for a Reverse Osmosis desalination plant and the subsequent unit water cost was calculated. The findings showed that supercritical coal is still the cheapest form of energy and thus when powering a Reverse Osmosis plant produces the cheapest water. However, wind energy in areas of high availability, i.e. high percentage of capacity, provides sufficient energy at a cheaper cost and thus is a competing source of energy to power a Reverse Osmosis plant. Furthermore, through technology learning, the cost of energy from renewable energy sources and unit water costs will become increasingly competitive, especially as the South African grid shifts away from conventional coal to include both nuclear and renewable energy sources, where it is shown that renewable energy sources are cheaper. In comparison to current municipal water tariffs, the renewable energy and desalination options could become even more competitive.

Maps were used to understand the water supply situation in coastal water management areas, in relation to the wind and solar energy potential. The findings illustrated that the

Western Coast of South Africa, with its water stress and high wind and solar energy potential, is the most suitable area to explore RE-D development.

In summary, this research indicates that there is an opportunity for South Africa to mitigate its water and energy stress by utilising its available renewable energy potential in combination with desalination technologies.

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8. Recommendations

8.1 Recommendations

As highlighted in Chapter 6.3, South Africa is making progress in the coordination of energy and water as seen in the latest IRP and non-governmental studies on the impact on water required for future build plans; however it is perceived that this is limited to energy technology choices only. Considering that both energy and water security are currently being challenged, it is recommended that opportunities for RE-D investment be explored due to its ability to mitigate both water and energy supply stresses. Increasing water supply through desalination is financially competitive with current provision methods, and by utilising renewable energy technologies further stress on the central electricity grid will be prevented.

8.2 Suggestions for further research

Findings from the literature reviewed and the scenarios analysed indicate that there appears to be three key paths for further exploration.

Firstly, an updated financial study is required for large-scale seawater desalination plants in South Africa using water from the West and East Coast sources. A review of local literature shows this to be outdated and an updated study will both assist municipal leaders experiencing water stress and engineers in advising such communities.

Secondly, an updated study is required on the South African water sector by WMA and municipalities, to quantify water demand and supply figures, and water tariffs. At present this information is outdated and not readily available. This is necessary to update national records and to assist with regional water strategies.

And finally, an economic analysis is required to determine the benefits that increasing the water availability to communities, will bring to the West Coast. Presently, the region is experiencing a water deficit, and is under further threat from climate variability. The

residential, agricultural and industrial opportunities that an increased water supply could bring to the region would promote both job creation and economic development.

9. Appendix

The following figures: 24-28, have been included to provide the detail of the process that was adopted when quantitatively analysing the levelised energy costs and final unit water cost. The Microsoft Excel software served as a modelling tool sufficient to process the data and extract the necessary information required.

Figure 24 provides an illustration of the input costs used as the foundation for the models. Information was extracted from a number of credible research papers.

Figure 24: Appendix: Input costs screenshot

Energy technology	Plant life	Efficiency	Availability	Investment Costs (R/kW)	Fixed Costs (R/kW)	Variable Costs (R/MWh)	Learning ratios	Source
Wind	20	100%	23%	16 424	253	-	19%	Marquard
Solar PV	15	100%	27%	50 042	97	-	20%	Marquard
CSP	30	100%	55%	56 218	474	-	15%	Marquard
Ocean	20	100%	55%	51 233	200	-	20%	Greenpeace international
Nuclear	40	31%	83%	37 445	751	4	2%	Marquard
Supercritical Coal	50	40%	86%	25 000	230	29	1%	Marquard

Assumptions	Unit	Description
Electricity Hours	365 days	
	24 hours	
	8760 Total hours pa	
Unit water cost	8	Upper average taken from RSA desalination guide
Elec usage	9 kWh/m ³	NuWater
Portion of unit cost	44%	Eltawil
	3.52	Calculated
Elec cost	0.4	Average 2009 cost
Factor	8.8	Calculated
Inflation	6%	
Total water cost	8.00	Calculated
	4.48	Calculated
Small-scale		
Solar energy required	17	Gilau and Small
Wind energy required	30	Gilau and Small
Unit water cost	10	Upper average taken from RSA desalination guide
Elec usage	9 kWh/m ³	NuWater
Portion of unit cost	44%	Eltawil
	4.4	Calculated
Elec cost	0.4	Average 2009 cost
Factor	11	Calculated
Inflation	6%	
Total water cost	10.00	Calculated

Figure 25 illustrates the linear extrapolation that was adopted to calculate the annual running costs of each small-scale energy generator. The figure illustrates the 3 options modelled: Wind, Solar PV and the Diesel Generator. The linear model discounted the annual expenses to Day 1 of the project, allowing an opportunity to compare the expense of per unit of water based on the reverse osmosis desalination plant operation per energy type.

Figure 25: Appendix: Small scale calculation screenshot

Test 1 - Comparing small-scale wind, solar PV and diesel powered generator at 6% DR																					
Discount Rate	6%																				
Inflation	6%																				
Option 1 - Wind	2009																				
Costs	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Investment	432.720																				
Fixed		7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590	7.590
- adj inflation			455	938	1450	1932	2567	3177	3823	4507	5233	6003	6818	7683	8599	9570	10600	11691	12848	14074	15374
- adj improvements																					
Variable																					
- adj inflation																					
- adj improvements																					
Total	432.720	7.590	8.045	8.528	9.040	9.582	10.157	10.767	11.413	12.097	12.823	13.593	14.408	15.273	16.189	17.160	18.190	19.281	20.438	21.664	22.964
Discounted	432.720	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160
NPV	628.767																				
Total Electricity	685.032																				
LEC	0.92																				
Water Cost	15.70																				
Option 2 - Solar PV	2009																				
Costs	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024					
Investment	850.714																				
Fixed		1649	1649	1649	1649	1649	1649	1649	1649	1649	1649	1649	1649	1649	1649	1649					
- adj inflation			99	204	315	433	558	690	830	979	1137	1304	1481	1669	1868	2079					
- adj improvements																					
Variable																					
- adj inflation																					
- adj improvements																					
Total	850.714	1649	1748	1853	1964	2082	2207	2339	2479	2628	2786	2953	3130	3318	3517	3728					
Discounted	850.714	1556	1556	1556	1556	1556	1556	1556	1556	1556	1556	1556	1556	1556	1556	1556					
NPV	872.493																				
Total Electricity	603.126																				
LEC	1.45																				
Water Cost	2151																				
Option 3 - Diesel generator	2009																				
Costs	2009	2010	2011	2012	2013	2014	2015	2016													
Investment	117.137																				
Fixed																					
- adj inflation																					
- adj improvements																					
Variable		251.009	251.009	251.009	251.009	251.009	251.009	251.009													
- adj inflation			15.061	31.025	47.947	65.884	84.898	105.052													
- adj improvements																					
Total	117.137	251.009	266.069	282.033	298.955	316.893	335.906	356.061													
Discounted	117.137	236.801	236.801	236.801	236.801	236.801	236.801	236.801													
NPV	1774.743																				
Total Electricity	600.000																				
LEC	2.36																				
Water Cost	38.14																				

Due to the energy technologies lasting for different durations, the final unit costs need to be collaborated to allow for simple conversion. Figure 26 provides a screenshot of this.

Figure 26: Appendix: Small scale adjustment screenshot

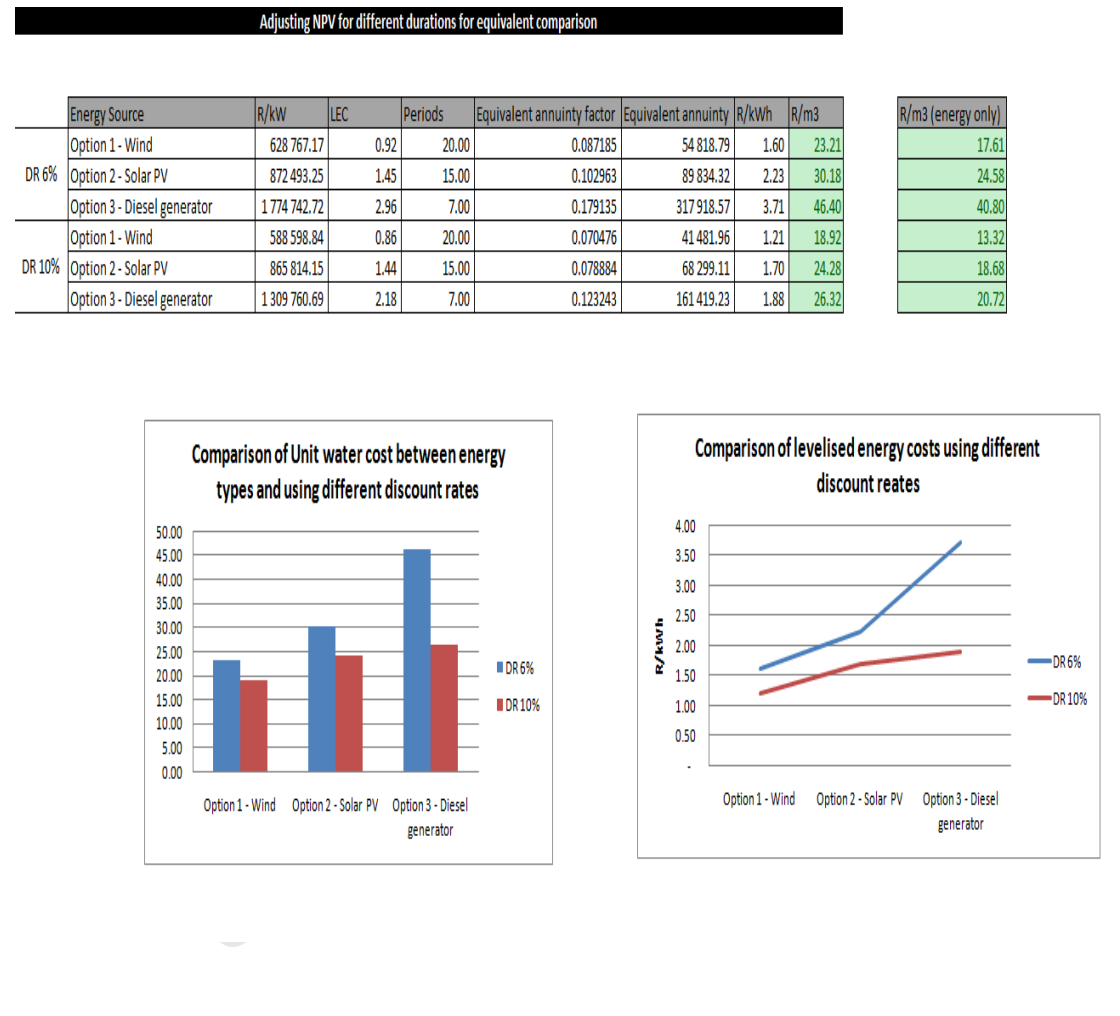


Figure 27 illustrates linear comparison of large scale grid connected technologies in a vertical fashion, different to the horizontal version used for the small-scale comparison. Technology learning was factored in these calculations to evaluate when in the future renewable energy may become more economically competitive with existing energy technologies.

Figure 27: Appendix: Large scale calculations screenshot

		Test 2 - Comparing large-scale wind, solar PV and diesel powered generator at 10% DR																						
Hours	8760																							
Discount	10%																							
		Wind (23%)				Wind (30%)				PV (27%)				PV (37%)				CSP (55%)						
		Investment Costs	Annualized	Fixed Cost	LEC (R/MWh)	Investment Costs	Annualized	Fixed Cost	LEC (R/MWh)	Investment Costs	Annualized	Fixed Co.	LEC (R/M)	Investment Costs	Annualized	Fixed Co.	LEC (R/M)	Investment Costs	Annualized	Fixed Co.	LEC (R/M)	Investment Costs		
2003																								
2004																								
2005																								
2006																								
2007																								
2008																								
2009		16424.00	R1923.16	253.00	1.08	16424.00	R1923.16	253.00	0.83	50042.00	R6579.21	97.00	2.82	50042.00	R6579.21	97.00	2.06	56217.50	R5963.51	474.00	1.34	56217.50		
2010		15831.09	R1853.51	253.00	1.05	15831.09	R1853.51	253.00	0.80	48040.32	R6316.04	97.00	2.71	48040.32	R6316.04	97.00	1.98	54952.61	R5829.33	474.00	1.31	54952.61		
2011		15253.59	R1732.39	253.00	1.02	15253.59	R1732.39	253.00	0.78	46118.71	R6063.40	97.00	2.60	46118.71	R6063.40	97.00	1.90	53716.17	R5698.17	474.00	1.28	53716.17		
2012		14708.72	R1727.68	253.00	0.98	14708.72	R1727.68	253.00	0.75	44273.96	R5820.86	97.00	2.50	44273.96	R5820.86	97.00	1.83	52507.56	R5589.96	474.00	1.25	52507.56		
2013		14177.74	R1665.31	253.00	0.95	14177.74	R1665.31	253.00	0.73	42503.00	R5588.03	97.00	2.40	42503.00	R5588.03	97.00	1.75	51326.14	R5444.64	474.00	1.23	51326.14		
2014		13665.92	R1605.19	253.00	0.92	13665.92	R1605.19	253.00	0.71	40802.88	R5364.51	97.00	2.31	40802.88	R5364.51	97.00	1.69	50171.30	R5322.13	474.00	1.20	50171.30		
2015		13172.58	R1547.25	253.00	0.89	13172.58	R1547.25	253.00	0.69	39170.77	R5149.93	97.00	2.22	39170.77	R5149.93	97.00	1.62	49042.45	R5202.39	474.00	1.18	49042.45		
2016		12697.05	R1491.39	253.00	0.87	12697.05	R1491.39	253.00	0.66	37603.93	R4943.93	97.00	2.13	37603.93	R4943.93	97.00	1.56	47938.99	R5085.33	474.00	1.15	47938.99		
2017		12238.69	R1437.55	253.00	0.84	12238.69	R1437.55	253.00	0.64	36099.78	R4746.17	97.00	2.05	36099.78	R4746.17	97.00	1.49	46860.36	R4970.91	474.00	1.13	46860.36		
2018		11796.87	R1385.66	253.00	0.81	11796.87	R1385.66	253.00	0.62	34655.79	R4556.33	97.00	1.97	34655.79	R4556.33	97.00	1.44	45806.01	R4859.07	474.00	1.11	45806.01		
2019		11371.00	R1335.63	253.00	0.79	11371.00	R1335.63	253.00	0.60	33289.55	R4374.07	97.00	1.89	33289.55	R4374.07	97.00	1.38	44775.37	R4749.74	474.00	1.08	44775.37		
2020		10960.51	R1287.42	253.00	0.76	10960.51	R1287.42	253.00	0.59	31938.77	R4199.11	97.00	1.82	31938.77	R4199.11	97.00	1.33	43767.92	R4642.87	474.00	1.06	43767.92		
2021		10564.83	R1240.94	253.00	0.74	10564.83	R1240.94	253.00	0.57	30661.22	R4031.15	97.00	1.75	30661.22	R4031.15	97.00	1.27	42783.15	R4538.40	474.00	1.04	42783.15		
2022		10183.44	R1196.14	253.00	0.72	10183.44	R1196.14	253.00	0.55	29434.77	R3869.90	97.00	1.68	29434.77	R3869.90	97.00	1.22	41820.53	R4436.29	474.00	1.02	41820.53		
2023		9815.82	R1152.96	253.00	0.70	9815.82	R1152.96	253.00	0.53	28257.38	R3715.10	97.00	1.61	28257.38	R3715.10	97.00	1.18	40879.56	R4336.47	474.00	1.00	40879.56		
2024		9461.47	R1111.34	253.00	0.68	9461.47	R1111.34	253.00	0.52	27127.09	R3566.50	97.00	1.55	27127.09	R3566.50	97.00	1.13	39959.77	R4238.90	474.00	0.98	39959.77		
2025		9119.91	R1071.22	253.00	0.66	9119.91	R1071.22	253.00	0.50	26042.00	R3423.84	97.00	1.49	26042.00	R3423.84	97.00	1.09	39060.68	R4143.53	474.00	0.96	39060.68		
2026		8790.68	R1032.55	253.00	0.64	8790.68	R1032.55	253.00	0.49	25000.32	R3286.89	97.00	1.43	25000.32	R3286.89	97.00	1.04	38181.81	R4050.30	474.00	0.94	38181.81		
2027		8473.34	R995.28	253.00	0.62	8473.34	R995.28	253.00	0.47	24000.31	R3155.41	97.00	1.38	24000.31	R3155.41	97.00	1.00	37322.72	R3959.17	474.00	0.92	37322.72		
2028		8167.45	R959.35	253.00	0.60	8167.45	R959.35	253.00	0.46	23040.30	R3029.19	97.00	1.32	23040.30	R3029.19	97.00	0.96	36482.96	R3870.09	474.00	0.90	36482.96		
2029		7872.61	R924.71	253.00	0.58	7872.61	R924.71	253.00	0.45	22118.69	R2908.03	97.00	1.27	22118.69	R2908.03	97.00	0.93	35662.09	R3783.01	474.00	0.88	35662.09		
2030		7588.41	R891.33	253.00	0.57	7588.41	R891.33	253.00	0.44	21233.94	R2791.71	97.00	1.22	21233.94	R2791.71	97.00	0.89	34859.70	R3697.89	474.00	0.87	34859.70		
2031		7314.46	R859.15	253.00	0.55	7314.46	R859.15	253.00	0.42	20384.58	R2680.04	97.00	1.17	20384.58	R2680.04	97.00	0.86	34075.35	R3614.69	474.00	0.85	34075.35		
2032		7050.41	R828.14	253.00	0.54	7050.41	R828.14	253.00	0.41	19569.20	R2572.84	97.00	1.13	19569.20	R2572.84	97.00	0.82	33308.66	R3533.36	474.00	0.83	33308.66		
2033		6795.89	R798.24	253.00	0.52	6795.89	R798.24	253.00	0.40	18786.43	R2469.92	97.00	1.09	18786.43	R2469.92	97.00	0.79	32559.21	R3453.86	474.00	0.82	32559.21		

Figure 28 illustrates the table used to calculate the final unit water costs for the large scale analysis. The purpose of this analysis was to identify at what date specific pairings of reverse osmosis desalination plant and a specific renewable energy become more competitive with energy from existing or coal-fired power plants.

Figure 28: Appendix: Unit water cost model screenshot

Final unit water costs using the results obtained from the LEC - 10% R																									
Unit water cost	8																								
Elec usage	9 kWh/m ³																								
Portion of unit cost	44%																								
	3.52																								
Elec cost	0.4																								
Factor	8.8																								
Inflation	6%																								
Total water cost	8																								
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Other Costs	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48
Inflation																									
Energy Costs																									
- Wind-23%	1.08	1.05	1.02	0.98	0.95	0.92	0.89	0.87	0.84	0.81	0.79	0.76	0.74	0.72	0.70	0.68	0.66	0.64	0.62	0.60	0.58	0.57	0.55	0.54	0.52
- Wind-30%	0.83	0.80	0.78	0.75	0.73	0.71	0.69	0.66	0.64	0.62	0.60	0.59	0.57	0.55	0.53	0.52	0.50	0.49	0.47	0.46	0.45	0.44	0.42	0.41	0.40
- PV-27%	2.82	2.71	2.60	2.50	2.40	2.31	2.22	2.13	2.05	1.97	1.89	1.82	1.75	1.68	1.61	1.55	1.49	1.43	1.38	1.32	1.27	1.22	1.17	1.13	1.09
- PV-37%	2.06	1.98	1.90	1.83	1.75	1.69	1.62	1.56	1.49	1.44	1.38	1.33	1.27	1.22	1.18	1.13	1.09	1.04	1.00	0.96	0.93	0.89	0.86	0.82	0.79
- CSP-55%	1.34	1.31	1.28	1.25	1.23	1.20	1.18	1.15	1.13	1.11	1.08	1.06	1.04	1.02	1.00	0.98	0.96	0.94	0.92	0.90	0.88	0.87	0.85	0.83	0.82
- CSP-37%	1.99	1.94	1.90	1.86	1.83	1.79	1.75	1.72	1.68	1.65	1.61	1.58	1.55	1.51	1.48	1.45	1.42	1.40	1.37	1.34	1.31	1.29	1.26	1.24	1.21
- Ocean-55%	1.29	1.24	1.19	1.15	1.10	1.06	1.02	0.98	0.94	0.91	0.87	0.84	0.81	0.78	0.75	0.72	0.69	0.67	0.64	0.62	0.59	0.57	0.55	0.53	0.51
- Nuclear	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.94	0.94	0.94	0.94	0.94	0.94
- Supercritical coe	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Adjusted Water costs																									
- Wind-23%	14.01	13.71	13.41	13.13	12.86	12.60	12.34	12.10	11.86	11.64	11.42	11.21	11.01	10.81	10.62	10.44	10.26	10.09	9.93	9.78	9.62	9.48	9.34	9.20	9.07
- Wind-30%	11.79	11.55	11.33	11.11	10.90	10.70	10.51	10.32	10.14	9.97	9.80	9.64	9.48	9.33	9.19	9.05	8.91	8.78	8.66	8.54	8.42	8.31	8.20	8.10	8.00
- PV-27%	29.32	28.34	27.40	26.50	25.63	24.80	24.00	23.24	22.50	21.79	21.12	20.46	19.84	19.24	18.66	18.11	17.58	17.07	16.58	16.11	15.66	15.23	14.81	14.41	14.03
- PV-37%	22.61	21.89	21.21	20.55	19.92	19.31	18.73	18.17	17.63	17.11	16.62	16.14	15.69	15.25	14.83	14.43	14.04	13.67	13.31	12.97	12.64	12.32	12.02	11.73	11.45
- CSP-55%	16.24	15.99	15.75	15.52	15.29	15.07	14.85	14.63	14.43	14.22	14.02	13.83	13.64	13.45	13.27	13.09	12.91	12.74	12.58	12.41	12.26	12.10	11.95	11.80	11.65
- CSP-37%	21.96	21.59	21.24	20.89	20.55	20.22	19.89	19.57	19.26	18.96	18.66	18.37	18.09	17.81	17.54	17.28	17.02	16.76	16.52	16.27	16.04	15.81	15.58	15.36	15.14
- Ocean-55%	15.84	15.40	14.98	14.57	14.18	13.81	13.45	13.10	12.77	12.46	12.15	11.86	11.58	11.31	11.05	10.80	10.57	10.34	10.12	9.91	9.70	9.51	9.32	9.14	8.97
- Nuclear	12.85	12.84	12.84	12.84	12.83	12.83	12.83	12.83	12.82	12.82	12.82	12.81	12.81	12.81	12.81	12.80	12.80	12.80	12.79	12.79	12.79	12.78	12.78	12.78	12.78
- Supercritical coe	9.51	9.51	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.49	9.49

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