Scenario Analysis of Renewable Energy Desalination Integration in South Africa

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Abstract

South Africa is an arid country. A "climate independent" solution is desalination. Infinite renewable energy sources could address the implementation of these technologies and the environmental impacts. Recommendations to increase the water-energy-climate security of South Africa are provided in this paper. The main objective was to investigate the requirements and environmental benefits of four energy sources for seawater desalination. Secondary data from published literature was analysed with the "Long-range Energy Alternatives Planning System", using scenario analysis. This compared the trade-offs between water supply, energy demand and climate change mitigation within a South African context. The four power sources were solar, wind, wave and geothermal. Geothermal was the least practical source for South Africa. The technologies for desalination were reverse osmosis and two thermal technologies (Multiple effect distillation and Multiple/Multi-stage flash distillation). It was concluded from both analyses that the most suitable alternative for desalination, was probably wave powered seawater reverse osmosis. In the Western Cape and KwaZulu-Natal, this could be combined with existing technologies.

Keywords
Renewable energy, seawater desalination, scenario analysis, iterative analysis, LEAP.

1. Introduction and background

Greenhouse gasses and climate change cause temperature changes and reduced rainfall. This results in droughts and water deficiencies, which need to be addressed (Kitley, 2011; Ragab and Prudhomme, 2002). Consequently, water scarcities are faced by countries worldwide (Gude, 2016b:1053; Karagiannis and Soldatos, 2008:448). The severity of water shortages globally is estimated to increase by 60%, primarily in Asia, Africa and Latin America, by 2025 (Thopil and Pouris, 2016:1107). One of the arid countries is South Africa (SA) (Thopil and Pouris, 2016:1107; CSIR; 2010:4), the area selected for this study.

The aim of the study was to provide recommendations for improving water-energy-climate security in SA. The objectives were to establish the opportunities and requirements in energy sources for producing water from desalinating seawater. Another objective was to identify trade-offs between climate change mitigation, water use and energy efficiency. Contributions were towards opportunities for alternative water purification technologies and energy sources in SA for resolving the water crisis without harming the environment and added strains to the grid.

SA depends on storage and transfer from water catchment areas (Kitley, 2011:14; Thopil and Pouris, 2016:1107) since rivers do not provide sufficient water (Thopil and Pouris, 2016:1107). Water irregularities due to erratic supply have been reported in SA (Kitley, 2011:14-18). Figure 1 presents the available and required water from the catchment areas, 10 years ago and in three years' time. It is evident that water scarcities have increased since the year 2000. Less than the required amount is being supplied from 15 of the 19 catchment areas (Thopil and Pouris, 2016:1107). Additionally, the country's average rainfall is far less than the global average rainfall (Thopil and Pouris, 2016:1107; Kitley, 2011:14; CSIR, 2010:4). Regions in the Western Cape (WC), Eastern Cape (EC) and KwaZulu-Natal (KZN) provinces are arid (Water Research Commision and Department of Water Affairs and Forestry, 2014). In particular, coastal regions in the EC and WC (Turner *et al.*, 2015:1), predominantly in Cape

Town (Water Research Commision and Department of Water Affairs and Forestry, 2014), as well as KZN (Turner *et al.*, 2015:1) are gradually "outgrowing" their fresh water resources available (Turner *et al.*, 2015:1). Droughts occur in regions of the EC and Southern Cape (SC) (Blersch and du Plessis, 2017:11; Turner *et al.*, 2015:1; McGrath, 2010:54); also in Richards Bay in KZN (DWS, 2017). As a result, the water available is less than what is required at present (Figure 1).

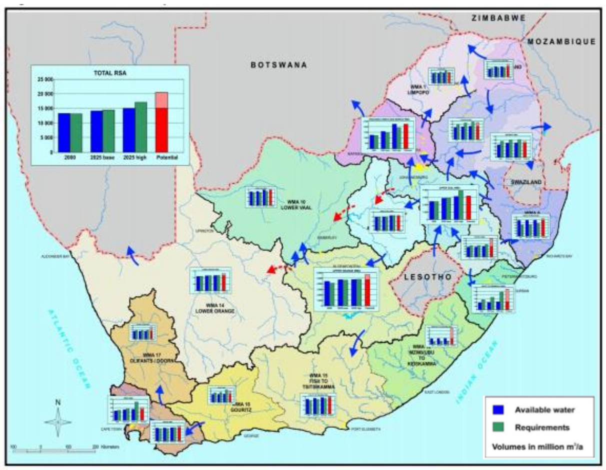


Figure 1: South Africa's water availability and requirements in 2000 and 2025
Source: Department of Water and Sanitation (2009:5)

Water purification is done using several different processes (Turner *et al.*, 2015; Swartz *et al.*, 2014:51). Brackish water (Blersch and du Plessis, 2017:11; van der Vegt *et al.*, 2011:13) or polluted groundwater can also be purified using desalination processes (Blersch and du Plessis, 2017:11). However, seawater (SW) is considered for this investigation due to its accessibility near to the driest regions in SA. Its capability for producing larger volumes (Blersch and du Plessis, 2017:11) is another contributing factor. Fresh water can be obtained from SW (Blersch and du Plessis, 2017:11) since desalination can remove salts from water through different processes (van der Vegt *et al.*, 2011:13; Banat, 2007). Thus, desalination is an alternative solution to water shortages (Blersch and du Plessis, 2017:11; Gude, 2016a:88; Turner *et al.*, 2015:2; van der Vegt *et al.*, 2011:5; Karagiannis and Soldatos, 2008:448; Kalogirou, 2005:243; García-Rodríguez, 2003:3; Ragab and Prudhomme, 2002). Popularity of desalination technologies is increasing to provide water for daily necessities as well as economic growth (Charcosset, 2009:214; Georgiou, Mohammed and Rozakis, 2015:459).

Thermal and membrane processes are the two primary types of desalination processes available (Mentis *et al.*, 2016:264; Subramani and Jacangelo, 2015:165). The two trending thermal technologies in some parts of the world are multi-stage flash distillation (MSF) and multiple effect distillation (MED) (Ghaffour *et al.*, 2015:96; Gude, 2016a:89; van der Vegt *et al.*, 2011:14). Reverse osmosis (RO) is the most commonly installed membrane technology globally (Gude, 2016a:89; Burn *et al.* 2015:4; Ghaffour *et al.*, 2015:96; Subramani and Jacangelo, 2015:165; van der Vegt *et al.*, 2011:14). It could be a vital source for the future supply of water in SA (Turner *et al.*, 2015:1). Assessments of SW desalination technologies are being done presently for regions within Cape Town, Durban, Port Elizabeth and Saldanah Bay, to determine its viability (Blersch and du Plessis, 2017:11). The subsequent section takes a closer look at the available water purification technologies, with a focus on desalination. This meets SA's goal to expand their available desalination technologies from 8 to 10% by 2030 (Kitley, 2011:9).

1.1 Water technologies in South Africa

Water reuse and desalination plants have previously been implemented to alleviate water shortages (Turner *et al.*, 2015:1; McGrath, 2010:54). The desalination plants were generally near the coast to desalinate SW (Charcosset, 2009:215). There are currently six small operational desalination plants in SA (Blersch and du Plessis, 2017:11). Half of them were implemented for emergencies due to droughts (Blersch and du Plessis, 2017:11). These include SW RO plants in Sedgefield, Mossel Bay and Plettenberg Bay. This makes them unique as they were made operational very rapidly (Turner *et al.*, 2015). Of the emergency schemes, only Plettenberg Bay plant is still operational (Bosman, 2017; Turner *et al.*, 2015:1; Swartz *et al.*, 2014:51; Kitley, 2011:32). It supplies 83 m^3/h (Kitley, 2011:32) like Knysna's desalination plant. Another non-operational desalination plant is the Lamberts Bay

RO plant (Bosman, 2017). A desalination plant was also implemented in Richards Bay recently to address the strains caused by the current drought. It produces 100 m^3/day (10 Ml/day) (DWS, 2017). The Albany Coast SW RO plant in the EC supplies 1.8 Ml/day (Turner *et al.*, 2015). Table 1 lists the reclamation and desalination plants in WC and KZN. These plants were selected for this study due to their location. It should be noted that it is necessary for the regions selected to be near the coast to desalinate SW (Charcosset, 2009:215).

Table 1: Existing water infrastructure in KZN and WC province

Plant	Umgeni water conventional[2]	Beaufort West reclamation[1]	George UF[1]	Mossel Bay UF/RO[1]	Mossel Bay SW RO[1]	Sedgefield SW RO[1]	Bitterfontein SW RO[2]
Plant Size (Ml/day)	NA	2.1	10[b]	5	15	1.5	0.288
Operational Status (Ml/day)		1.2	0	0	0	0	
O&M Cost (R/m^3)	1.28	6.92[a]	2.11[a]	2.72[a]	6.81[a]	7.16[a]	11.22
Energy Use (kWh/m^3)	R0.23/m^3	2.07	0.23	0.73	4.39	3.97	R3.39/m^3

Note: UF is the ultrafiltration plants located in the WC Province.
[a]Operations and maintenance (O&M) Cost in 2014/15
[b]Full capacity tested at 8.5 Ml/day
Source: [1]Turner *et al.* (2015); [2]Swartz *et al.* (2014:51)

Desalination of SW has become an essential freshwater source in arid countries globally. These water sources are growing in SA, particularly in the WC and the KZN Province due to droughts (Blersch and du Plessis, 2017:11; DWS, 2017; Turner *et al.*, 2015:1). Therefore, there are many opportunities in implementing these technologies. However, there also barriers which are discussed in the following sections.

1.2 Challenges in desalination

The primary constraint to using to desalination relates to costs (Cipollina *et al.*, 2015:3137; Subramani and Jacangelo, 2015:165; van der Vegt *et al.*, 2011:10; Eltawil, Zhengming and Yuan, 2009:2251; Banat, 2007). The main cost is linked to the source of energy (Subramani and Jacangelo, 2015:165; van der Vegt *et al.*, 2011:10; Eltawil, Zhengming and Yuan, 2009:2251; Banat, 2007). Non-renewable energy use also results in more greenhouse gas (GHG) emissions (Subramani and Jacangelo, 2015:165; van der Vegt *et al.*, 2011:10). This is owed to the use of conventional sources, such as fossil fuels (Subramani and Jacangelo, 2015:165) or diesel, through direct (van der Vegt *et al.*, 2011:10) or indirect integration (van der Vegt *et al.*, 2011:11). When using conventional sources, the cost and environmental challenges can be minimalised through less energy use.

Alternatives to the conventional sources can be used to power desalination plants. These include solar, wind, wave and geothermal sources (Gude, 2016a:89). However, there are difficulties in finding the best economic design for integrating desalination with renewable energy (RE) that is also viable in isolated areas (Eltawil, Zhengming and Yuan, 2009). The type of energy required for the process (heat and/or electrical) plays a major role in selecting a compatible combination for RE desalination. Table 2 presents a summary of the RE sources (S) t hat are compatible with RO, MSF and MED processes according to various sources. The chosen RE desalination amalgamations are discussed in the methodology section following the discussion of the challenges faced in desalination. This is discussed in the subsequent section prior to the research method used.

1.3 Challenges in desalination within South Africa

Challenges lie in powering these technologies from conventional sources due to the current energy shortages (Kitley, 2011:10) and climate change (CSIR, 2010:58). This is owed to 90% of SA's power being generated from coal power plants (Thopil and Pouris, 2016:1107; McGrath, 2010:38). The availability of infinite RE S is a suitable alternative (van der Vegt *et al.*, 2011; Charcosset, 2009:215; Kalogirou, 2005; García-Rodríguez, 2003; Ragab and Prudhomme, 2002). However, only 1% of the desalination technologies are powered from RE S (IEA-ET SAP and IRENA, 2012:1). T herefore, the next section takes a closer look at RES in SA.

Table 2: Suitable amalgamations

RE S Technology	**Solar PV[1]**	**Wind**	**Wave**	**Solar CSP[2]**	**Geothermal**	**Compatible power source**
RO	X	X	X	X	X	Wind: mechanical or electrical Ocean: electrical or mechanical Solar CSP: electrical Geothermal: electrical
	Sources: Cipollina *et al.* (2015:3121); Gude (2015:880); Goosen *et al.* (2011:101); Kitley (2011:37); Goosen, Mahmoudi, & Ghaffour (2010:1426); & Papapetrou, Wieghaus and Biercamp (2010:14); Eltawil, Zhengming and Yuan (2009:2247); Mathioulakis, Belessiotis and Delyannis (2007:349)		Source: Cipollina *et al.* (2015:3121); Gude (2015:880); & Papapetrou, Wieghaus and Biercamp (2010:14)	Source: Papapetrou, Wieghaus and Biercamp (2010:14)	Sources: Cipollina *et al.* (2015:3121); Kitley (2011:37); Papapetrou, Wieghaus and Biercamp (2010:14); Eltawil, Zhengming and Yuan (2009:2247); Mathioulakis, Belessiotis and Delyannis (2007:349)	
MSF				X	X	Solar CSP: thermal Geothermal: thermal
				Source: Gude (2015:880); & Papapetrou, Wieghaus and Biercamp (2010:14).	Sources: Cipollina *et al.* (2015:3121); Gude (2015:880); Kitley (2011:37); Papapetrou, Wieghaus and Biercamp (2010:14); Eltawil, Zhengming and Yuan (2009:2247); Mathioulakis, Belessiotis and Delyannis (2007:349)	
MED	X		X	X	X	Ocean: thermal Solar CSP: thermal Geothermal: thermal
	Source: Gude (2015:880)		Source: Papapetrou, Wieghaus and Biercamp (2010:14)	Sources: Gude (2015:880); & Papapetrou, Wieghaus and Biercamp (2010:14)	Sources: Cipollina *et al.* (2015:3121); Gude (2015:880); Kitley (2011:37); Papapetrou, Wieghaus and Biercamp (2010:14); Eltawil, Zhengming and Yuan (2009:2247); Mathioulakis, Belessiotis and Delyannis (2007:349)	

[1]Photovoltaic (PV)
[2]Concentrated Solar Power (CSP)

1.4 Potential RE S in South Africa

Availability of RE S is dependent on the location. SA's West Coast is ideal for implementing RE desalination, from a provincial assessment (Kitley, 2011). Solar, wind and wave energy sources are widely available in SA. The hours of sunlight annually are twofold compared to Europe (4.5 to 6.5 kWh/m^2 solar irradiance (Kitley, 2011:58; McGrath, 2010:51)). Therefore, solar energy is available through PV panels or thermal technologies, such as CSP (547.6 GW across SA) (Kitley, 2011:58). This is owed to the strong direct normal irradiance (DNI) in the Northern Cape (510 GW), Free-State (25 GW), WC (10 GW) and EC (1 GW). This is beneficial since these technologies can be coupled with desalination technologies (Kitley, 2011:58).

There are vast opportunities for wind energy in SA, particularly along the coast (Kitley, 2011:57; McGrath, 2010:49), and offshore (Kitley, 2011:57), in the WC, EC, Northern Cape, and KZN (Kitley, 2011:81). The greatest potential of these sources is in the Western and Southern Coasts. Geothermal energy was seldom researched owing to the geology formation, lack of government support and required costs (Smit, 2010).

In SA, wave energy offshore can provide an estimated 20 to 40 kW per meter wave front (McGrath, 2010:53). However, wave technologies are at the prototype stage and this energy source behaves in an inconsistent manner. Therefore, no standard wave technology appears to be available (Goosen *et al.*, 2011:100). The subsequent section discusses the methods used to analyse the potential RE S that were mentioned in combination with suitable desalination technologies.

2. Methodology

Scenario analysis is commonly used for diverse energy systems (Heaps, 2016, Novosel *et al.*, 2015:271; Novosel *et al.*, 2014:75). Various scenario-based modelling software tools are available, such as EnergyPlan (Novosel *et al.*, 2015:271; Novosel *et al.*, 2014:74) and Long-range Energy Alternatives Planning System (LEAP) (Heaps, 2016). The most suitable RE S amalgamation can be determined (Novosel *et al.*, 2015: 271). Additionally, desalination was also recently executed in EnergyPLAN to examine its impact on the energy system (Novosel *et al.*, 2015: 272). Therefore, secondary data was gathered by reviewing universal literature to formulate and analyse scenarios in LEAP. Three desalination technologies were selected with a suitable RE power source (desalination amalgamation) to formulate the scenarios owing to rationale provided in literature, such as the most frequently implemented technologies and a compatible energy source. The scenarios are:

- Scenario 1a: Solar PV sources powering SW RO.
- Scenario 1b: Wind energy sources powering SW RO.
- Scenario 1c: Wave energy sources powering SW RO.
- Scenario 2: Solar CSP sources powering MSF.
- Scenario 3a: Solar CSP sources powering MED.
- Scenario 3b: Geothermal sources powering MED.

The membrane technology selected was RO since it is the most commonly used desalination technology, globally and in SA (Blersch and du Plessis, 2017:11; Gude, 2016a:89; Burn *et al.* 2015:4; Ghaffour *et al.*, 2015:96; Subramani and Jacangelo, 2015:165; van der Vegt *et al.*, 2011:14), in addition to the rising opportunities (Turner *et al.*, 2015:1), as formerly mentioned in the introduction. This is mainly owed to its better energy efficiency (Georgiou, Mohammed and Rozakis, 2015:461; Charcosset, 2009:226; Karagiannis and Soldatos, 2008:455). Other reasons comprise of its moderately simple operation, lower water production costs (Georgiou, Mohammed and Rozakis, 2015:461), and the advancements made in membrane technologies (Karagiannis and Soldatos, 2008:455). The thermal technologies selected were due to them being the most frequently implemented thermal desalination technologies (Gude, 2016a:89; Ghaffour *et al.*, 2015:96; van der Vegt *et al.*, 2011:14), as previously mentioned.

The power sources selected for the investigation were based on previous existing cases or studies that would be most suitable for SA's driest coastal regions. Therefore, geothermal sources that could be coupled with RO technologies were excluded in this investigation. This is owed to solar, wind and wave energy sources being compatible with RO technologies, which are abundant in SA (inland and offshore). They are far more suitable than geothermal sources. Geothermal sources were only included for MED technologies for a more complete comparison. The possibility of wave energy (Papapetrou, Wieghaus and Biercamp, 2010:14) or solar PV (Gude, 2015:880) sources integrated with MED technologies were excluded in this study due to insufficient investigations available.

The trade-offs of each scenario were first evaluated in LEAP since there is a strong link between water and energy (Gude, 2016b:1039; El-nashar, 2010), as well as the environment (Gude, 2016b:1040) and should be addressed holistically (Gude, 2016b:1039; CSIR, 2010:58). Therefore, three variables were evaluated for each scenario:

- The energy required to provide a unit of water by using the final energy demand analysis, as shown in Equation 1:

$$\boldsymbol{E_D = W_A \times E_I} \qquad 1$$

Where,

E_D is the energy demand required dependent on the scenario technology, measured in kilowatt per hour (kWh) per day;
W_A is the total activity level linked to the technology, the water volume in cubic meter (m^3) per day;
E_I is the energy intensity needed to produce water (kWh/m^3), linked to the technology.

- The demand operating cost to provide a unit of water by using the final energy demand analysis, via Equation 2:

$$C_D = C_A \times W_A \qquad 2$$

Where,

C_D is the water demand cost depending on the scenario technology type, measured in US dollars ($) per day (converted to South African Rands for the iterative analysis);
C_A is the cost per activity level linked to the technology, the unit water operating cost in US$ for the LEAP analysis or South African Rands (R) for the iterative analysis per m^3;
W_A is the activity level for the cost analysis, the water capacity (m^3) per day depending on the technology.

- The emissions omitted from using a RES instead of a conventional source, such as coal, as shown in Equation 3:

$$E_U = \frac{CO_2/W_R}{E_T} \qquad 3$$

Where,

E_u is the unit of carbon dioxide (kg.CO_2) emission produced per m^3 for energy technologies (kWh/m^3);
CO_2 is the carbon dioxide emission produced (kg.CO_2);
W_R is the water requirements (m^3) dependent on the energy technology;
E_T is the energy technology used (kWh/m^3).

Subsequently, an iterative process was used to establish the implementation of scenarios versus existing water technologies in two provinces, WC and KZN, through sharing the load at different percentages ranging from 0 to 100% implemented in multiples of 2. This was achieved by evaluating the integration of the scenarios with these technologies, since benefits could be maximised and costs minimised by considering the present system as an integral portion (Blersch and du Plessis, 2017:20). Therefore, operational costs were determined for the split options (100-0%; 50-50%; 60-40%; 40-60%; 80-20%; 20-80%) and the energy requirements were determined for the least costly options. Recommendations could be made from formulating constraints to establish the validity of the scenarios and split options. If the following constraints comply for the scenario or existing technology installed for a specific split percentage, then they should be implemented as indicated in Equation 4, 5 and 6:

$$W_t \leq P_{ij}^t \qquad 4$$

Where,

W_t is the future water shortage (m^3/day) within the driest areas for the year 2025 estimated from the available and required water provided in Department of Water and Sanitation (2009:5) (refer to Figure 1);
P_{ij}^t is the water capacity produced per scenario in m^3 per day with *i* being the desalination technology, *j* being the RES coupled with *i*, and t being the selected year during which the scenario was assessed;

$$C_{ij}^t \leq R_{ij}^t \qquad 5$$

Where,

C_{ij}^t is the prospective operational cost for producing a unit of water in each scenario and/or existing technology at a split percentage in US$ or R per day;
R_{ij}^t is the operational cost of 100% implementation of a scenario/existing technology in US$ or R per day;
The purchasing power parity (PPP) exchange rate of R5.85 per US$ for the year 2017 (*OECD.Stat*, 2017) was used to convert the operational costs from US$ to R, since the PPP is based on the living local costs.

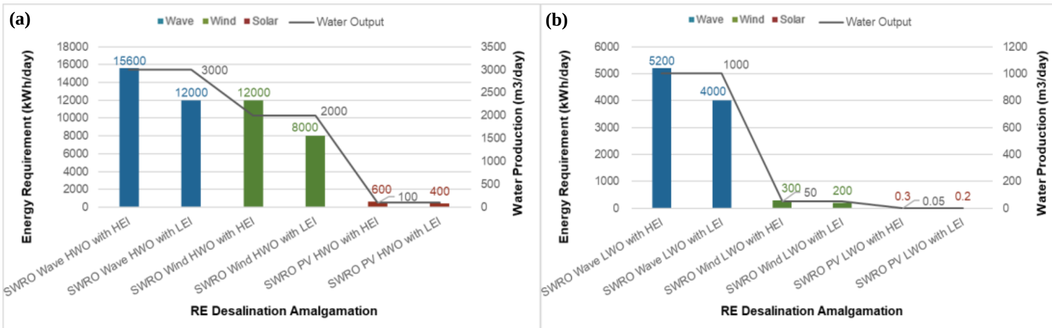
$$E_{ij}^t \leq A_j^t \qquad 6$$

Where,

E_{ij}^t is the energy demand required per least costly scenario and/or existing technology in kWh/day;
A_j^t is the energy demand for 100% implementation of a scenario/regional existing technology in kWh/day;

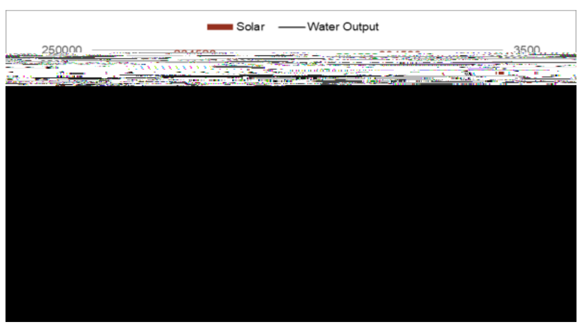
3. Results

It can be seen from Figure 2 that SW RO coupled with wave energy required the highest energy demand to produce both a maximum water volume of 3000 m^3/day and a minimum of 1000 m^3/day. This was followed by wind energy producing 50 to 2000 m^3/day and solar PV energy producing 0.05 to 100 m^3/day. There was quite a drop in the energy required to power SW RO membrane technologies to produce both maximum and minimum water volumes from solar PV sources in comparison to wind and wave energy sources. However, this was owed to the amount of water that could be produced since SW RO technologies powered by all three energy sources had similar ranges of required energy input capacities. The minimum and maximum energy inputs for SW RO from both solar PV and wind energy sources were the same, as well as the minimum energy input for wave energy with a lower maximum energy input. To produce the largest water volume from SW RO desalination technologies, the energy requirement appeared to be the same for the lowest energy input from wave energy and the highest energy input from wind energy.

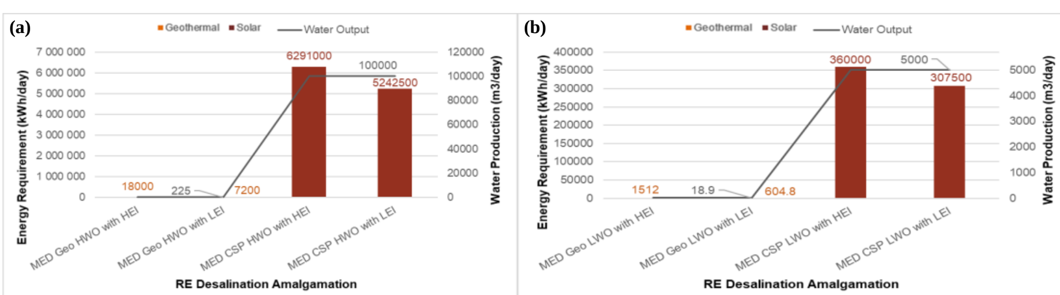


Note: high water output (HWO); low water output (LWO); high energy input (HEI); low energy input (LEI)
Figure 2: Energy demand for scenario 1 producing (a) maximum and (b) minimum water capacity

The energy requirements for producing a low and high volume of water in Scenario 2 and 3 was noticeably higher than the first scenario, as presented in Figure 3 and Figure 4. The water volume lies within a similar range for Scenario 1c and 2. Therefore, wave energy coupled with SW RO was a more suitable alternative to MSF technologies powered by solar CSP since the energy requirements were higher for Scenario 2.



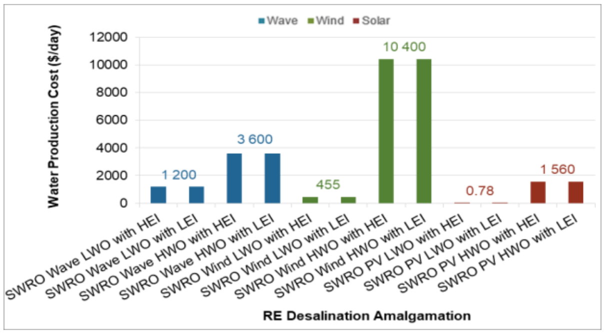
Note: parabolic trough collectors (PTC); low water output (LWO); high water output (HWO)
Figure 3: Energy demand for scenario 2 producing high and low water capacity



Note: high water output (HWO); low water output (LWO); high energy input (HEI); low energy input (LEI)
Figure 4: Energy demand for scenario 3 producing (a) maximum and (b) minimum water capacity

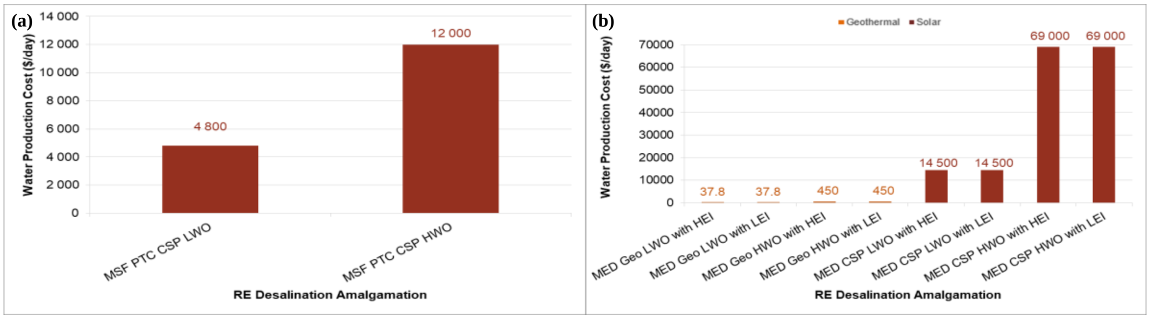
The energy requirements in Scenario 3a were considerably higher, but the water volumes that could be supplied were larger. Scenario 3b's water capacity range was like that of Scenario 1a. Therefore, by comparing the energy requirements between these two scenarios, SW RO technologies powered by solar PV sources had lower energy requirements and were thus more suitable than geothermal sources coupled with MED. However, this comparison only looked at the energy requirements and excluded other factors such as cost, location, availability, etc.

It can be seen from Figure 5 that wind energy required the highest cost; however, the water volumes that could be provided were much more than that of SW RO coupled with solar PV sources in this scenario. Therefore, the demand costs were dependent on the amount of water that can be produced within each scenario. The highest operational costs were required for solar PV sources powering SW RO, which were more than the operational costs of SW RO technologies coupled with other sources in Scenario 1, as well as the thermal combinations in the second and third scenario. Wave energy sources powering SW RO desalination technologies had the lowest operational costs in comparison to the alternatives in the first scenario in addition to the options in Scenario 2 and 3. Therefore, if lower volumes were required, wind energy sources were the most suitable in terms of operational costs for Scenario 1, whereas wave energy sources were more beneficial for higher water volumes. This could be verified by taking note of the cost of producing the maximum water volume in Scenario 1a (100 m^3/day) in comparison to the cost of producing the lowest water volume (50 m^3/day) in Scenario 1b. In addition to this, the cost is greater for producing the highest volume of water in Scenario 1b (2000 m^3/day) in comparison to the cost of producing the water volume range (1000 - 3000 m^3/day) in Scenario 1c.



Note: low water output (LWO); high water output (HWO); high energy input (HEI); low energy input (LEI)
Figure 5: Operating costs of suitable RE desalination amalgamations for scenario 1

It can be seen from Figure 6, that the second and third scenario required less operational costs than Scenario 1, meaning that the thermal desalination (MSF and MED) combinations were cheaper than the membrane technologies (SW RO) except for wave energy sources powering the membrane technology (SW RO). The higher costs indicated in Figure 6 provided higher water capacities.



Note: low water output (LWO); high water output (HWO); high energy input (HEI); low energy input (LEI)
Figure 6: Operating costs of suitable RE desalination amalgamations for (a) scenario 2 and (b) scenario 3

The emissions omitted from the use of RE S was determined by replacing them with conventional sources as presented in Table 3. Therefore, the environmental advantages of implementing the scenarios could be established, indicating that it is more beneficial to implement RE S for thermal technologies. The gap in water supply was estimated and is presented in Table 4 to determine whether the water production output of the formulated scenarios was more than the size of water shortage. All the scenarios were found to be capable of supplying the water shortage, which lies within the constraint (Equation 4).

Table 3: CO2 emissions for desalination technologies coupled with energy fuels

Technology Amalgamation	**Environmental Loading**	**Scenario**
RO-Conventional	1.78 kg.CO_2/m^3 for a 4 kWh/m^3 energy input (Raluy, Serra and Uche, 2006:2366-2367; Raluy *et al.* (2004:450-454)	Scenario 1
MSF-Coal	34.68 kg.CO_2/m^3 (Raluy *et al.* 2004:450-454)	Scenario 2
MED-Coal	26.94 kg.CO_2/m^3 (Raluy *et al.* 2004:450-454)	Scenario 3

Source: Raluy, Serra and Uche (2006:2366-2367); Raluy *et al.*, 2004:450-454)

Table 4: Future water demand estimates and shortages

	Water Availability (m^3/a)			
Location	**KZN**		**WC**	
Year 2025	**Base Range**	**High Range**	**Base Range**	**High Range**
	610	610 – 700	700 – 750	750
Average	610	655	700	750
	Water Requirements/Demand (m^3/a)			
Location	**KZN**		**WC**	
Year 2025	**Base Range**	**High Range**	**Base Range**	**High Range**
	910 – 1100	1500 – 1510	780	1300 – 1400
Average	1005	1505	780	1350
	Water Shortage (m^3/a)			
Location	**KZN**		**WC**	
Year 2025	**Base Range**	**High Range**	**Base Range**	**High Range**
	300 – 490	890 – 810	80 – 30	550 – 650
Average	395	850	55	600
	Water Shortage (m^3/day)			
Location	**KZN**		**WC**	
Year 2025	**Base Range**	**High Range**	**Base Range**	**High Range**
	0.822 - 1,342	2.438 - 2,219	0.219 – 0.082	1.507 – 1.781
Average	1.082	2.329	0.151	1.644

The operational costs were determined for the different split options. The results are included for the 100-0% split options in Table 5 and Table 6, which all the splits were compared to for checking the cost and energy constraints (Equation 5 and 6). Thus, only the raw data was included in the article. The main outcomes were the same for the other split options in comparison to the 50-50% split alternatives. The results indicated that the operational costs of all the wastewater treatment plants were lower than the scenarios and existing desalination plants, except for the Beaufort West reclamation plant in the WC, for the maximum 100-0% split option. Scenario 1c, Scenario 3b, and the Mossel Bay SW RO desalination plant in the WC had lower costs operationally than the Beaufort West plant, in addition to the SW RO desalination plant in Sedgefield and Bitterfontein, both located in the WC, as well as the other scenarios (3a, 2, 1b, 1a), in that order, with negligible differences in cost.

The costs shared between the technologies at a certain split percentage could be added to compare them to the corresponding technology used at full capacity (100-0% split possibility). Therefore, establishing viable and non-viable options was possible (Equation 5 in Section 2). The results indicated that none of the options were viable when the existing technologies were combined with Scenario 3a and Scenario 2. Scenario 3b or 1c were viable options when combined with some of the technologies. For example, suitable options for combining Scenario 3b or 1c with one of the following existing technologies: Mossel Bay's SW RO plant; Beaufort West's plant; Sedgefield's or Bitterfontein's SW RO plant; were viable through a 50-50%, 40-60%, 60-40%, 20-80% or 80-20% shared load for the smallest cost possibility. However, non-viable options for combining Scenario 3b or 1c with existing technologies were Umgeni's reclamation plant, the reclamation plant in George or Mossel Bay's UF/RO plant.

Table 5: Minimum and maximum cost of producing the average water shortage from a 100-0% split

Technology	Minimum Average Water Production Cost (R/day) [1]				Maximum Average Water Production Cost (R/day)			
	KZN		WC		KZN		WC	
	Base Range	High Range	Base Range	High Range	Best Range	High Range	Base Range	High Range
Umgeni	1.39	2.98	-		1.39	2.98	-	
George UF	-		0.32	3.47	-		0.32	3.47
Mossel Bay UF/RO	-		0.41	4.47	-		0.41	4.47
Scenario 3b	3.93	8.45	0.55	5.96	12.08	25.99	1.68	18.35
Scenario 1c	4.23	9.10	0.59	6.42	7.25	15.59	1.01	11.01
Mossel Bay SW RO	-		1.03	11.19	-		1.03	11.19
Beaufort West	-		1.04	11.38	-		1.04	11.38
Sedgefield SW RO	-		1.08	11.77	-		1.08	11.77
Bitterfontein SW RO	-		1.69	18.44	-		1.69	18.44
Scenario 3a	13.89	29.89	1.93	21.10	17.51	37.68	2.44	26.60
Scenario 2	15.10	32.49	2.10	22.93	24.15	51.98	3.36	36.69
Scenario 1b	39.25	84.46	5.47	59.62	54.95	118.25	7.65	83.47
Scenario 1a	70.05	150.74	9.75	106.40	94.20	202.71	13.12	143.09

Alternatively, for the largest cost possibility, practical options were Scenario 3b or 1c combined with Bitterfontein; or combining either Mossel Bay's SW RO plant, Beaufort West's plant or Sedgefield's plant with Scenario 1c. The non-viable options for the smallest costs were also unsuitable for the largest cost alternative, as well as Mossel Bay SW RO's plant, the reclamation plant in Beaufort West or Sedgefield's SW RO plant combined with Scenario 3b. The energy requirements were determined for the least costly split options and are presented in Table 6. Furthermore, viable and non-viable options could be determined by comparing the shared energy demands of these least costly options with 100% implementation (Equation 6 in Section 2). The results indicated that the only viable option was Scenario 1c and that Scenario 3b required the most energy compared to the other split alternatives of lowest cost.

Table 6: Minimum and maximum energy requirement from a 100-0% split

Technology	Minimum Average Energy Requirements/Demand (kWh/Day)				Maximum Average Energy Requirements/Demand (kWh/Day)			
	KZN		WC		KZN		WC	
	Base Range	High Range	Base Range	High Range	Base Range	High Range	Base Range	High Range
Umgeni	Unknown		-		Unknown		-	
George UF	-		0.03	0.38	-		0.03	0.38
Mossel Bay UF/RO	-		0.11	1.20	-		0.11	1.20
Scenario 3b	34.63	74.52	4.82	52.60	86.58	186.30	12.05	131.51
Scenario 1c	4.33	9.32	0.60	6.58	5.63	12.11	0.78	8.55
Mossel Bay SW RO	-		0.66	7.22	-		0.66	7.22
Beaufort West	-		0.31	3.40	-		0.31	3.40

[1] For US dollar conversions, either use the PPP exchange rate of R5.85/US$ or the actual exchange rate of R14.71/US$, for the year 2017 (*OECD.Stat*, 2017).

An important observation from the findings was that the desalination plant in Mossel Bay, WC, which is currently not operational, was cheaper to operate than the reclamation plant in Beautfort West, WC, as well as most of the scenarios. It should also be noted that the cost difference between the reclamation plant in Beaufort West and the three SW RO plants considered in this investigation was minimal, with the Bitterfontein SW RO plant costing the most, in terms of its operations, with a larger gap in cost difference. The conclusions based on the main findings are discussed in the following section.

4. Conclusions and Recommendations

The three trade-offs (water, energy and the environment) were addressed with the alternatives provided in this study. The main conclusions from the analysis were that reverse osmosis was the preferred technology since thermal technologies (MSF and MED) needed larger energy demands. This was in agreement with the desalination technology trends globally (Georgiou, Mohammed and Rozakis, 2015:461; Goosen *et al.*, 2011:98; van der Vegt *et al.*, 2011:14; Charcosset, 2009:226; Eltawil, Zhengming and Yuan, 2009:2251; Karagiannis and Soldatos, 2008:455). The results also showed that MED required less energy than MSF, which coincided with the literature by van der Vegt *et al.* (2011:14). However, MSF and MED had lower operational costs than membrane technologies (SW RO), which contradicted the literature by Gude (2016a:90) and Georgiou, Mohammed and Rozakis (2015:461).

The findings showed that wave energy sources powering SW RO technologies required the lowest operational costs in comparison to other scenarios. Wind energy sources were most suitable for producing lower water capacities (small to large). Alternatively, wave energy was more appropriate to produce larger volumes (large sizes). Solar PV sources powering SW RO was fit for supplying low volumes of water (small to medium), while wind or wave energy was more fit for supplying higher capacities. However, they required the most operational costs. It was interesting to note that the operational costs appeared to be more for less water capacities produced. Possible combinations to share the load with existing technologies in SA was SW RO powered by wave energy at a percentage ranging from 20 to 80%, as well as 100% implementation. Reasons for this were:

- Less operational costs; and
- Less energy demands (reduced or similar).

Therefore, wave energy powering SW RO technologies was the optimum scenario for shared implementation of SA's existing technologies in the WC and KZN Province. Additionally, it was also the most suitable alternative compared to all the scenarios. Geothermal sources integrated with MED technologies was the second-best alternative for shared integration. This was owed to the maximum cost of the plant in this scenario being lower and similar to the operational cost of the Bitterfontein's SW RO plant. Solar PV sources provided an expensive alternative in comparison to the other scenarios as well as the existing technologies in the WC and KZN provinces and should, therefore, be avoided. Wind (powering RO) and solar CSP (powering MSF or MED) were also costly options compared to the existing infrastructure within the two provinces. Solar CSP sources powering the thermal technologies were found to be unsuitable when combined with existing technologies. The Umgeni conventional plant in KZN, the UF plant in George and Mossel Bay's UF/RO, both in the WC, should be kept operational. However, this is from an operational cost perspective. The implementation of MED-Geothermal and SW RO-Wave would be beneficial since there was a jump in the costs between these two scenarios and the SW RO plant in Mossel Bay as well the reclamation plant in Beaufort West, followed by the SW RO plants in Sedgefield and Bitterfontein.

Desalination technologies are recommended for addressing the problems that SA face. This complies with the National Desalination Strategy along with the Draft Strategy for Reuse (Turner *et al.*, 2015:1). Thermal technologies are not very prominent solutions in SA. Therefore, it can be confirmed that RO membrane technologies are more suitable solutions in SA, particularly in the WC and KZN provinces. This supports SA's desalination strategies that have already being implemented in some regions, primarily as emergency schemes. However, there are cleaner and cheaper alternatives with lower energy demands through the implementation of RE desalination, such as SW RO coupled with wave energy sources as well as MED powered by geothermal sources. This was proven by comparing these alternatives to the non-operational desalination plants installed in the WC for emergencies, such as in Mossel Bay, Sedgefield and Bitterfontein. In addition to this, these alternatives are also more suitable than some reclamation plants, such as in Beaufort West, in terms of cost, energy and the environment. Therefore, desalination plants should be integrated with existing water reuse plants to alleviate the load that the plant cannot produce. This complies with the same strategy mentioned above since it suggested that desalination and reuse should be considered in upcoming systems (Turner *et al.*, 2015:1). It is recommended that more studies should be done to establish its potential in SA.

Sustainable methods that comply with the updated National Water Resource Strategy (NWRS2) from the Department of Water Affairs (2013) can be achieved through these recommendations. The RE alternative approach to power the desalination technologies also complies with the Department of Energy's goal of expanding RES due to the energy demand and CO_2 emission status in SA (Government Communication and Information System, 2015:65). Additionally, this also coincides with the National Development Plan (Government Communication and Information System, 2015:65) and the National Climate Change Response Policy (Government Communication and Information System, 2015:64). These policies primarily recommended solar, wind and hydro sources, however, the findings from this analysis indicated that it would be more beneficial to implement wave energy technologies due to the lower costs and energy involved for powering desalination technologies, compared to the costlier solar PV, wind and solar CSP sources.

Investments should be considered for implementing these technologies, which are widely available in the arid coastal regions, such as in the WC and KZN provinces. It is also recommended that large desalination plants should be implemented since the operational costs were lower for large water capacities and wave energy would be able to produce these capacities. If geothermal sources were more prominent in SA, then thermal technologies, mainly MED, integrated with these sources would be a practical alternative for shared implementation between existing and non-existing infrastructure in the WC and KZN provinces. However, it should be noted that these technologies need high energy demands. Therefore, more investigations regarding the potential of geothermal sources in SA should be considered, which is in accord with Smit (2010). There are also gaps in the current research locally and globally regarding the exact energy demands, water production volumes, along with the costs for all types of RE desalination integrations.

Further research could include hybrids, such as combing Forward Osmosis (FO) membranes to RO membranes to improve RO operations, amongst other alternatives, since some of FO's advantages outweigh RO's disadvantages as demonstrated by Goh *et al.* (2016:54). The thermal technologies (MSF or MED) could also be combined with RO to add flexibility, as mentioned by van der Vegt *et al.* (2011:15), to improve the desalination technology in the first scenario, as well as the desalination technologies considered in the subsequent two scenarios, allowing the brine from the plant to be discharged easier with these integrations, which can resolve post-treatment costs associated with RO according to van der Vegt *et al.* (2011:15). RE hybrids could also be selected for future research to improve the efficiency of energy sources in terms of consistency. Alternatively, other sources such as biomass could also be considered as a source for powering desalination in KZN as indicated by the Department of Energy (2015).

Additional environmental risks from the desalination technologies could also be evaluated. For instance, MSF and MED technologies have high-risk environmental impacts, such as heat, brine, cleaning solvents and energy, while RO technologies have an elevated risk in noise environmental impacts (Kitley, 2011:30). The desalination technologies selected for the analysis all release brine allowing further research regarding the generated brine and heat storage for thermal technologies. The environmental impacts from the energy source used could also be assessed in future research for several airborne emissions from various conventional energy sources, such as natural gas, coal and oil, as well as hybrids as stated by Raluy, Serra and Uche (2006) and Raluy *et al.* (2004), since only CO_2 airborne emissions were considered in this investigation. Further research could also evaluate additional costs that were excluded in this study since only operational costs were assessed, as well as the regional energy constraints that would influence the implementation of desalination technologies in SA.

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