# Techno economic viability of desalination processes in South Africa

**By**

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# ABSTRACT

**TITLE:** Techno economic viability of desalination processes in South Africa

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The provision of fresh water to sustain current economic development and the ever increasing population is one of the world's greatest challenges and will become increasingly acute in the immediate future. South Africa is currently utilizing 98% of its available fresh water and with the current growth in population and economy fresh water will rapidly become a limited resource. Cape Town, Port Elizabeth and Durban have been identified by the Department of Water Affairs and Forestry as coastal cities that will be under immense fresh water availability pressure around 2025. Desalination was identified as a viable method to increase coastal freshwater supply.

Desalination costs are greatly improved by co-locating the desalination plant at a viable energy/power source. Costs are primarily improved by sharing existing seawater inlet and outfall infrastructure as well as utilizing waste heat produced by the energy source. Generally power plants are the best candidates for desalination co-location. As a large part of the industrial developments are located in the coastal regions, the co-location of seawater desalination plants becomes a viable option. Koeberg nuclear power station at Cape Town, the Thyspunt site proposed for the nuclear power plant fleet and the Coega site proposed for the combined cycle gas turbine power plant at Port Elizabeth and the Shakaskraal site proposed for the combined cycle gas turbine power plant at Durban were identified as possible co-location options.

This dissertation presents a techno-economic viability study of different desalination processes in South Africa. The evaluated processes included reverse osmosis, multi stage flash and multi effect distillation as well as a hybrid combination of multi stage flash-reverse osmosis and multi effect distillation-reverse osmosis. The main factors affecting desalination economics such as the selection of the desalination technology, energy source, plant size, plant configuration and certain site specific factors including seawater temperature and quality were assessed and taken into account during the costing evaluations. The independent desalination economic costing programs DEEP 4.0 and WTCost II© were used for the cost evaluation at each identified site.

The results from both costing programs identified reverse osmosis as the most economically viable desalination process to be applied on the South African coast. The water transport cost was identified as a costing factor that had a substantial influence on the total cost of all desalination processes, especially on small-scale desalination plants.

# OPSOMMING

**TITEL:** Tegno-Ekonomiese lewensvatbaarheid van ontsoutingsprosesse in Suid Afrika

**OUTEUR:** Louis Jacobus Laubscher

**STUDIELEIER:** Dr. Barend Botha

Die volhoubare voorsiening van varswater om die huidige ekonomiese ontwikkeling en toenemende bevolkingsgroei te onderhou, is een van die grootste uitdagings vir die wêreld in die onmiddellike toekoms. Suid-Afrika gebruik tans 98% van sy totale beskikbare waterbronne en met die huidige groeitempo in die bevolking en ekonomie, sal varswater gou as ‘n hulpbron ingeperk word. Kaapstad, Port Elizabeth en Durban is deur die Departement van Waterwerke en Bosbou geïdentifiseer as kusdorpe wat in 2025 onder heuwige varswater tekortkominge sal ly. Seewater ontsoutingsprosesse is geïdentifiseer as ‘n lewensvatbare metode om varswater te voorsien.

Seewater ontsoutingskostes kan grootliks verlaag word deur die ontsoutings-aanlegte by ‘n bestaande energiebron te plaas (gekombineerde-vestiging). Kostes word hoofsaaklik gespaar deur gebruik te maak van bestaande seewater inlaat en uitlaat infrastruktuur en uitskot hitte wat deur die energiebron (fasiliteit) vervaardig word. Kragstasies word gewoonlik aangewend vir hierdie doeleindes. Aangesien ‘n groot gedeelte van die ontwikkeling tans op die kusgebiede plaasvind, kan die lewensvatbaarheid van seewater onstouting in die gebiede so verhoog word. Die Koeberg kernkragstasie naby Kaapstad, die beplande Thyspunt kernkragstasies en beplande gekombineerde siklus gasturbine kragstasie naby Port Elizabeth en die beplande Shakaskraal gekombineerde siklus gasturbine kragstasie naby Durban was geïdentifiseer as moonlike gekombineerde-vestigings opsies.

Die skripsie bied ‘n tegno-ekonomiese lewensvatbaarheidstudie van verskillende ontsoutingsprosesse in Suid-Afrika. Die prosesse wat beoordeel is sluit omgekeerde osmose, multi-stadium flits distilasie, multi-effek distilasie en ‘n hibriede kombinasie van die prosesse in.

Verskeie hooffaktore soos die gebruik van verskeie ontsoutingsprosesse; energie- en kragbronne; die kapasiteit van die ontsoutingsaanleg; die konfigurasie van die ontsoutings-aanleg en gebied-spesifieke fakore soos seewater temperatuur en kwaliteit is geidentifiseer en

in ag geneem in die koste berekeninge. Die onafhanklike ekonomiese ontsoutingskoste beoordelingsprogramme DEEP 4.0 en WTCost II© was gebruik vir die koste berekeninge.

Die resultate van beide ekonomiese ontsoutingskoste beoordelingsprogramme het aangedui dat omgekeerde osmose die ekonomies voordeligste ontsoutingsproses is om by elkeen van die gekose gebiede in Suid-Afrika aan te wend. Daar is ook bevind dat die watervervoerkoste ‘n beduidende bydra tot die totale ontsoutingskoste het, veral in kleiner ontsoutings-aanlegte.

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| | |
|---|---|
| **As** | Specific heat transfer area |
| **BPST** | Back Pressure Steam Turbine |
| **BR** | Brine Recycle |
| **CCGT** | Combine Cycle Gas Turbine |
| **DWAF** | Department of Water Affairs and Forestry |
| **ED** | Electro Dialysis |
| **ENR** | Engineering News Record |
| **ESCWA** | Economic and Social Commission for Western Asia |
| **HT-MED** | High-temperature |
| **IDZ** | Industrial Development Area |
| **kWh** | Kilowatt hours |
| **LNG** | Liquefied Natural Gas |
| **LT-MED** | Low-temperature |
| **MED** | Multi Effect Distillation/Desalination |
| **MSF** | Multi Stage Flash |
| **Necsa** | National Energy Corporation of South African |
| **Nersa** | National Energy Regulator of South African |
| **NNR** | National Nuclear Regulator |
| **O&M** | Operational and maintenance cost |
| **PBMR** | Pebble Bed Modular Reactor |
| **ppm** | parts per million |
| **PR** | Thermal performance ratio |
| **RO** | Reverse Osmosis |
| **SMcw** | Specific flow rate of cooling water |
| **TDS** | Total Dissolved Solids |
| **W** | Specific power consumption |
| **WTC** | Water Transport Cost |

# CHAPTER 1

## Introduction

# 1 Introduction

## 1.1 Background

South Africa as many other developing countries such as Mexico, Pakistan, and large parts of China, India, Near East and North Africa, currently suffers from a fast increasing acute water scarcity. As one of the most important resources for sustained development it remains an issue that needs to be addressed urgently. These countries also largely depend on irrigated agriculture for survival, which represents the bulk of the demand for water in these countries. The three largest water consuming sectors in South Africa are agriculture (62%), domestic (27%) and urban (23%). The smaller water consuming sectors are mining (2.5%), power generation (2%), industrial (3.5%), forestry (3%) and rural (4%) (McGrath, 2010). Agriculture is therefore also usually the first sector affected by increased scarcity of water of acceptable quality, directly resulting in a decreased capacity to maintain per capita food production while also trying to meet water needs for domestic, industrial and environmental purposes. In order to support their water needs, countries therefore need to focus on the efficient use of all available water sources (groundwater, surface water and rainfall) and on water allocation strategies that will maximize the economic and social returns to limited water resources, and at the same time enhance the water productivity of all sectors (Hinrichsen, Robey, & Upadhyay, 1997). It is therefore essential that sustainable freshwater availability is treated as one of the most important, if not the most important, issues to be addressed in every country, but even more so in the developing countries.

The increasing demand on the availability of fresh water in South Africa emphasizes the need to act proactively to ensure that the sustainable fresh water supply does not follow the same path as that of other African countries of even that of the dwindling electricity supply capacity of South Africa. Proactive implementation of programs to install new power generation capacity when the increasing need was initially predicted could most probably have avoided the load shedding problem. This raises the question of what will be learnt through this experience.

With the increasing water demand pushing South Africa onto the verge of a water shortage crisis fast it should be clear that it is essential that proactive plans be implemented as soon as possible to prevent happening recurrence of the electricity situation (McGrath, 2010). One such plan could be to investigate the potential of using seawater desalination to convert the ample supply of seawater to usable water, especially as coastal regions come under increased fresh water supply pressure. Improving desalination technology has further also made this an increasing global research interest for quite some time. One of the important successes in exploiting the potential for seawater desalination is the drastic cost reductions achieved during the last decade, thus making desalination more viable economically. This resulted in a number of large scale, commercially proven, desalination plants worldwide. The two main desalination technologies are thermal desalination and membrane desalination. Thermal desalination consists mainly of multi effect distillation (MED) and multi flash distillation (MSF). These processes consume heat as energy and can, therefore, be considered for co-generation configurations using excess steam from the power turbine as the heat source. Membrane desalination consists of mainly reverse osmosis (RO). The RO process consumes electricity rather than heat as energy source and is a more recent technology than thermal desalination. Of the total installed desalting capacities in the world, 25% consists of MSF, 8% of MED and 53% RO and 14% of other desalination technologies (United Nations, 2009).

Although significant reductions have been achieved, it remains important to try and maximize the economic viability of the process. One option for improving the economic viability even further is utilizing the waste heat from other industrial applications. Locating the desalination plant at its power (heat) source also results in economic advantages such as lowering desalination operating cost.

Desalination plants consist of the following plant configurations (IAEA, 2000):

*Stand alone desalination plants;* consist of a power source that only produces power/heat/electricity for the desalination plant; and

*Co-generation desalination plants; where* the power source produces electricity and water as end products.

South Africa is in the fortunate position to have a vast coastline, which makes the country a prime candidate to implement seawater desalination to increase the costal fresh water supplies. The need therefore exists to determine which seawater desalination technology would be best suited to be implemented on the South African coast.

## 1.2 Problem statement

As with most other countries, South Africa’s water resources are on the brink of a crisis and drastic action and decisions need to be taken to ensure that the country’s water availability does not become limited and restricted. This decision making requires certain information regarding tapping as yet unused water resources such as the seawater desalination. Seawater desalination is a well known and established technology to produce fresh water. It has been utilized extensively worldwide to increase fresh water availability. The question posed in this thesis is what desalination technology would be best suited for current and future conditions in South Africa.

Presently, there is very little information available on the implementation of seawater desalination in South Africa together with the major site specific factors influencing the overall economics of such a project. There are various coastal regions in South Africa coming under increasing fresh water availability pressure due to population and economic growth. There is a need to perform studies to determine the economic viability of the available desalination technologies in different coastal regions. This will lay the foundation to help ease current and future decision making regarding seawater desalination.

Electricity tariffs have increased by 25% annually from 2010 to 2012. RO desalination plants only use electricity as their energy source therefore increasing production costs every time the electricity tariff increases. This could lead to situations where the thermal desalination plants utilizing waste heat as heat source, could actually become more cost effective than membrane desalination plants utilizing electricity as the energy source in the near future.

Thermal desalination (MED and MSF) plants use heat source together with electricity as power source. By utilizing waste heat produced by any viable source, large cost reductions can be achieved increasing the economic viability of desalination processes. However, with the current volatility in the fossil fuel price and the possibility of implementing carbon tax, co-locating desalination plants at fossil fuelled power plant producing $CO_2$ emissions could lower the future feasibility significantly.

One power source which is not influenced by the current volatility of fossil fuel prices and the implementation of carbon tax is nuclear power stations. Nuclear power stations also produce a large amount of waste heat which can be utilized by desalination plants as energy source. Co-locating a seawater desalination plant at nuclear power plants could therefore lead to the possibility of more stable desalination production costs. Nuclear desalination has also been implemented successfully in various countries around the world.

During the development of the PBMR the question therefore arose whether the feasibility could be increased adding desalination. One of the spinoffs of the PBMR is the availability of waste heat produced by the power plant. Connecting this with desalination, therefore, offers the opportunity for producing electricity as well as freshwater, subsequently addressing both electricity and freshwater supply problems. In 2009, it was announced that the PBMR project would be terminated. This lead to a change in the future prospects of new nuclear power plants. However, with the cancelation of the PBMR the government announced its commitment to still invest in nuclear power plants to increase the country's power generation capacity. The focus of possible realistic nuclear heat sources in this study therefore shifted from the PBMR to Koeberg and the potential future nuclear power stations.

## 1.3 Research objective

The objective of this study is to determine which seawater desalination technology would be most economically viable in the different coastal regions of South Africa. This is accomplished by researching the following factors:

- Identifying specific sites on the South African coast under increasing fresh water availability pressure;
- Studying different types of desalination technologies to identify the critical parameters for siting and cost;
- Investigating different desalination plant configurations;
- Identifying facilities producing waste heat for co-location configurations in order to optimise efficient use of resources;
- Identifying the major factors influencing desalination economics;
- Identifying site specific parameters influencing desalination economics including; inlet water temperature and existing infrastructure; and
- Investigating different coupling methods connecting the desalination plant and the power/heat source (power plant) for waste heat utilization.

By researching all of the above mentioned factors a comparison can be made between the economic viability of the different desalination technologies situated at various locations along the South African coast.

The scope of this study is, therefore, to determine which desalination process would be the most economically viable for South Africa by incorporating possible realistically viable energy sources producing waste heat to increase the viability of seawater desalination.

## 1.4 Methodology

This economic viability study is performed using commercially available independent established computer software costing models WTCost II© (WTC) and DEEP 4.0. The software programs will be used to compile and interpret the results to verify trends identified between the different scenarios. The results from the independent established computer software costing models will be compared to validate the results. It should be noted that the scope of this study is only to use the software programs and not to compare and analyse the programs to each other, rather only the results.

Five different scenarios will be established containing all possible configurations mentioned above. The water production, transport and total water cost for each scenario will then be determined where applicable. The results obtained from the software programmes will be analysed whereby conclusions and recommendations will be drawn. Comparing the results will enable the identification of the preferred desalination process for the various South African locations. The methodology used can then be applied to other locations as well.

# CHAPTER 2

Literature Study

# 2 Literature study

## 2.1 Introduction

This chapter includes the general information on the different desalination technologies including reverse osmosis (RO), multi effect distillation (MED) and multi stage distillation (MSF). These are the technologies which have been used predominantly worldwide. General desalination economics is also included in this chapter together with possible heat sources for implementing seawater desalination in South Africa with the main focus on nuclear power. Possible water shortage coastal areas in South Africa are identified where seawater desalination can be implemented.

## 2.2 The need for desalination

Water is, literally, the source of life on earth. Human civilization cannot exist without water. Therefore, water should be seen as the most important natural resource on earth. Although seventy percent of the planet is covered with water, only 2.5% of that is fresh water (Shiklomanov, 1999). Of the 2.5% almost 70% is frozen in the arctic ice caps of Antarctica and Greenland. The other 30% is found in soil water and deep aquifers or in the form of monsoons or floods that are difficult to contain and exploit. This means that only 0.08% of the world's water is actually accessible for direct human use and even that is very erratically dispersed. Currently, 2.5 billion people live in areas that are water-stressed and 1.7 billion of them live in water-scarce areas, where water availability is less than 1 000 $m^3$/year per person. Statistics show that in 2025, people living in water-stressed areas will rise to 2.4 billion and in water-scarce areas to 3.5 billion (IAEA-TECDOC-1326, 2000).

The major factors playing a role in the decline of fresh water availability are:

- Population increase;
- The demand for fresh water has been rising in response to industrial development;
- Increased reliance on irrigated agriculture;
- Massive urbanization; and
- Rising living standards.

In this century, while the world population has tripled, water withdrawals have increased by more than six times. Since 1940, annual global water withdrawals increased by an average of 2.5% to 3% a year compared with annual population growth of 1.5% to 2%. Over the past decade, water withdrawals have increased by 4% to 8% a year. The fresh water supply made available for human use is shrinking, due to the result of increasing levels of fresh water resource pollution. In some countries, fresh water resources like lakes and rivers have become polluted by despicable wastes, including untreated to treated municipal sewage, toxic wastes and chemicals from industrial areas and harmful chemicals from agricultural activities. The world, including South Africa, needs to act as soon as possible; firstly, to protect and maintain its current fresh water supply and, secondly, to increase this supply to meet future demand (Hinrichsen, Robey & Upadhyay, 1998).

Closer to home, South Africa is classified as a semi-arid country. The most limiting natural resource is fresh water. The fresh water resources in South Africa are almost fully utilized and under heavy stress. This is due to the massive increase in population growth and economic development rates. The population in South Africa increased exponentially during the last century. The current total level is over 40 million (estimated around 47.4 million). An increase in population means an increase in fresh water demand. It is predicted that by 2030 the fresh water demand will increase by 50%. Economic growth is directly coupled to industrial growth. The increase in industries brings an increase in fresh water demand. Many current fresh water resources are being polluted by industrial effluence, domestic and commercial sewage, acid mine drainage, agricultural runoff and litter (Cilliers, 2008). Most of the water resource infrastructure and water services need to be upgraded to keep up with demand.

A decrease of only 1% in quality and usability of water in South Africa may result in the loss of 200,000 jobs, a drop of 5,7% in disposable income per capita, and an increase of 5% or ZAR18,1 billion in government spending (Biyase, 2010).

It is well known that fresh water is becoming the limiting resource in South Africa, and supply will become a major restriction to the future socio-economic development of the country, in terms of both the amount of water available and the quality of what is available. It is, therefore, paramount to secure the country’s current fresh water resources and future availability to ensure the stability for present and future growth for South Africa.

According to McGrath (2010) the current water use per sector in South Africa is:

- Agriculture 62%,
- Domestic 27%,
- Urban 23%;
- Rural 4%,
- Mining 2.5%,
- Industrial 3.5%,
- Power generation 2.0%, and
- Forestation 3.0%.

The three largest water consuming sectors are agriculture, domestic and urban with agriculture as the largest. Within 50 years, the western regions of South Africa will be drier, experience less rainfall and interior air temperatures will increase (McGrath, 2010). With the Western Cape dependant on surface water, an increase in air temperature would increase the rate of evaporation in rivers and dams thereby further reducing water levels. Cape Town has in the past year experienced one of the worst precipitation figures in 90 years. The department of water affairs and forestry (DWAF) has disclosed that the western part of the Western Cape is in a severely dry period and a drought, such as experienced in the Southern Cape, could have dire consequences (Thomas, 2010).

The national water resource strategy (NWRS) states that the national water deficit by 2025 would be 2044 million cubic meters. Of all the water management areas; the Berg in the Western Cape, Mvoti to Mzimkulu in Kwazulu-Natal, and the Upper Vaal in Gauteng would be affected the most. The Western Cape and Southern Cape are prone to drought and mostly rely on surface water for fresh water supply (DWAF, 2004).

According to the DWAF in recent years, the technology in this field has improved significantly and the associated energy use and costs have decreased to the extent that feasibility must be taken seriously especially in the Western Cape. The possible affects of climate change on the availability of surface and groundwater puts another important perspective on the desalination of seawater (DWAF, 2006). This statement indicates that the government has already identified the Western Cape as a potential site for desalination.

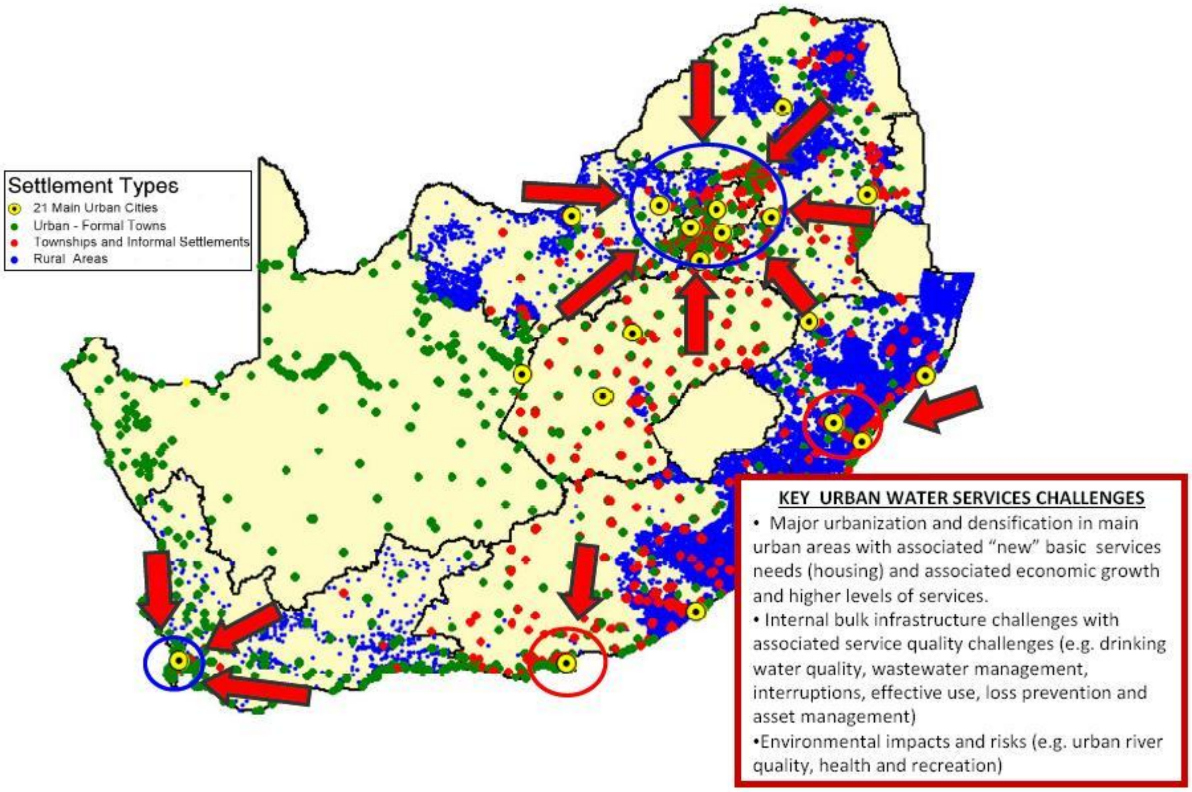



**Figure 1: Areas where urbanization and densification are putting stress on freshwater availability (DWAF, 2006).**

As indicated in Figure 1, the Western Cape is not the only part in South Africa where freshwater availability is put under stress. Freshwater availability in the Gauteng, Eastern Cape and Kwazulu-Natal are, in addition, put under continuing stress due to urbanization and densification. Cape Town, Port Elizabeth (PE) and Durban are the cities identified in Figure 1 located on the South African coast where freshwater supply needs to be increased and, therefore, prime candidates for potential fresh water production from seawater.

One way to secure fresh water availability is seawater desalination. Arid countries, especially in the gulf region, use seawater desalination as a primary fresh water resource. The technologies have improved extensively over the last 50 years making it more affordable. South Africa is in a privileged position with an extensive coastline and, therefore, the logical step is to make use of this potential freshwater resource. Seawater desalination can increase and sustain the country's coastal fresh water supply and thereby ensure future economic growth in these regions.

The demands for fresh water would continue to increase as populations grow worldwide and standards of living improve. Conservation measures in South Africa such as the upgrading of water networks to minimize leakages and recycling of used water can only decrease future demands somewhat. Infrastructure securing fresh water availability is needed as soon as possible to ensure future growth potential in the country.

With the increasing need for fresh water clearly identified, desalination is one of the most used methods of producing freshwater from unusable water sources like seawater and brackish land water. Of these unusable sources, seawater (67%) is the predominant 'unusable' source used to produce fresh water, since it is a predominant source available (Figure 2). In 1999, MSF accounted approximately for 78% of the global production capacity and RO only 10%. In 2008, RO accounted for approximately 53%, MSF 25% and MED 8% of the global seawater desalination capacity as indicated in Figure 3. This shows that in the last 10 years the focus of the dominant desalination technology shifted from thermal desalination (MSF) to membrane desalination (RO) (United Nations, 2009).

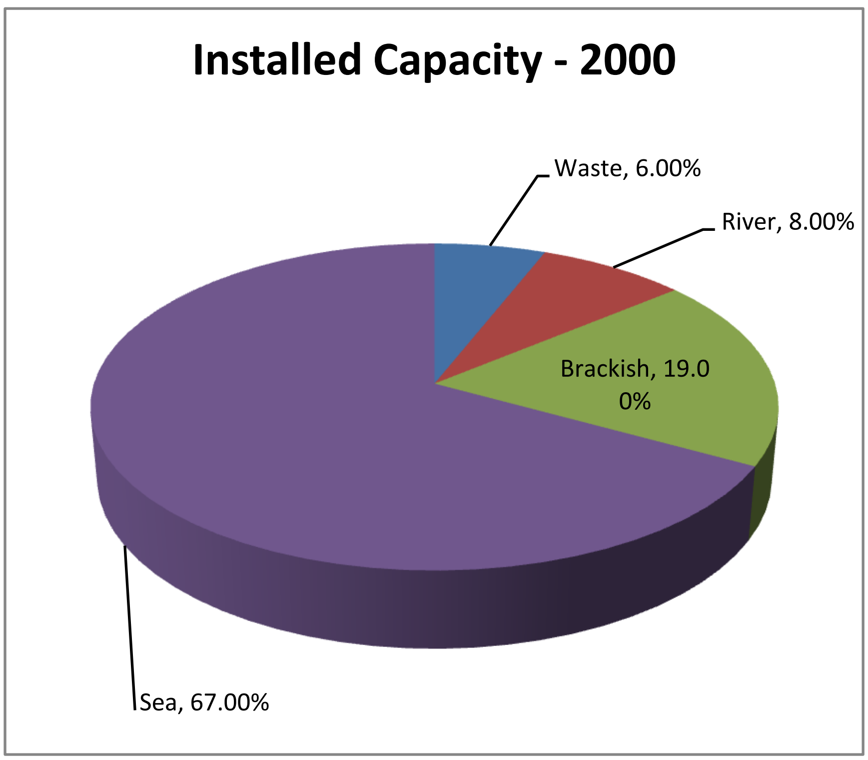



**Figure 2: Worldwide feedwater quality used in desalination (United Nations, 2009).**

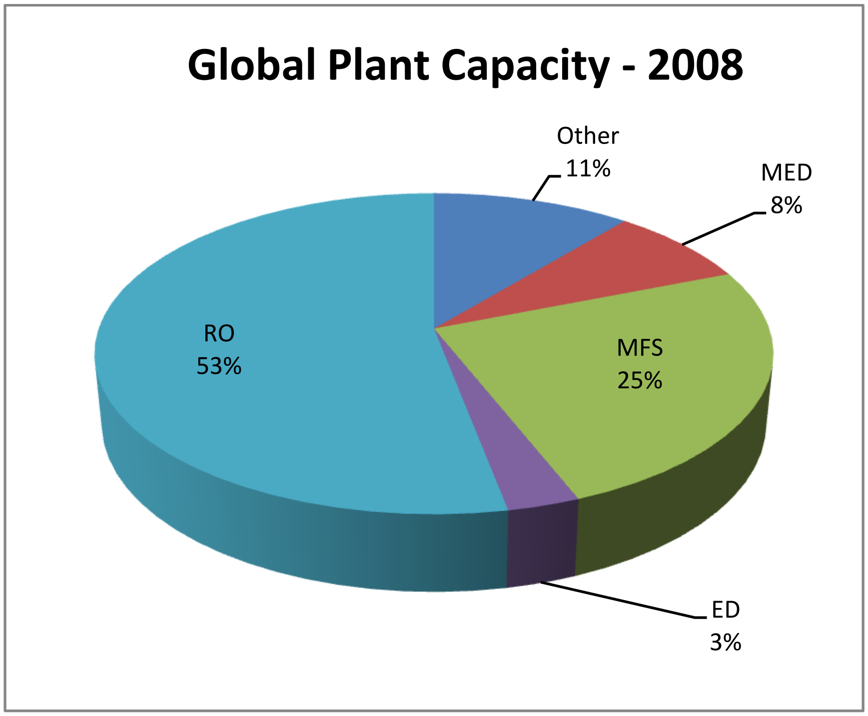



**Figure 3: Global desalination plant capacity by technology (United Nations, 2009).**

### 2.2.1 Local water need in South Africa

Since South Africa is coming under increasing fresh water availability pressure (especially in coastal regions), the logical step was to select a potentially viable method to be implemented locally. Of all the methods used to produce fresh water from seawater, desalination is globally the most used method and currently the most popular choice in addressing this problem. Desalination is a proven technology and under continuous technological and economical improvement. Therefore, desalination was selected as the most promising, viable technology to implement on the South African coast.

## 2.3 Existing desalination technologies

MSF, MED and RO are the most common desalination technologies in operation today. Currently, the RO has surpassed MSF desalination as the most used technology. As the newest technology, it has become dominant in the industry. In the last decade there has been a large improvement in MED and RO technologies to rival MSF desalination, so much so that product water cost has fallen by 30 percent per decade. In 1999, MSF accounted for 78 percent of global production and RO accounted for 10 percent. In 2008, MSF only accounted for approximately 25 percent and RO 53 percent of global production (United Nations, 2009).

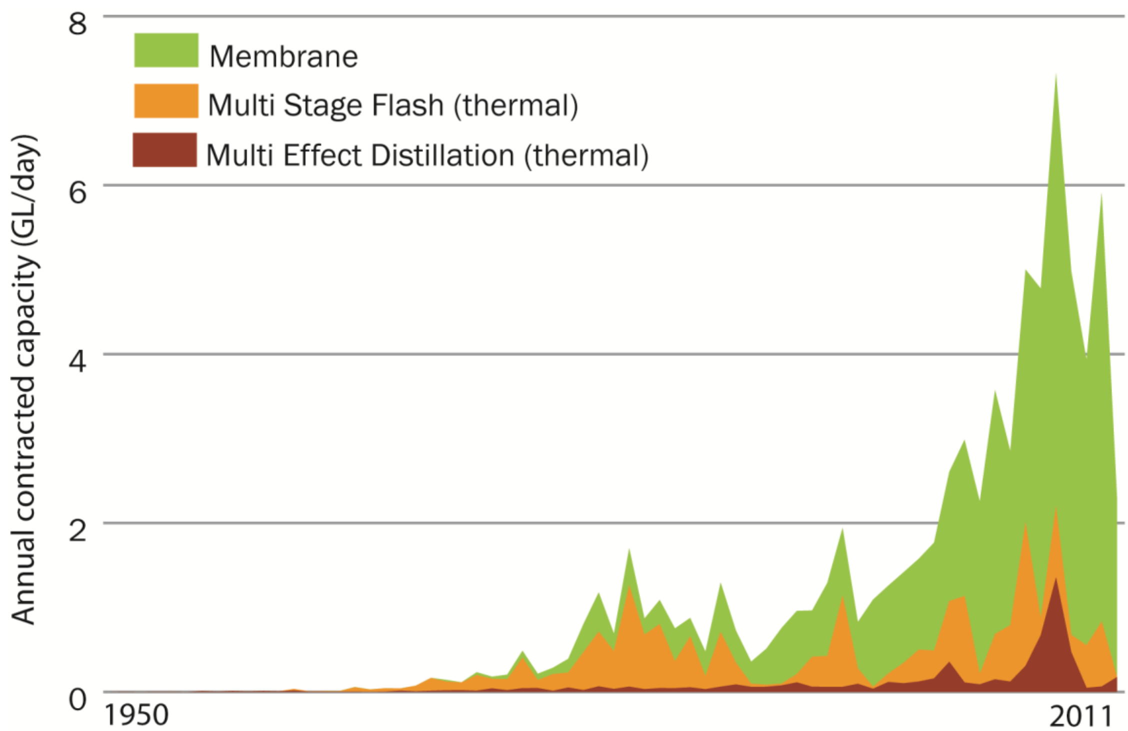



**Figure 4: Schematic illustration of global desalination technology trends (Deputy, 2011).**

Figure 4 shows how the global focus shifted from MSF to RO as the preferred desalination technology. The ESCWA countries have been practising desalination for over 50 years due to freshwater being extremely limited. Desalination has been the bridge for these countries to narrow the gap between the increase in water demand and supply due to population growth, socio-economic development and climate change. The three principal desalination technologies in these countries are also MSF, MED and RO. It is important to note that thermal desalination technologies are primarily used in fossil fuel rich countries. These countries normally subsidise the provision of fossil fuel to power plants, thereby subsidising the cost of electricity and steam used for thermal-based desalination technologies. This energy subsidy, therefore, tips the favour in the energy intensive, thermal-based desalination when deciding which technology to use. In the non-oil countries, all the major desalination plants built or under construction have used membrane technologies (United Nations, 2009).

**Table 1: Energy consumption and water cost for various desalination technologies indicated in 2010 (Jabbar, 2010)**

| Process | Electrical ($kWh/m^3$) | Specific investment cost ($\$/m^3/day$) | General total product cost estimate ($\$/m^3$) |
|---|---|---|---|
| MSF | 3.5 – 5 | 1 100 – 1 500 | 1.10 -1.25 |
| MED | 1.5 – 2.5 | 900 – 1 000 | 0.75 – 0.85 |
| RO | 5 -9 | 700 – 900 | 0.68 – 0.90 |

Table 1 contains estimated costs stated by Jabbar (2010). This indicates that RO has the lowest cost from all the desalination technologies. In a recent study by Mezher, et al. (2011), similar energy consumption and cost values were identified.

### 2.3.1 Thermal desalination processes

The first thermal desalination process usde submerged evaporators. Evaporation takes place over submerged heat exchange tubes within the liquid phase. The problem with this method was the salt scale formation on the heat exchange tubes. The three main scale formations are calcium sulphate, magnesium hydroxide and calcium carbonate. The salt scale has significantly lower heat transfer conduction properties than the tube material. This caused severe loss in heat transfer to the water which reduces the thermal efficiency causing plant shutdowns to clean the tubes to restore the thermal efficiency. This technology was replaced with evaporation which takes place on the surface of heated tubes known as flash desalination. Scaling still takes place, but is minimized by proper pre-treatment and by not allowing the brine temperature to exceed the maximum, prescribed, brine temperature (United Nations, 2001).

The main thermal desalination technologies are *MSF* (multi stage flash) desalination and *MED* (multi effect desalination). Thermal desalination processes are also subjected to corrosion. The main factors influencing seawater and concentrated stream corrosion are pH balance, temperature, high chloride concentration and dissolved oxygen. Corrosion is minimized by using corrosion resistant material (high performance steel) throughout the flash chambers, feed and concentrate streams (Watson, Morin, & Henthorne, 2003).

After the distillation process, product water is unstable and corrosive due to the lack of minerals. Post-treatment is necessary to replace the needed minerals before the supply can be delivered to the distribution system (Watson et al., 2003). The general guidelines used for stabilization are:

- pH = 8 to 9;
- Alkalinity = 40 mg/l as calcium carbonate, CaCO3, or greater;
- Total hardness = 40 mg/l as CaCO3, or greater; and
- Langelier saturation index (LSI) = positive.

The advantage of thermal desalination processes is that they can be used with lower quality water than other processes and require less chemical pre-treatment than membrane processes. Thermal desalination is primarily a steam driven process. The performance ratio determines the quantity of steam necessary for the desalination process. The performance ratio is defined as the mass of the desalinated water produced per unit of energy input. Thermal energy at moderately low temperatures and pressures is used in the distillation process (Kita, Lau, Milonas, & Wright, 2005).

Co-generation is the simultaneous production of both potable water and electricity. In co-generation plants, steam is taken from a power plant at low pressure, after the steam has generated electricity. The configuration where the desalination plant is placed next to a power station reduces the primary fuel cost significantly and, thereby, reducing the product water cost. Folager (2003) indicates that the cost of energy in desalination is between 50 and 75 percent of operating costs and co-generation costs can be 20 to 40 percent less than single-purpose desalination plants.

Thermal desalination processes typically need less feedwater pre-treatment than RO desalination plants and can generally use low quality feedwater. The plants do not need to shut down production as often as RO plants for cleaning and replacement of equipment and filters. There is also waste produced by backwash pre-treatment filters. The main downside to thermal desalination is that it is an energy intensive process. Therefore, it is best to build plants in areas where energy cost is not the determining factor (Watson, Morin, & Henthorne, 2003).

MSF and MED plant performance is measured by the gained output ratio (GOR). The GOR is determined by dividing the mass of the product water by the mass of the driving steam. The

GOR is also closely proportional to the number of stages in thermal desalination. Normally, the number of stages range between 2.5 to 4 times the desired GOR (Bogart, 2003).

#### 2.3.1.1 MSF: multi stage flash desalination

MSF was, up to around the year 2000, the most used desalination technology. These plants have been implemented for more than 50 years and the configuration is very well known. MSF is, therefore, seen as a matured technology (Bogart, 2003). There are two process configurations for the MSF process: “once through” (OT) and “brine recycle” (BR). Each of these configurations has two designs: “long tube” and “cross tube”. In the “long tube” design the tubing is parallel to the concentrate flow of the vessel and in “cross tube” the tubing is perpendicular to the concentrate flow in the vessel. As the amount of stages increase in the MSF design, the efficiency also increases. The down side of increasing the number of stages is the increase in capital cost. Therefore, there is a trade-off between designing a plant with an optimum efficiency and designing a plant with an optimum economics. Increasing the efficiency by increasing the amount of stages is easier and less expensive in long-tube design than in cross-tube design. A single vessel can contain up to five flashing stages. The long-tube design requires significantly fewer tube sheets and lower pumping power (Watson et al., 2003).

The efficiency of the MSF system depends on a number of common performance parameters. The most important parameters include the following:

a) *Thermal performance ratio (PR);* defined as the flow rate of fresh product water relative to the heating steam. This gives a measure of the specific process energy consumption;

b) *Specific power consumption (W);* defined as the ratio of energy consumption, expressed in kilowatt hours (kWh), to product water volume. For MSF and MED systems, the specific power consumption of the pumping units, instrumentation and control devices is approximately 4kWh/m$^3$ and 2.5 kWh/m$^3$, respectively;

c) *Specific flow rate of cooling water (SMcw);* defined as the ratio of the flow rate of desalinated water output. This is a dimensionless quantity which higher values imply more energy rejected into surrounding area and higher energy consumption owing to the increased flow cooling water pumped through the system. For MSF and MED, the value generally ranges from 3 to 10. The actual value depends on the feedwater temperature, an increase in the amount of heating steam and an increase in cooling water flow rate; and

d) *Specific heat transfer area (As);* defined as the total heat transfer area per unit product flow rate. When operating a MSF plant between 90ºC and 110ºC, the heat transfer area is around 200-300 $m^2/(kg/s)$; for a MED plant operating in the range of 60ºC to 70ºC, a specific heat transfer area of 700-800 $m^2/(kg/s)$.

Parameter a), b), and c) determine the process efficiency and, therefore, the running cost, while parameter d) plays a major role in specifying the expenditure involved. In the OT configuration, the feedwater is pumped through the recovery section, the concentrate heater and then passes through the flash chambers without recycling. The concentrate is then disposed of directly. The biggest advantages is the higher operating temperature, lower boiling point elevation and reduced calcium sulphate scaling due to the brine passing through the recovery tubing section at standard seawater concentration, 36 000 TDS mg/l for the South African coastline (United Nations, 2001).

The biggest downside to this is that the entire feed has to be pre-treated before entering the unit to minimize scaling and corrosion, and the supply is pumped twice at the intake and after the de-carbonator. Therefore, the de-carbonator is a larger unit than for the "recycle" configuration and thus more expensive (Watson, et al., 2003: 63).

MSF plants at industrial facilities normally produce distilled water at rates ranging from 1,000 to 10 000 $m^3/d$, whereas, MSF plants intended for producing drinking water have distillation rate ranges from 90 000 to 180 000 $m^3/d$. The feedwater is firstly subjected to pre-treatment to reduce scaling and fouling, and then the product water is subjected to post-treatment to replace the necessary minerals, increase the carbonate hardness, and restore the pH balance, sterilization and to produce drinkable product water (United Nations, 2001).

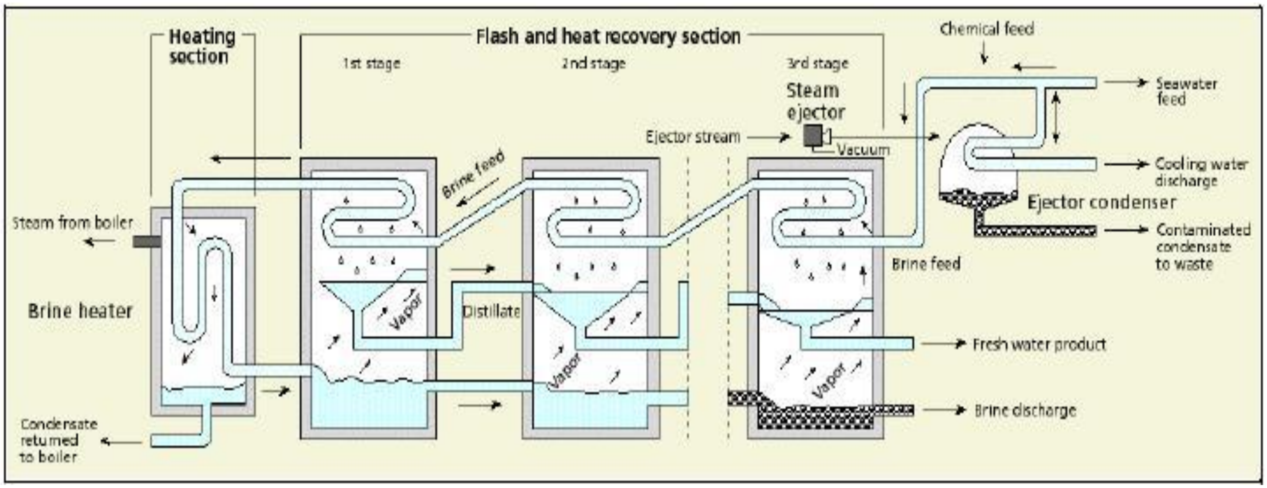



**Figure 5: Basic MSF concept layout.**

Each stage of an MSF plan operates at progressively lower pressures, as water boils at lower temperatures as illustrated in Figure 5. The MSF generally follows the following steps:

1. The feedwater (seawater) is sent to a chemical pre-treatment system where either a chemical additive or acid treatment is given to suppress the formation of alkaline scales in the heat transfer tubes. Here, the feedwater is de-aerated to reduce dissolved oxygen and carbon dioxide to minimize corrosion and improve the heat transfer performance;
2. Feedwater in the MSF modules is then pre-heated;
3. Brine heaters heat the brine (seawater feed) yet again to the maximum brine temperature and the water is then subjected to a flashing process in the flash evaporator;
4. The evaporator is normally divided into several chambers called flash stages and there are usually less than 40 stages in an operational MSF plant. The stages are kept at progressively reduced pressures. The flash chamber is kept below the saturation vapour water pressure and a small amount of the brine that enters evaporates into vapour;
5. Vapour then passes through the mist eliminator and condenses on the outer surface of the heat exchanging tubes, giving its heat to the incoming brine flowing inside the heat exchanging tubes;
6. Un-flashed brine moves to the next stage where the same process is repeated; and
7. The condensate is collected as the product water.

The difference between the MSF and MED process is that in the MSF process it generates and condenses its vapour in the same stage. This configuration allows for heat recovery. Heat recovery is when feedwater passing through the heat exchanger in the upper section of the flash chamber gains heat as it condenses the vapour to distillate. The amount of water that flashes is directly related to the temperature difference between the two stages. An increase in this temperature difference leads to an increase in the amount of brine that flashes (Watson, et al., 2003).

The maximum brine temperature is limited between 90 and 110°C for MSF systems and is an important design factor, especially for corrosion resistance. MSF can produce pure water containing 5-25 parts per million (PPM) total dissolved solids (TDS) from seawater containing 35 000 up to 45 000 PPM TDS (IAEA, 2000). Its capital cost ranges from 1 100 to 1 500 $/m^3/day installed capacity (Table 1). MSF plants' biggest benefit is that they are designed for large unit sizes and are still the major seawater desalination process based on installed capacity.

In a MSF desalination plant with a high inlet brine temperature, the first few stages are subjected to a high amount of corrosion, therefore, it is only necessary to use cladding on the first few stages to minimize corrosion (Hamed, Ba-Mardouf, Al-Washmi, Al-Shail, Abdalla & Al-Wadie, 2007:11; United Nations, 2001).

Material selection for "long tube" and "cross-tube" configurations, differs due to the fact that the velocity of the concentrate is twice the speed in the "long-tube" than in the "cross tube". The high concentrate velocity subjects the tubes to a large amount of corrosion and impingement attacks, therefore, the tubes must be fully clad with stainless steel grade 316L, or a material with equal properties. A maximum inlet brine temperature is limited at 90.6ºC, even though a maximum brine temperature of 110ºC can be used for the OT process (Watson, et al., 2003).

#### 2.3.1.2 MED: multi effect desalination

MED is based on the following principals. If the ambient pressure is progressively reduced in a series of consecutive events, the feedwater then undergoes boiling multiple times without the supply of additional heat following the first effect (Watson, et al., 2003). The feedwater is pre-heated and then heated to the boiling point of the first stage/effect. The pre-heating is done by spraying the seawater on the evaporator tubes. Steam from the boiler or an additional source is used to heat the evaporator tubes internally. Steam is condensed down the line within the tubes and condensate is recycled to the boiler for re-use (IAEA, 2000). Figure 6 illustrates the basic layout of the MED process.

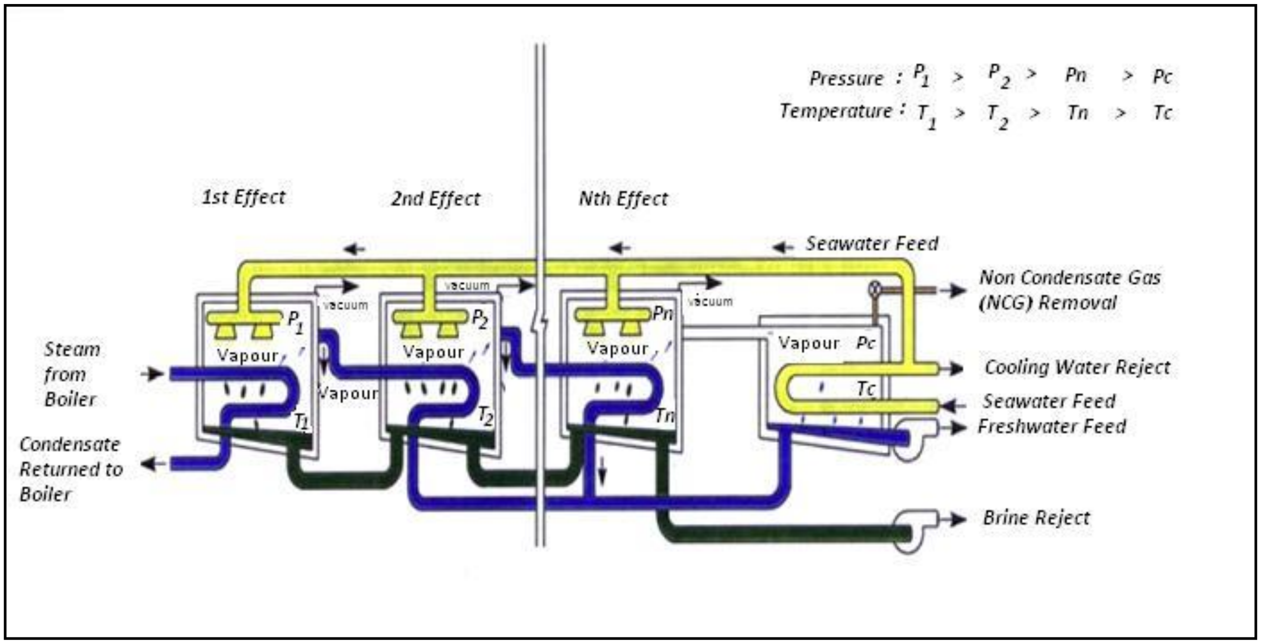



**Figure 6: General MED system setup.**

The brine in the first stage is only partially evaporated while the rest moves to the second stage where it is again sprayed onto the tube bundle. The tube bundle is heated at the same time by the vapour created by the first stage. The vapour produced on the tubes is in essence the product water produced. This process gives up heat to evaporate another portion of the remaining seawater in the next effect. This continues up to 16 times in large MED plants. The remaining seawater in each stage flows to the following stage where it is applied to the corresponding tube bundle (United Nations, 2001).

MED follows the same principle as MSF. There are three main MED configurations and it is primarily based on the layout of the heat exchanger tubes. This gives: horizontal tube, vertically stacked tube bundles (Watson, et al., 2003). MED facilities are classified by their configuration as low-temperature (LT-MED) or high-temperature (HT-MED) plants, depending on the income steam temperature. The LT-MED system can be as low as 60-70ºC and the outgoing temperature can be as low as 40ºC. The advantage of running a LT-MED system is the prevention of scale formation. This process can make use of steam that is not economically suitable for generating electricity and is more energy efficient than MSF desalination (IAEA, 2000).

Capital cost for MED plants vary from 900 to 1000 $/m³/day capacity (Table 1). MED has recently received a great deal of consideration and development for medium size plants in UAE and for large scale plants in India ($4 \times 12{,}000$ m³/d) (IAEA, 2000).

The pre-treatment for MED plants corresponds to that of MSF plants. The pre-treatment reduces scale formation, reducing plant maintenance and shutdown time for cleaning and removal of scaling. Acid and polyphosphate are used to prevent calcium carbonate scale formation. Vent gases from the deaerator/degassifier and non-condensable gases evolving during evaporation are removed from the system by a vacuum system (United Nations, 2001).

### 2.3.2 Membrane desalination processes

Synthetic membrane desalination was first introduced in the 1960s. They played an increasing part in water desalination in the 1980s. The fact that membrane processes possess definite advantages over traditional, principally phase-change, desalination methods account for their relative popularity and for the present interest in their development and commercialisation worldwide (AIEA, 2005).

The main technologies in membrane desalination are reverse osmosis (RO) and electro dialysis (ED). RO is used for desalination of seawater and brackish water, while ED is used only for desalination of brackish water. The major challenges in membrane desalination are the scaling and fouling of membranes. These challenges can be reduced by improving membrane technology and improving feed pre-treatment processes (improved anti-scaling and anti-fouling chemicals). Energy consumption in RO is dramatically reduced by installing devices for recovering energy from reject brine. Recently, high efficiency pressure exchangers have been introduced in commercial plants in place of conventional turbines for energy recovering, which resulted in significant reduction in energy consumption (Hinrichsen, et al., 1997).

## 2.3.2.1.1 Reverse osmosis

Osmosis is known as the diffusion of water through a semi-permeable membrane from a solution with low salinity (low TDS) to a solution with high salinity (high TDS). Reverse osmosis is the same thing; water in a higher salinity is forced to flow through a membrane to a region where the salinity is negligible (Figure 8). This separates the salt from the water, thereby, producing fresh water (United Nation, 2009). The process is called Hydrostatic water pressure and is an energy consuming process. Figure 7 illustrates the difference between osmosis and reverse osmosis. Most importantly the energy required is directly proportional to the salinity of the feedwater. Normal seawater salinity is close to 35,100 mg/litre (Bogard, 2003).

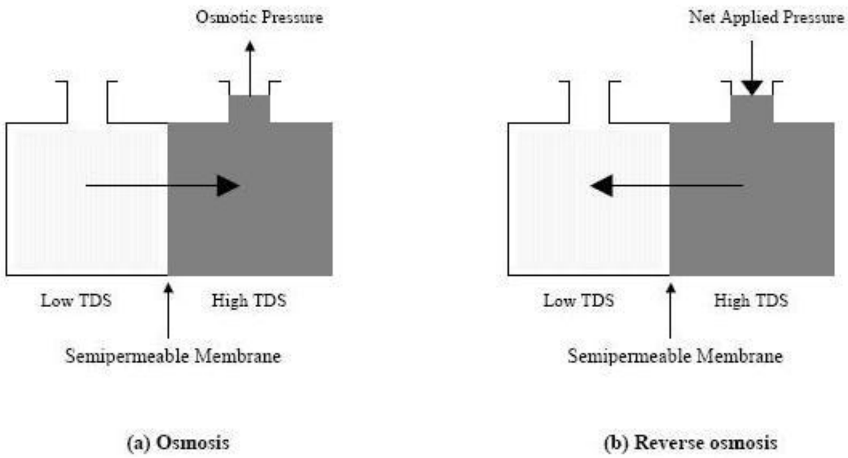



**Figure 7: Osmosis and reverse osmosis process.**

The energy used in RO plants is normally electricity, and the largest power consumer is the high-pressure pump, which delivers flow at a head of 60-80 bar. Large capacity RO plants can recover up to 30-40% of the energy from high pressure reject brine by energy recovery systems such as pelton wheels, hydro-turbines or turbochargers. Energy recovery in seawater desalination results in fresh water production at around 4-6 kW(e).h/m³ (IAEA, 2000). Capital cost from these seawater RO plants range from 700 to 900 $\$/m^3$/day (Table 1).

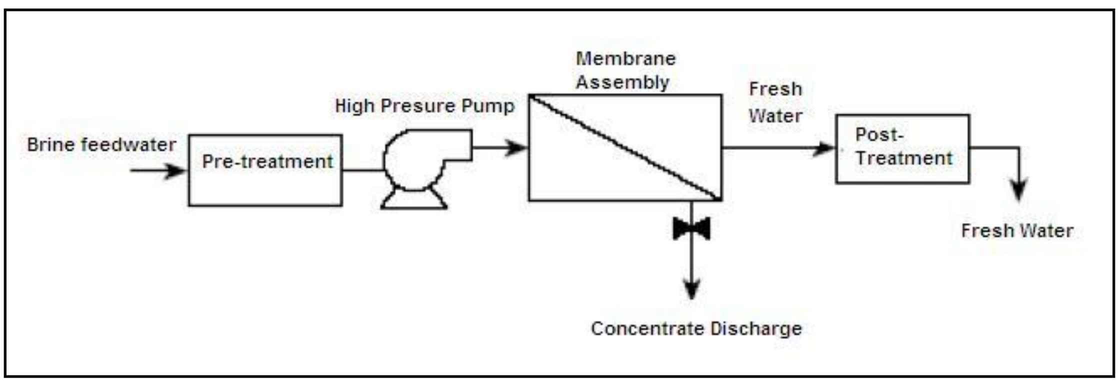



**Figure 8: General basic RO layout.**

Figure 8 illustrates an uncomplicated RO system which consists of four general stages. These stages are:

- In the first stage, the feedwater/brine is mechanically pre-filtered and chemically pre-treated to ensure that there are no particles or deposits present that may clog or damage the RO membranes and that there are no microbial product that may damage the membrane filters;
- Feedwater is pressurized by a high pressure pump;
- The membrane separates the fresh water from the feedwater; and
- The fresh water is chemically post-treated so that the product water meets the stated water standards.

Pre-filtering and treatment is of fundamental importance for the RO process as 99.99% of all bacteria and suspended particles in the feedwater are removed in this first stage. The chemicals in the pre-treatment ensure plant life and maintain capacity by adding membrane cleaners to control membrane fouling from organics and metal oxides and anti scaling chemicals to improve membrane life cycle. The main factors influencing the RO process are the feedwater temperature and pressure. As the feedwater temperature increases, the pressure needed to pump the feedwater through the membranes decreases. This decrease in pressure brings a decrease in power requirement to pump the feedwater which results in lower operating costs. A rise of about 5 degrees brings about a 5% drop in power requirement. This makes RO an excellent candidate to use in co-generation using the access heat from the low-pressure turbine to increase the feedwater temperature (Kita, et al., 2005).

The Californian Coastal Commission (2004) states several advantages and disadvantages of RO technology over thermal desalination.

**Advantages over thermal desalination:**

- Less energy required;
- Feedwater has lower thermal impacts since feedwater does not have to be heated;
- Fewer corrosion problems;
- Higher recovery rates; and
- Less surface area than distillation plants for the same amount of water production.

**Disadvantages over thermal desalination:**

- It is generally more sensitive to poor water quality, resulting in the need to shutdown facilities during severe storms or periods of high runoff when there are increased amounts of suspended particles in the feedwater;
- It requires more frequent cleaning and maintenance, often using various chemicals and cleaning agents, and often requiring partial of full shutdown during cleaning;
- The membranes are sensitive to fouling due to bacterial contamination or other causes, which may require more frequent replacement and result in higher cost;
- It requires more extensive pre-treatment, often with the use of biocides, coagulants and other compounds; and
- The process and use of cleaning agents generates wastes that may include toxic chemicals, metals, and other constituents that are either discharged to the surface water or are separated and sent to a wastewater facility or landfill.

### 2.3.3 Hybrid desalination

A hybrid plant is the combination of thermally driven and electrically driven (membrane) desalination processes. A hybrid, membrane-thermal-power configuration holds several advantages over mono surplus and dual purpose plants. These advantages are regarded as economical and environmentally sound, have flexibility in operation, less specific energy consumption, low construction cost, high plant availability and better power and water matching (Marcovecchio, et al., 2005).

Running membrane and thermal processes on the same location reduces the pre- and post-treatment chemical costs. Operating seawater RO together with MSF/MED process one can run the RO process with a high TDS which results in lowering the membrane replacement cost by up to 40%. The annual replacement of the membranes is substituted by replacing the membranes only every 3 to 5 years (Watson, et al., 2003). The same intake and outlet is used for both plants reducing the capital cost. The outlet rejection seawater from the MSF distiller or the last effect of the MED plant can be used for the intake of the RO plant. This increases the intake water temperature. A 3% increase in product water can be obtained for an increase of 1 degree Celsius for the RO process. An increase of 48% in product water recovery has been reached by increasing the feedwater temperature from 15 to 30 degree Celsius.

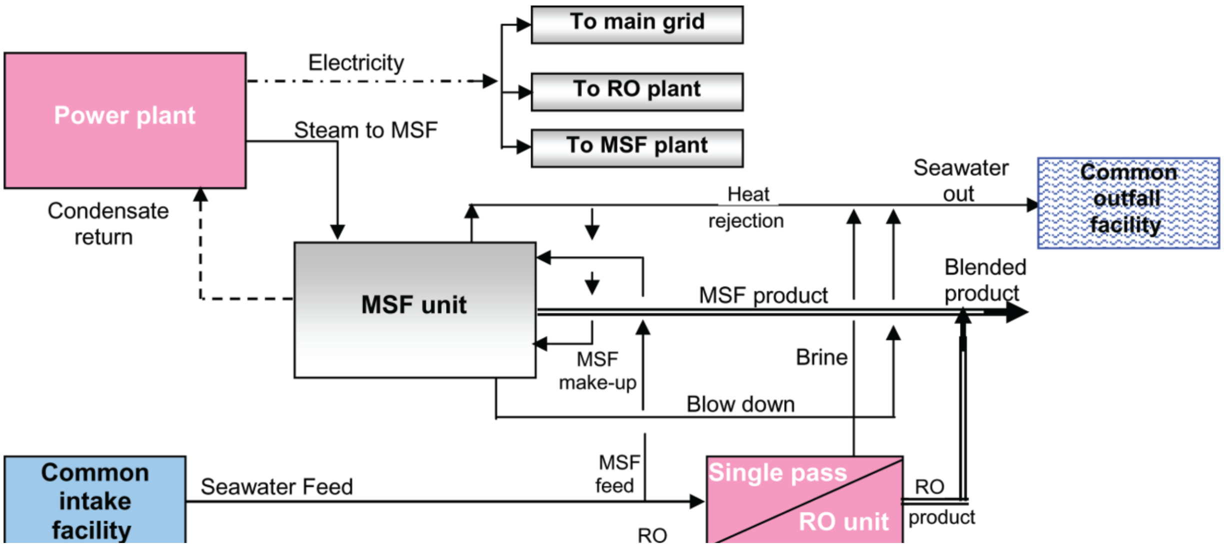



**Figure 9: MSF-RO hybrid plant layout (Osman, 2007).**

Figure 9 illustrates a typical MFS-RO hybrid plant layout. An increase in feedwater temperature for the RO plant results in an increased rate of water permeation through the membrane, since the viscosity of the solution is reduced and higher diffusion rate of water through the membrane is obtained (Al-Mutaz, 2005).

## 2.4 Waste disposal methods

There are several methods in disposing of concentrate flow. Effluent disposal options include:

- Surface water discharge;
- Disposal to the front end of a sewage treatment plant for processing;
- Deep well injection;
- Land application;
- Evaporation ponds/salt processing ponds; and
- Concentrate concentrators.

Surface discharge is the most used method for seawater and brackish water disposal. This includes the concentrate stream to discharge directly into a larger body of water (ocean, river or the effluent of sewage treatment plant) (Watson, et al., 2003).

The following legislation and permit requirements are applicable (Swartz, et al., 2006):

- **The National Environmental Management Act (Act 107/98, NEMA)**
  NEMA promotes sustainable development and regulates the procedures and steps to be taken when a development is considered for approval. It specifically promotes the cooperation between different role players and cooperative governance. In this regard, it prescribes cooperation between government departments, such as (DWAF), the department of environmental affairs and tourism (DEAT) and the relevant local authority. In specific instances, institutions such as Nature Conservation Boards will also need to be consulted.

- **Environmental Conservation Act (Act 73/89, ECA)**
  ECA, through regulation 1182, prescribes specific requirements for specific actions that might have a detrimental impact on the environment. These actions are listed in schedule one of the regulations and include ‘construction or upgrade of all structures below the high-water mark of the sea’ and ‘schemes for the abstraction or utilisation of ground or surface water for bulk supply purposes’. Regulation 1182 contains all the relevant steps to be taken for the required environmental impact assessment. It is extremely important to note that the involvement of interested and affected parties forms an integral part of this process.

- **National Water Act (Act 36 of 1998, NWA) and Water Services Act (Act 108 of 1997, WSA).**

These two Acts regulate the water industry and deal primarily with the management structures and the licensing procedures required before water can be abstracted from a source.

## 2.5 Coupling methods

Desalination plants are generally coupled to thermal plants like power stations. For a plant requiring higher power to water ratio, normally the backpressure method is recommended. On the other hand, the extraction method is preferred for satisfying low power to water requirements (Watson, et al., 2003).

*Backpressure method:* all the steam is expanded in the turbine to an elevated turbine backpressure depending on its design. Then low grade steam exiting the turbine is passed directly to the brine heater where it releases its latent heat of vaporization. The condensate is returned to the heat source. This method requires relatively low investment and has a good efficiency when operated at rated capacity. However, backpressure systems cannot vary their power to water ratio.

*Extraction method:* this enables the water plant to be permanently supplied with expanded steam, independently of power load.

*Low pressure steam:* this can be supplied to a desalination plant from an existing low pressure turbine by operating at higher exhaust pressure, but in general this is limited to around 0.2 bar. The power loss is low in this case, resulting in low steam cost. However, the low steam pressure limits the top brine temperature, and thus a high GOR cannot be achieved. The steam can be extracted from the crossover pipe to the low pressure turbine. This steam has a relatively high energy content compared to that required for low temperature heating purposes. This results in a higher relative power loss. On the other hand, a high GOR can be achieved in the desalination plant by incorporating a larger number of stages/effects subject to design limitations.

*Backpressure turbine*: the steam exhaust at desired conditions would be coupled to the desalination plant. This arrangement enables the coupling of all types of thermal desalination plants with a nuclear power plant giving constant water output.

An extraction/condensing turbine is suggested over a backpressure turbine when coupling a desalination plant to a power plant. A backpressure turbine implies the heat that is not going to be used in the desalination plant is going to be wasted instead of producing electricity.

Coupling between a desalination plant and any nuclear plant needs an intermediate loop to ensure no possibility of radiation contamination as indicated in Figure 10.

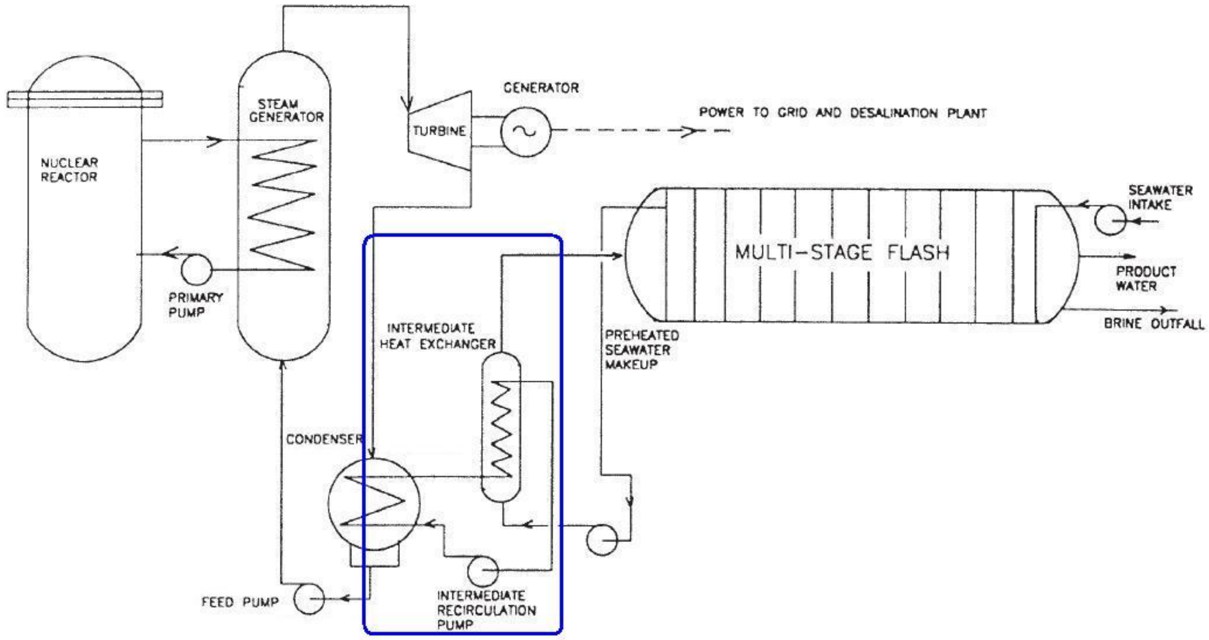



**Figure 10: Intermediate loop coupling between a nuclear plant and a MSF plant.**

## 2.6 General factors influencing desalination plant site selection

In selecting an appropriate site for any seawater desalination facility the following decisions need to be addressed. Firstly, one needs to decide on which desalination technology one wants to use, as this will have a large influence on the final site selection. Site selection can, therefore, be different between thermal desalination and membrane desalination.

In selecting a desalination technology, the major factor to consider is its location, specifically, in proximity to the power supply and heat source and the type of energy source (electricity, renewable, nuclear, coal, oil or natural gas).

Thermal desalination cost can be reduced by co-locating at the energy/heat source. A co-generation plant configuration can produce electricity together with the water as product. Electricity for the desalination plant can be utilized directly from the power plant at a lower rate than from the normal grid connection, therefore, reducing the operating cost. Waste heat is also freely available from power plants, which further reduce the operating cost of thermal desalination plants (less heat needed for the evaporation process). It should be noted that thermal desalination plants can utilize waste heat from any suitable industrial plant and not just power plants. Co-locating at an established facility or site can, in addition, also reduce capital cost by make use of existing infrastructure located on the site. These include utilities, roads, power distribution connections, water distribution connections, water in- and outlet infrastructure.

Membrane desalination relies solely on electricity as energy source. Small cost reductions can be achieved by increasing the feedwater inlet temperature. This reduces the pumping power needed for the RO process and reduces the amount of electricity used during operation reducing operating cost. Co-locating membrane desalination plants has the same advantages as thermal co-generation configurations.

Factors like the purpose (main motivation) of the desalination plant also play a predominant role in siting. If the main motivation for the building of the desalination plant is to relieve current or future freshwater availability pressure, the plant should be located in the vicinity of the region where the water availability pressure is the highest. For example, it makes no sense building a desalination plant in Durban to produce freshwater for Cape Town. If the motivation is purely related to producing revenue, the plant should be located at the site with the highest market potential. The product water should then also be sold in the market with the highest potential income (e.g. bottled water is currently more expensive that petrol and a multibillion dollar industry globally).

After selection of an energy/heat source and incorporating the motivation for the building of a desalination plant the following factors should be assessed:

- Location in proximity to the water and electricity distribution connection;
- Location in proximity to a highway or railroad (i.e., for product and chemical deliveries);
- Seawater quality (TDS);
- Location in proximity to the concentrate disposal point (environmental impact); and
- Cost of land.

As mentioned previously, locating a desalination facility at an establish site automatically puts the facility close to certain utilities, which can lower capital cost. Locating the facility close to a highway or railroad can reduce any related transportation cost incurred by the desalination facility.

## 2.7 Economic advances

### 2.7.1 Improvement in desalination economics

To make desalination feasible it has to be economically viable, which means that desalination should be profitable. At the moment, water can be seen as the next crude oil. In any country there is an increasing need for fresh water, while at the same time industrial activity also increases which also increases the need for product water which can increase water pollution. Thus, more fresh water is needed every day and a reduced amount of fresh water is available every day. Figure 11 shows the global population growth, water demand, consumption and accessibility. The graph shows that demand will surpass accessibility by 2014.

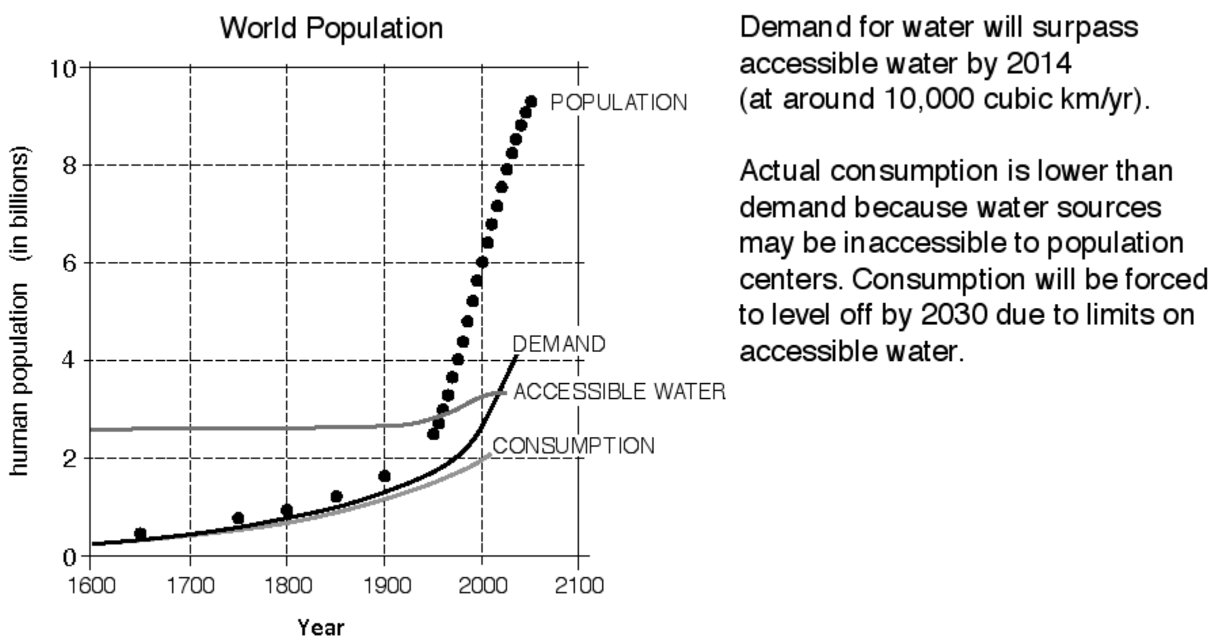



**Figure 11: Growth of global population, water consumption, demand and availability (Polmeratz, 2004).**

Thermal desalination (distillation) involves physical properties of seawater and methods to add the necessary energy to create the phase change and currently little can be done to affect the cost basis of the process. The technology is still an energy intensive process. With the best available technology applications, distillation processes produce high quality desalinated water, but require excessive amounts of energy with high capital and production costs. The biggest technology improvement in thermal desalination over the years was lowering the system pressure. Thermal desalination offers little advantage in the area of technological improvements. The last 30 years have mostly focused on RO (Kita, et al., 2005).

### 2.7.2 Improvement costs

The most important factor for decision making in desalination is based on economics. This consists of total costs and benefits and is calculated by taking the sum of all the costs/expenses related to the production of the product water divided by the total amount of desalinated product water produced. General desalination economics is dependent on the following major factors (IAEA, 2000):

- Quality of feedwater
- Plant capacity and sizing (economics of scale)
- Energy cost
- Type of desalination technology
- Regulatory requirements
- Site characteristics
- Concentrate disposal.

The average desalination costs in thermal and especially in membrane desalination have reduced substantial over the last few years. This is due to the dramatic improvement in thermal and especially membrane technology. Desalination implementation worldwide also increased considerably, especially over the last 5 to 10 years. Figure 12 shows the increase in desalination capacity globally which is especially renowned for its dependence on desalination for its fresh water supply (Reddy, 2008).

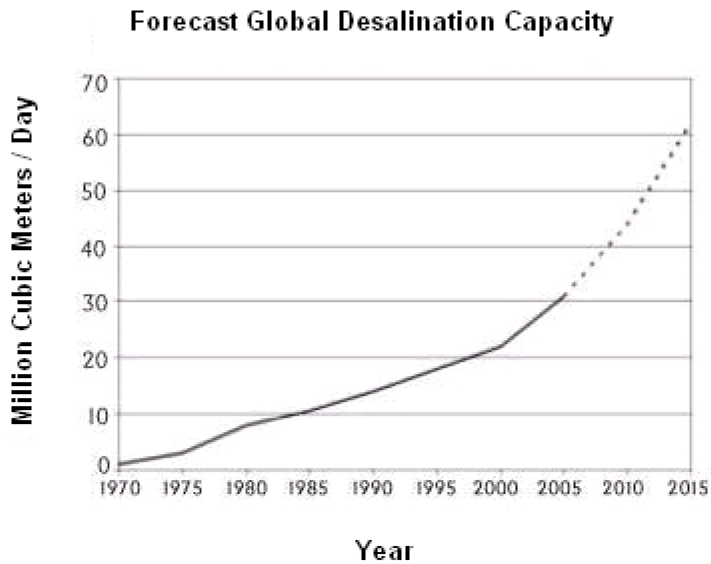



**Figure 12: Growth in desalination capacity (Global water intelligence, 2004).**

Figure 12 shows an almost exponential growth of desalination capacity from 2000 to 2005. The graph indicates that the growth pattern is likely to continue into the future. The growth can mainly be contributed to RO plants indicated in Figure 4. This is due to the progress in desalination technology which led to a decrease in desalination costs. The improvement in technology is driven by increase in water demand throughout the world and especially in the Middle East. RO is now the main installed desalination technology worldwide. This is due to the large advancement in membrane technology which makes it more economically viable.

### 2.7.3 MSF economic advances

MSF technology is the oldest and most used thermal desalination technology. A main contributor to the decrease in cost over the last 50 years is the improvement in the investment cost and the desalination production unit water cost. The product unit water cost decreased.

Reddy (2008) indicates an average investment cost reduction of US$1 000–2 000/$m^3$/day pre 1990 to US$1 000–1 500/$m^3$/day post 1995. This shows that the investment cost decreased over a period of time in spite of inflation. An improvement of around US$9/$m^3$ to less than US$1/$m^3$ in production unit water cost was achieved over the 40 years (Figure 13). This is approximately a decrease by a factor of 10.

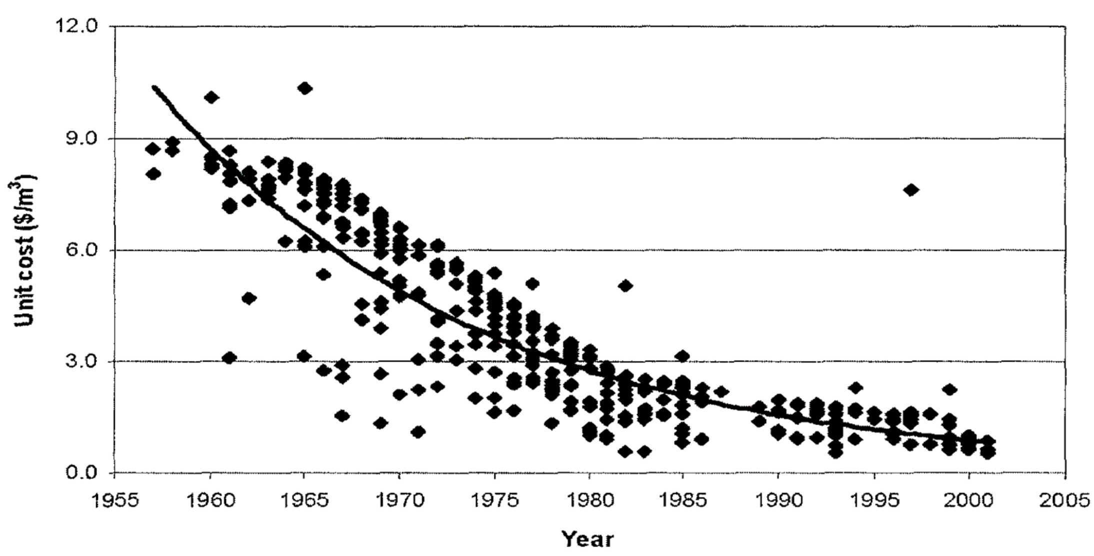



**Figure 13: Unit water cost by MSF process over 40 years (Reddy2008).**

A more or less 50% reduction in installation cost acts as the major factor in the product unit water cost reduction even though there was a 40% increased cost in raw material and an increase in excess of 100% in labour cost. According to Reddy (2008), the main factors playing a role are:

- A severe competition between RO and MSF plant contractors and suppliers. This led to a forced improvement in technical specification that improved/reduced installation cost;
- An improved material selection with enhanced mechanical properties, higher corrosion resistance and improvements in heat transfer properties helped in reducing investment cost;
- Knowledge and experience of previous projects helped in improving the process and equipment design for the MSF project. These enhancements are specifically connected to the increase in unit water capacity. In the 1960's, MSF plant capacity was 2 to 3 MGD, and in the 1970's MSF plant capacity was 2 to 5 MGD. In the 1980's MSF plant capacity was 3 to 7.5 MGD. In the 1990's MSF plant capacity was 3.5 to 12 MGD and after 2000, MSF plant capacity was 7–20 MGD;
- By lessening the harsh specifications by users with respect to fouling factors, distiller hydraulic test pressures, distillate purity, brine load, construction material specifications, heat exchange tube thickness, bypass on control valves, removable water boxes and

redundancy of equipment and instrumentation helped the contractor to arrive at appropriate options, which led to the reduction in the investment cost;

- The BOOT contract allowed contractors to add additional improvements to the plant which also help improve costs; and
- The top brine temperature increased to 112ºC improving plant performance reducing product unit water cost.

All these improvements helped to reduce a MSF unit water cost to around US$1.0/$m^3$ and investment cost to about US$900 $m^3$/day capacity.

### 2.7.4 MED economic advances

According to Reddy (2008), MED followed the same path in cost reduction over the years as MSF plants. The biggest drawback to large seawater MED plants is scaling and fouling. Overall improvements in heat transfer coefficients allowed the reduction of the top brine temperature to be around 70ºC. This together with the improvement in pretreatment lowers scale formation and, therefore, increased unit sizing. MED plants typically comprise units producing 2 000 to 10 000 $m^3$/day. MED plants generally use between 8 and 16 effects with a performance ratio of about 12. The internal electrical power usage is around 2 to 3 kilowatt hours (kWh)/$m^3$ for plants with a capacity production ratio that ranges between 45% and 120% of nominal capacity.

MED desalination improved in the following aspects over the last 10 years resulting in a reduction of the water cost:

- Plant capacity increased from 6 MGD to 10 MGD;
- Coupling with thermal vapour compression, improving horizontal-tube evaporation;
- Stabilization of low-temperature operation; and
- Improvements in material selection for heat transfer tubes (aluminium).

In the Arabian Gulf, MED unit product water cost has been reported as low as US$0.55- 0.7/$m^3$, with a capital cost around US$850/$m^3$/day. This is lower than MSF plants but still higher than RO costs.

### 2.7.5 RO economic advances

RO has the largest share of the total installed world capacity. The main contributor to the lowering in production cost is the improvement in membrane technology. These improvements include higher flux, higher salt rejection at lower operating temperatures, longer membrane lifetime and improvement in membrane material. Membrane costs have decreased by 86% between 1995 and 2005 despite of inflation.

Energy and pressure recovery devices together with co-location with power plants resulted in a drop in cost of 80%. It improved to a point where energy cost contributes 30 to 40% of the total cost of RO desalination. Koch Membranes introduced a new membrane, the MegaMagnum. The membrane will reduce capital cost for desalination as well as operations and maintenance by reducing the number of membranes from 7 to 1. Koch and the Bureau of Reclamation (a compilation of companies and agencies together with the US navy's seawater desalination test facility), estimate a 15 to 30% decrease in capital cost and a 5 to 9% decrease in life cycle cost (Kita, 2005).

In Figure 14, the actual investment cost of SWRO plants is plotted against the contracted year given. The data shows that the investment costs before 1995 are more scattered than after 1995. This indicates how desalination costs have decreased as the technology improved over time. After 1995 the data is more densely grouped between US$500 and 1 500/m$^3$/day capacity.

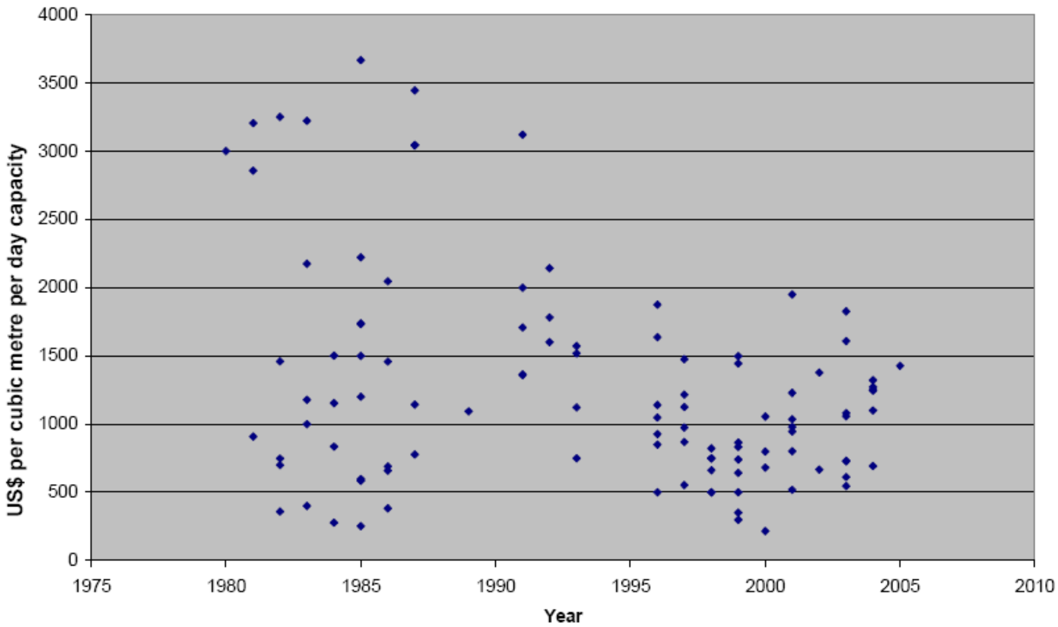



**Figure 14: MED unit water cost of RO from around 1980 to 2005 (Reddy, 2008).**

From this one can see that the investment cost decreased over the last few years to such an extent that the unit water cost decreased to about *US$0.5/m³* presently, which is currently the lowest of all the desalination technologies (Figure 15) (Reddy, 2008).

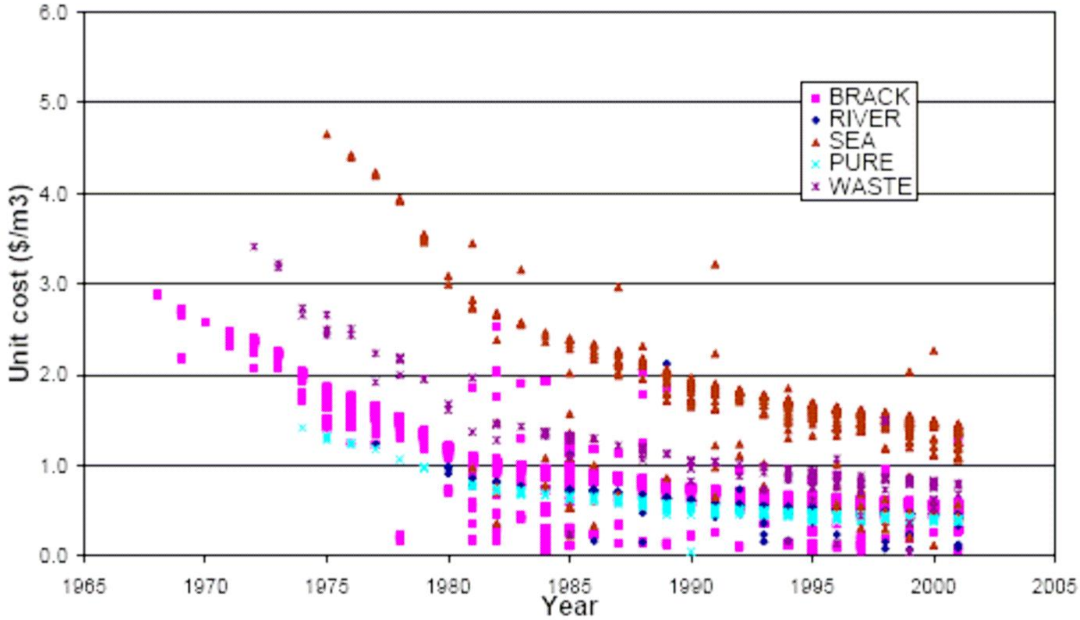



**Figure 15: Unit water cost of RO from around 1967 to 2001 (Reddy, 2008).**

## 2.8 General desalination economic modelling

In most feasibility studies the cost of water desalination is done in US dollar per cubic meter (US$/m$^3$) of product water. This figure is acquired by dividing the total sum of all expenses related to the production of desalinated water including the energy consumed in all production, testing and storage phases, by the total amount of desalinated water produced. The capital investment costs are taken into account with reference to a predetermined discount rate. Indirect costs are influenced by major cost components and by inherent uncertainties during the conceptual design phases. Plant life time, interest rates, the duration of construction and energy prices are all factors that can change significantly over time, which have a direct impact on the unit product costs. If any of these factors increase, the production cost of the plant will increase, lowering the feasibility of the plant (United Nations, 2001).

Desalination cost is affected by various factors. With the implementing of desalination plants, the cost factor is site specific and dependent on various factors. It is important to look at the following guidelines before the processes of selection and costing. Swartz (2006) states that the guidelines on desalination and cost estimation are provided with the understanding that such information shall be utilised within context and with due consideration and understanding of the following aspects:

- **Saline water source, energy source and process selection**

  Desalination processes are energy demanding. All assessments of a desalination process are completed with a proper understanding of the energy requirements and the available sources and the cost of energy. The decision must be made between fossil fuel energy, nuclear and other energy renewable resources like solar power. The feedwater, the required plant capacity and the source of energy plays the major roles in selecting the most appropriate desalination process;

- **Fouling, scaling formation and plant availability**

  Pure water contains the following; dissolved gasses, dissolved and suspended inorganic solids, dissolved and suspended organic matter and suspended micro-organisms. The concentration of these components affects various forms of scale formation and contamination of plant equipment during the desalination process. Continuous fouling and scaling can be the most crippling side-effects of desalination processes. Well designed desalination plants always incorporate a well designed and suitable pre-treatment system. The properties of the feedwater can change with its seasonal change and can, therefore, influence the pre-treatment strategy of the desalination plant. This will result in a good understanding of the impact of this change on the desalination process;

- **Disposal of concentrate and environmental consideration**

  The disposal of the concentrate is unavoidable and must be disposed of in an appropriate and environmentally friendly manner. The concentrate can be up to several times more saline than the feedwater. The disposal can contribute to a major part in the total project cost;

- **Physical location of plant and cost of distribution**

  It is important to establish a sensible tie-in system from the desalination plant to the main water system to increase the municipal water supply. Thus, it is important to select the optimum placing/location of the desalination plant according to its feedwater source and its tie-in point. If the desalination plant is placed in the wrong location it can contribute to significant additional capital and general operating costs;

- **Manufacturing specifications and plant life**

Choosing material for the construction of the plant and equipment is important. Using incorrect material and second-rate equipment can have severe consequences on the maintenance cost and the general operability and availability of the plant. Clear and precise definitions of the minimum required plant life and construction specifications are crucial to avoid plant failure and consequent overhaul after a few years of operation;

- **Plant configuration**

*Stand-alone* is when the energy/heat source utilized by the desalination plant is dedicated to produce energy/heat only to the desalination plant producing fresh water.

*Co-generation* is when the desalination plant is located at a power plant. The plant uses the low pressure/temperature steam from the power plant as the heating source to the desalination plant. The power plant still produce electricity as product and the desalination plant produce fresh water as product and both are sold for revenue. Co-generation normally works with MSF, MED, or hybrid MSF/MED-RO although using the preheated condenser cooling water as feedwater of RO is also a possibility. Co-generation decreases the specific energy requirements of a desalination process resulting in reduced green house gas emissions. On the economical side, co-generation results in a decreased unit cost of water, making it a method of choice in the UAE where the infrastructure development requires both power and water.

### 2.8.1 Main driver of desalination cost

All desalination technologies need some sort of energy input. Literature indicates that the selection of the energy source had the largest influence on desalination costs. The selection of the energy source is directly related to the desalination technology. Membrane desalination only uses electricity as energy source, whereas thermal desalination can utilize any heat source producing steam. The heat source can utilize different fuel types including oil, coal, natural gas, electricity of nuclear.

A study from the United Nation (2009) shows desalination cost as dependant on the oil price. At 40$ per barrel, the supply cost is $\$1.2/m^3$; at \$80 per barrel the cost rises to $\$2.40/m^3$; and at \$120 per barrel cost is $\$3.49/m^3$. With the high price for energy for thermal desalination, the impression is that RO should be preferred in cases where oil is above \$20 per barrel.

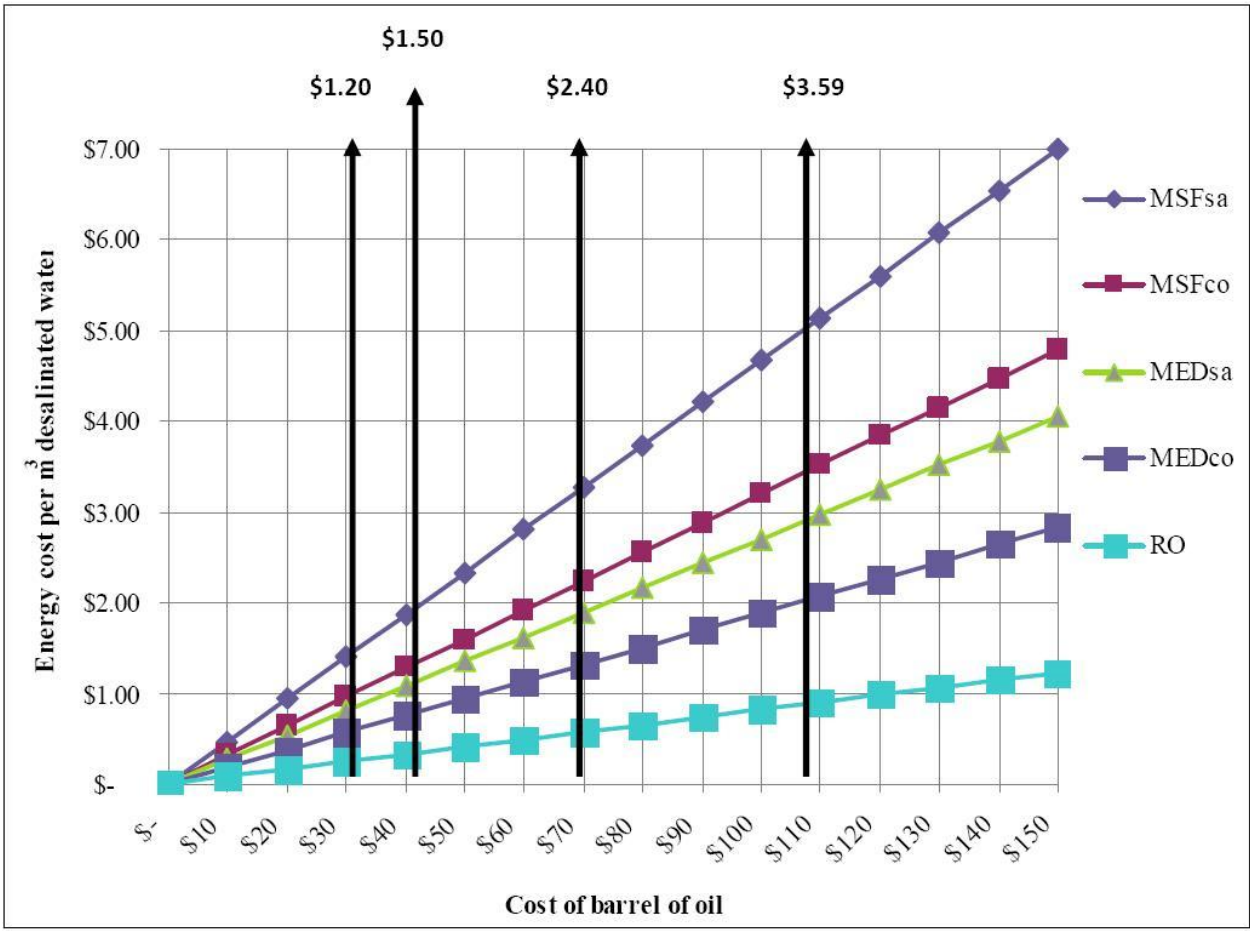



**Figure 16: The cost of desalination in relation to the cost of oil (United Nations, 2009).**

Figure 16 indicates that RO is least affected by an increase in the oil price. The figure indicates how co-generation plant configurations are more economical than stand-alone plant configurations as stated previously.

### 2.8.2 Desalination implementation cost

Desalination plant implementation cost can be regarded as capital cost, operational and maintenance (O&M) cost and other project costs. The general experience for seawater desalination plants shows capital cost to be 30 to 50% of the overall product water cost, energy cost 50 to 30% and O&M cost 15 to 20%.

#### 2.8.2.1 Capital cost

Capital cost is also known as the construction cost. This includes direct and indirect capital cost. Indirect capital cost is estimated as percentages of the total direct capital cost (United Nations, 2001).

**Direct Cost**

- ***Land cost;*** land costs may vary considerably, there may be zero sum or nominal sums charged by the municipality and/or sums that depend on location and other site attributes. Government owned plants are normally constructed on public land, entailing no charges;
- ***Well supply;*** the plant capacity and the well depth contribute to the well construction cost. The general well depth is estimated around 500m³/d at average well construction cost at US$650 per meter of depth;
- ***Process equipment;*** the cost depends generally on the plant capacity, process type and feedwater quality. Process equipment includes instrumentation and control equipment, pipelines, membranes (if RO), valves, electric wiring, pumps, process cleaning systems and pre- and post treatment equipment. For plants with a capacity of 27 000 m³/d, MSF and MED processes are higher than those for RO and average around $40 million. Whereas a 100 000 capacity RO plant can cost up to $50 million;
- ***Auxiliary equipment;*** auxiliary equipment includes open water intakes or wells, transmission piping, storage tanks, generators, transformers, pumps, pipelines, valves and electric wiring. Cost can be lowered if local suppliers, inputs and materials are used;
- ***Building cost;*** building cost is site specific and can vary widely. The cost also depends on site condition and type of construction. This normally includes facilities such as the control room, laboratory, offices and workshops;
- ***Membrane cost;*** the cost depends on the plant capacity and ranges between US$500 and US$1,000 per module, with production rates of 50-100 m³/d; and
- ***Concentrate disposal;*** the cost depends on the type of desalination process used, capacity, discharge location and environmental regulations.

**Indirect cost**

- ***Freight and insurance;*** freight and insurance costs makes up 5% of the total direct cost;

- ***Construction overhead;*** construction overhead costs include labour cost, fringe benefits, field supervision, temporary facilities (canteen, common room, recreational facilities, rest rooms etc), construction equipment, small tools, miscellaneous items and contractor's profit. This cost is generally estimated as 15% of the direct material and labour cost;
- ***Owner's cost;*** the owner's cost includes land acquisition, engineering design, contract administration, administrative expenses, commissioning and/or start-up costs, and legal fees. This cost generally works out at 10% of the direct materials and labour costs;
- ***Contingencies;*** the contingencies costs are included for possible additional services. It is generally estimated at 10% of the total direct costs.

#### 2.8.2.2 Operating and maintenance (O & M) costs

Operating and maintenance costs stretch over the lifetime of the plant and consist of fixed costs and variable costs. The operating cost covers all costs acquired during the actual operation following plant commissioning.

***Fixed cost;*** fixed cost is composed of insurance costs and amortization costs. Insurance costs are normally estimated at 0.5% of the total capital cost. Amortization costs normally relate to the annual interest payments for direct and indirect costs and depend on the interest rate and lifetime of the plant. An average amortization value is around 5%, but can range between 5 and 10 % (Reddy, 2008).

***Variable cost;*** variable cost is composed of cost of labour, energy, membrane replacement, chemicals, and maintenance on spare parts. The labour cost is site specific and depends on the following factors: private or public plant ownership, local conditions and special arrangements like plant outsourcing operations. The energy costs consist of the type of energy needed to operate the different types of desalination technology. Energy cost can be minimized considerably with co-location. The membrane replacement cost is interconnected with the feedwater salinity. Feedwater salinity is site specific and is minimized by using the correct pre-treatment procedures and facilities. The chemical cost is depended on the pre-post-treatment and cleaning process together with the amount and type of chemical used (Watson, 2003). The price of chemicals depends on the market price. The maintenance cost is normally less than 2% of the capital cost on an annual basis (United Nations, 2001).

### 2.8.3 Water transport and environmental externalities

Too often, only capital and O&M costs of desalination are considered in desalination cost estimates. Making use of this cost methodology does not give a true reflection of the total cost involved in desalination. The part missing from the methodology is the cost of bringing the water to the consumer. The full cost of desalination, therefore, includes two other costs, namely; water transport costs and environmental costs as indicated in Figure 17.

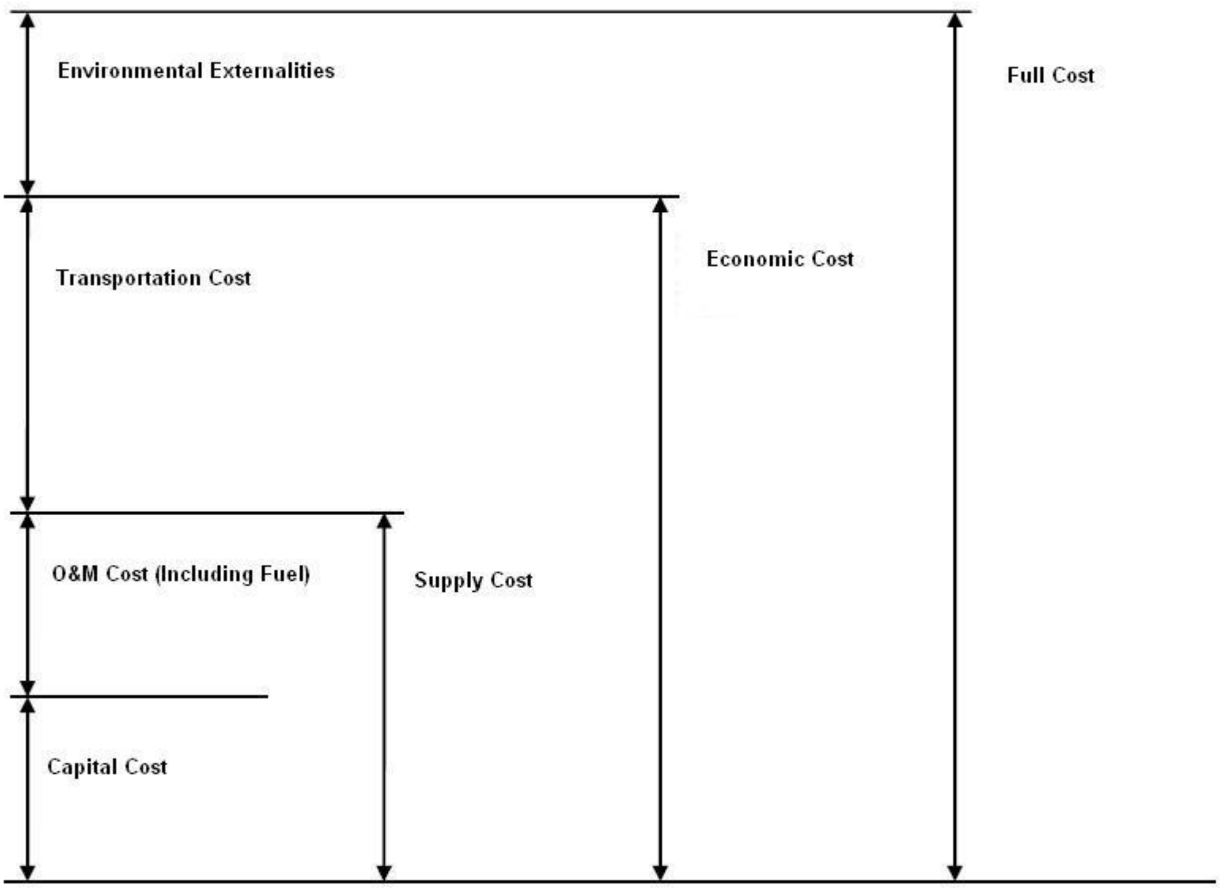



**Figure 17: Total cost of desalination.**

#### 2.8.3.1 Transportation cost

Transportation cost is the cost of transporting water from the desalination plant to the needed location. Adding transportation cost to the supply cost gives the economic cost of desalination. However, water transport cost does not influence water production cost, it should rather be seen as site specific and not a desalination technology specific cost (Figure 17).

#### 2.8.3.2 Environmental externalities

Environmental externalities include any positive or negative effects on the environment created by the desalination process. Overwhelmingly, the desalination effects of the desalination processes are negative. This includes the effluent pumped into the sea and air. The costs that are very difficult to determine are the effluent deposits, chemicals, and saline brines or sludges, and the pumping of effluent into the sea. The cost that can be determined in a more straightforward way is the cost of $CO_2$ emissions from the desalination plant. Carbon tax will increase costs further, especially thermal desalination technologies. The South African government indicated that carbon tax imposed on directly on all measured emissions at ZAR75 (9$) a ton of $CO_2$ and rising to around ZAR200 (25$) a ton (Flak, 2011).

### 2.8.4 Undocumented factors effecting desalination cost data

The United Nation (2009) states that determining an accurate supply cost of desalination is difficult. This is due to the lack of global standards of desalination reporting. Reported costs of desalination water per cubic metre are generally reported in a summary form. These summary reports do not specify what is included in the cost and may not contain such cost factors as land acquisition and regulatory cost or contingency factors that can significantly influence the cost of desalination. Government subsidies are generally not indicated in the reports. This includes direct subsidies and fuel subsidies.

### 2.8.5 Utilizing by-product/brine as a possible revenue stream

The potential to add value to this resource (brine) as a means of offsetting the operation cost of a desalination plant should be investigated. Given the high cost of building and operating desalination plants, brine water must be viewed as a possible asset. By taking advantage of this asset, net costs can be reduced to produce fresh water. Brine water value-adding enterprises are now accepted as an effective means to reduce overall cost, while meeting set environmental standards (C/Land & Water Australia, 2002).

Brine can be utilised by the following processes:

- Salt harvesting
- Irrigation
- Aquaculture
- Solar ponds

- Integrated value-adding and disposal.

**Salt harvesting**

Salt and other minerals that can be extracted from the brine by mechanical means or via crystallisation in evaporation basins are increasingly being harvested as a high value product for agricultural, industrial and domestic use. These products can also be sold for purposes including stock feed, medical, and chemical use.

Significant capital costs are associated with setting up salt harvesting schemes including the cost of construction of an appropriately lined evaporations plant. Solar pond costs also include ongoing operational and maintenance costs including labour and equipment used for salt harvesting, cleaning and packaging. Generally, only medium to large scale salt harvesting plants are profitable. However, smaller scale ventures may successfully cater to a smaller, niche market.

**Irrigation**

With some modifications to irrigation practices, dilution of saline water has been shown to be effective for irrigating particular horticultural crops including, olives, almonds, pistachios etc.

**Aquaculture**

Prior to evaporation and other means of disposal, adding value to the brine via saline aquaculture is possible. The proceeds from aquaculture can potentially off-set the cost of running a desalination plant. Brine shrimp production is an example. Shrimp are grown in saline water within the evaporation ponds. The shrimp acts as biological filter, thereby enhancing the quality of the salt retrieved from the site. There are other experimental projects where different species of fish are trailed for their suitability. Algae producing beta carotene can also be grown. Carotene is currently growing in popularity as a dietary supplement and food colorant.

**Solar ponds**

A solar pond is a body of water that collects and stores solar energy via a salinity gradient in the depth of the water. Generally, a pond consists of three layers; an upper less saline, lower density layer, a middle layer of increasing salinity, and a lower layer of uniform high salinity and density. The high salinity of the lower layer makes it denser than the other layers, trapping the water and preventing the heat gained from the solar radiation rising and dissipating via convection to the atmosphere. From all the layers, the bottom layer stores the most heat, with saline water temperatures of up to 100 °C. The hot saline water can then be utilised to produce heat or electricity.

**Integrated value-adding and disposal**

By combining all of the above mentioned into a single process the greater the chance is of, at least partially, offsetting the cost associated with brine disposal. The process divides the brined stream in different steps by blending the brine with sewage. Each cell is utilised for a different process. In Australia, a system known as serial biological control uses a number of options to manage a saline water resource. In the system, ground water is pumped and used to irrigate a salt tolerant woodlot. The trees use some of the water and what's left passes through the soil into a tile drain several meters below the soil. As the saline water passes through the soil it gathers an even higher salt concentration. The high saline water in the tile drain is then piped to the evaporation basin housing caged marine fish. As the water evaporates salt concentration increases. The saline water is moved to a second evaporation pond where salt levels increase even more. Eventually, the saline water will evaporate allowing for the harvesting of the crystallised salt. The system reduces ground water levels; renovates salt affected land, provides income from woodlot (timber etc.), provides income from marine fish and provides income from salt.

## 2.9 Potential energy sources in South Africa

### 2.9.1 Current electricity availability conditions in South Africa

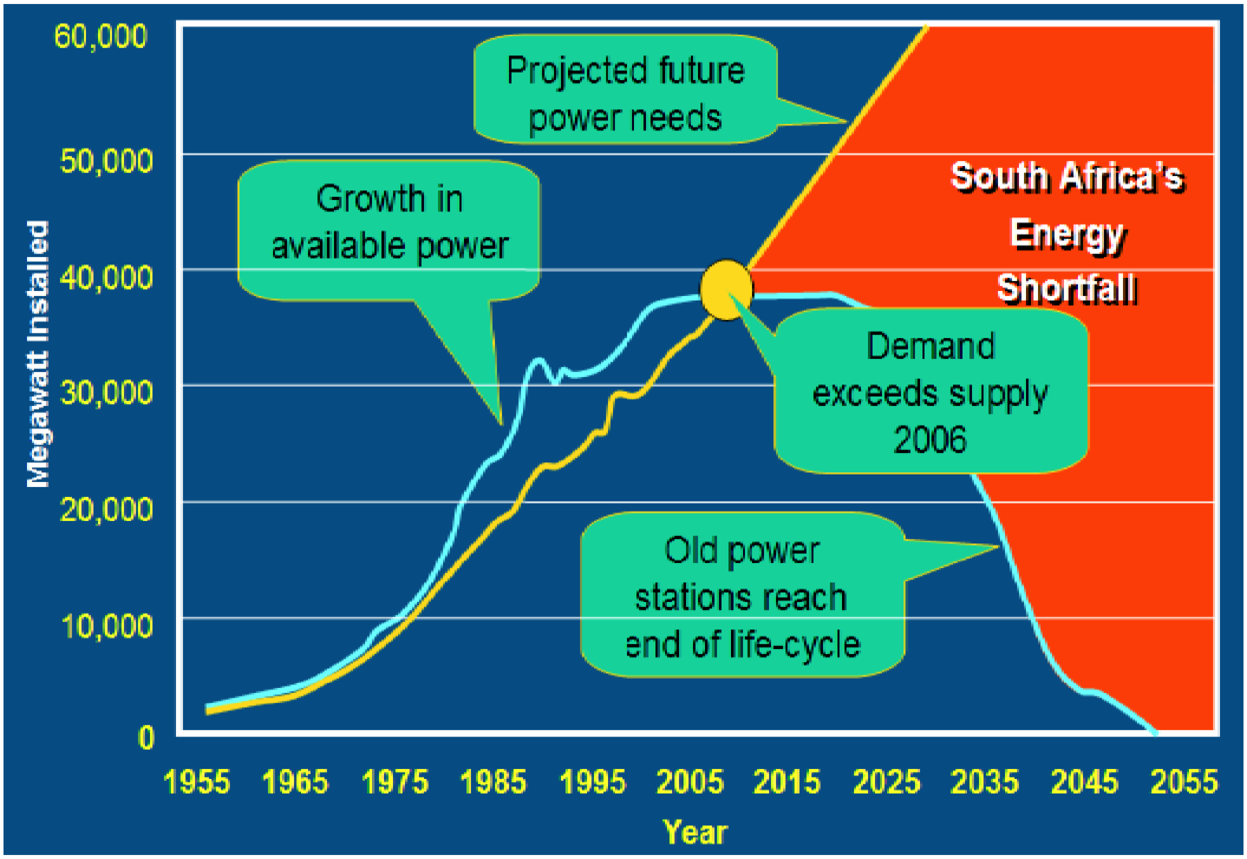



**Figure 18: Local energy growth projection and demand (PBMR.co.za).**

South Africa has been experiencing power supply problems from 2006 due to demand exceeding supply, which led to ESKOM implementing load-shedding (Figure 18). Load-shedding is a procedure in which parts of an electric power system are disconnected in an attempt to prevent failure of the entire system due to overloading. It is expected that ESKOM will again implement load-shedding from 2012 onwards.

With ESKOM replacing the aging power plant fleet, electricity cost has increased drastically over the last few years and will continue to increase well into the future. Then from 2011 up to 2013, an average increase of approximatly 25% per year has been approved by goverment. Table 2 shows the current approved scheduled electricity retail price increases by ESKOM.

**Table 2: ESKOM retail price adjustment (ESKOM.co.za)**

| Standard average prices and percentage price increases | 2010/11 | 2011/12 | 2012/13 |
|---|---|---|---|
| Standard average price (c/kWh) | 41.57 c/kWh | 52.30 c/kWh | 65.85c/kWh |
| Percentage Price increase (%) | 24.8% | 25.8% | 25.9% |

A continuous increase in the electricity price will negatively influence the feasibility membrane desalination which only utilises electricity as an energy source. In 2012/13 the cost of electricity will rise to 65.85 c/kWh. Assuming 8 Rand equals 1 Dollar, the price will be 0.0823 $/kWh.

With the large need for electricity in the country, it would be unrealistic to assign a new power station for the sole purpose of supplying power/electricity to the desalination facility. The logical approach is rather to assign a new desalination plant to an existing or new power plant for co-generation purposes, thereby, co-producing electricity and fresh water as a revenue product.

### 2.9.2 Power plants in South Africa

The two major energy sources in South Africa producing electricity consist predominantly of large coal fuelled power plants together with one nuclear fuelled power plant (Koeberg). Most of South Africa's coal-fired electricity is generated by large-scale plants built near the coal mines of two extensive coal-producing areas; both of which are far inland on the eastern side of the country. This requires long power lines from the coal power stations to load centers situated at the coastal region of the county. This results in high capital costs and transmission losses. The transporting of coal over long distances to power stations situated far away, for instance at the western coast as is not an option, it is far too costly. The fossil fuel reserves are also limited and the process is pollution intensive.

South Africa is in the process of committing to about 9 000 MWatt of newly, installed nuclear-fuelled power plants. This coincides with a commitment to expand the countries renewable energy capacity. The sites selected for the siting phase of the project are Schulpfontein, Brazil, Bantamsklip and Thyspunt. Of the mentioned sites, Thyspunt is the most favourable site of the four. The location of these sites is indicated in Figure 19. Thyspunt located close to Port Elizabeth (PE) is seen as the most favorable site for the proposed new nuclear fleet.

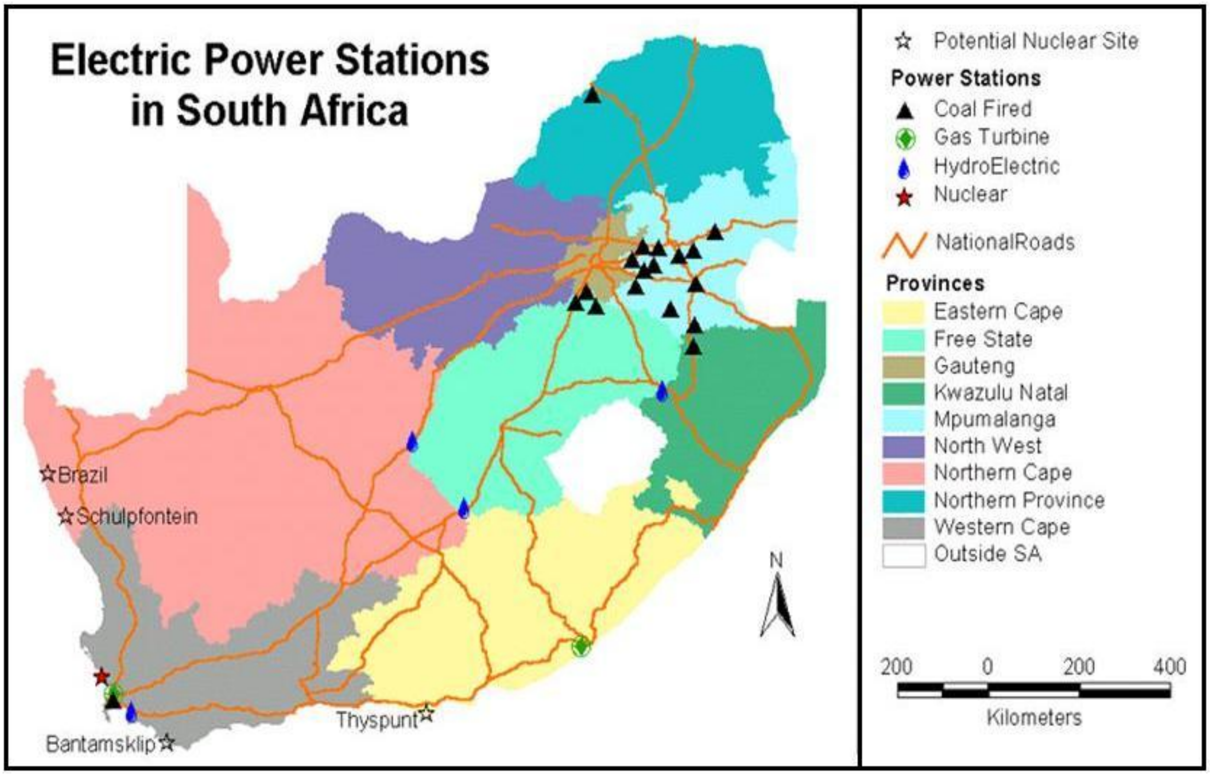



**Figure 19: Locations of power stations in South Africa (Eskom.co.za).**

The locations of the current operating power stations located in South Africa are also indicated in Figure 19. Currently the only large scale power plant located at the coast is the Koeberg nuclear power station. Koeberg is, therefore, the only viable power plant for co-generation applications.

It should be noted that this study originated due to the pebble bed modular reactor (PBMR). The PBMR demonstration plant could have been built at Koeberg in the Western Cape. The original idea of the thesis was to evaluate the economic viability of different desalination technologies utilizing waste heat from the PBMR. Co-generation with the PBMR could have increased the economic viability of the PBMR itself. However, the government retracted all funding of the project which led to the closure of the PBMR. The focus shifted from only utilizing the PMBR as energy/heat source to other possible facilities located along the coast. Other locations were also considered to give a thorough representation of the possible sea water desalination locations in South Africa. The main focus of the dissertation resided on which seawater desalination technology would be most economically viable for development in South Africa.

#### 2.9.2.1 Renewable energy

The main attractions of renewable energy are their security of supply and the fact that they are environmentally friendly compared to fossil fuels. Renewable desalination plants do not produce $CO_2$, which is a main advantage of such plants that translates into cost savings of up to \$0.50/$m^3$ of water (United Nations, 2009). Linking desalination to renewable energy makes sense from an environmental and sustainability point of view. Kita (2005) states that globally, several small-scale, low capacity, renewable energy driven desalination facilities have been built, mostly in arid regions with high renewable energy capacity. However, there are several barriers that need to be bridged before these technologies can be effectively linked for large-scale desalination processes. Firstly, is the present state and cost of renewable energy technologies, while a second consideration is the desalination capacity versus demand. Most renewable sources cannot supply the constant and uninterrupted power needed in the desalination process (Quteishat, 2003)

The coupling of energy sources with RO desalination plants has been an increased interest to development. However, the renewable energy sources are still more expensive than traditional resources. Therefore, the unit cost operation for RO coupled with renewable energy is higher than for typical RO plants. The main renewable energy sources available are solar, wind, and geothermal energy. The thermal energy sources are most often used with distillation desalination, while wind and photovoltaic solar energy are commonly paired with RO desalination. Overall, the energy sources most often used are solar energy (70% of market) and RO which has the majority (62%) of the renewable energy desalination market. The development of small RO systems in rural areas has been limited due to high capital cost investment required, but the use of renewable energy could enable more communities to take advantage of RO technology (Bhausaheb, & Pangarkar et al., 2011).

Currently, there are large prospects in the development and implementation of renewable energy power plants. Such energy sources include wind, solar, wave and gas powered plants. For large scale desalination plants, wind and solar power as energy source is currently not an option. Desalination as previously mentioned in Chapter 2 needs a constant supply of energy/heat to operate at maximum capacity. Wind and solar power cannot guarantee a constant power production, therefore, currently solar and wind desalination would not be a feasible option as an energy source for large scale desalination plants.

A new renewable technology that can produce constant electricity is called wave power. South Africa has a significant offshore wave power resource. The estimated power per meter of wave front is approximately 20 to 40 kW. It is believed that by 2013 up to 24 MW of wave power could be installed off the coast of South Africa. The future potential resource could contribute 8 to 10 GW towards the South African electricity supply. The most promising areas include the west and south coasts. Desalination of seawater for limited productive use in coastal locations is considered highly feasible. Desalination for coastal locations will require implementation mechanisms to effect changes such as regulatory and market-based instruments, self-regulation, awareness and education.(142). As yet, there are no plans to implement any ocean energy desalination projects (McGrath, 2010).

## 2.10 Economic models

Researchers, policymakers and planners generally make use of less accurate costing methods than process engineers, plant suppliers and consultants. Each makes use of different levels of costing accuracy. They usually make use of their own developed costing methods, but there are also publicly available costing methods. Two publicly available programs used in most feasibility studies are desalination economic evaluation program DEEP 4.0 and WTCost©II (WTC). The difference between the two is that WTC is more detailed and has provisions to generate user-desire flow sheets for commercial desalination processes in use including various pre- and post-treatment options. It estimates a capital cost for each equipment module in the membrane desalination process considered and thus it should provide more accurate estimates than DEEP for membrane processes (Reddy, 2008).

## 2.11 Issues to be addressed

In building desalination plants, there are certain major decisions that one has to make. These decisions have a huge influence on the total economics of the project. The major issues to address are:

- The selection of the desalination technology;
- Product water usage (municipal, agricultural or industrial);
- Location;
- Viable energy sources;

- Plant setup and size (product output);
- Water transport costs; and
- Water intake and waste disposal/outfall (environmental extremities).

## 2.12 Conclusion

There has been a significant improvement in the entire field of desalination technologies bearing in mind that this is an ongoing process. The world realizes that fresh water availability is shrinking by the day. Studies show that South Africa is going to experience fresh water shortages from around 2020/2025. Of these locations (cities) identified three are situated on the coast which makes them suitable candidates for future seawater desalination. The cities are Cape Town, PE and Durban. Currently, only Cape Town has a large scale operating power plant located on the coast. This gives the advantage of co-locating the desalination plant at the power plant and utilizing waste heat which improves the economic viability of thermal desalination facilities.

The three most popular seawater desalination technologies used globally include RO (membrane process), MSF (thermal process) and MED (thermal process). Of these technologies, RO economics have improved the most over the last decade of all the available technologies. Currently, more than half of the world's installed capacity is from RO desalination. This desalination technology only utilizes electricity as an energy source and can, therefore, possibly be located at any site where there is an electric grid connection. The cost of SWRO from previous economic models has shown to be the most cost effective. Thermal desalination technologies have also indicated a large cost reduction over the last decade, however, it remains an energy intensive technology. Co-locating thermal desalination at any facilities producing waste heat, reduces the amount of heat needed for the distillation process. Costs are further reduced by utilizing existing infrastructure including utilities, water intake and outlet structures.

South Africa is currently experiencing large electricity availability problems. To cover the costs of new power stations, the government has increased the cost of electricity by approximately 25% annually. If the cost of electricity keeps rising, RO, which can only rely on electricity as an energy source, may become the least economically viable desalination technology for South Africa in the future.

In Chapter 3 the various major issues are addressed and defined in selecting various applicable scenarios applicable for South Africa. These scenarios will then be assessed by the costing programs WTC and DEEP 4.0. Both programs will be used to validate results. The results from the costing programs will then be assessed to determine which technology, plant setup and product output will be the most economically viable for South Africa.

# CHAPTER 3

## Methodology

# 3 General desalination economic modelling

Chapter 3 shows the methodology followed to determine the results in Chapter 4. This includes the selection of the energy source, the site location and the desalination economic software program used in the different scenarios (plant setup and configuration).

## 3.1 Methodology

It is a difficult task to decide which desalination technology to use while including optimal plant size. The plant size/capacity plays a large role in the overall plant economy. The construction cost is generally between 30 to 50% of the total cost. Increasing the capacity of the plant drastically increases the construction and energy cost of the plant, but by increasing the plant capacity one decrease the production costs of the product as depicted in Figure 20 (Watson, et al., 2003). Therefore, the most economical plant will be the plant that gives the lowest production, construction and energy cost at an optimal plant size to give the greatest net income over the plant lifetime (Miller, 2003).

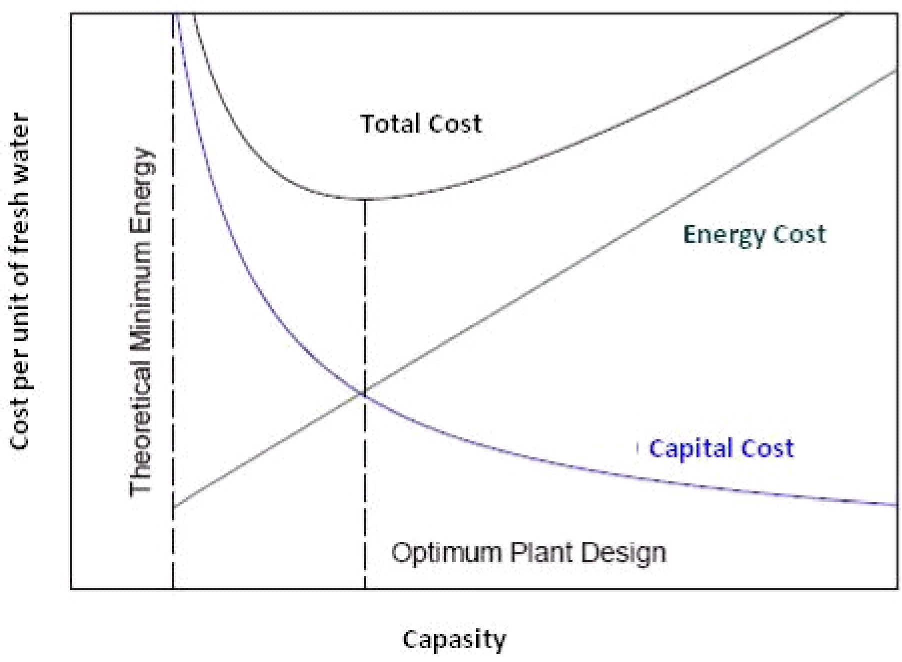



**Figure 20: Optimum desalination plant design (Miller 2003)**

The methodology in Chapter 3 follows the following steps:

1. Desalination technology;

2. Site selection;
3. Heat/energy source selection;
4. Coupling method;
5. Plant setup and configuration;
6. Acquire the relative computer software to determine the applicable costs;
7. Compilation of all costing scenarios; and
8. Sensitivity study selection.

After the completion of the above-mentioned steps, the relevant desalination economic software program is then used to determine all the costs of the different scenarios. The construction cost, production cost, indirect cost and total cost of all the scenarios will then be compared in Excel to determine which plant setup is the most economically feasible in Chapter 4.

## 3.2 Desalinisation technology

The desalination technologies selected for this study are:

- RO (membrane)
- MSF (thermal)
- MED (thermal)
- MSF–RO (hybrid)
- MED–RO (hybrid).

All technologies will be evaluated to identify the technology that will be the most economically viable for utilisation at the South African coast. The hybrid plant water productions will be split 50/50. (50% MSF and 50% RO = total water production).

## 3.3 Locations selected in South Africa

The site selection process often results in an evaluation of two or more possible sites. With South Africa's vast coastline there are many locations that are suitable for desalination. The South African coastline can be divided in three sections. These sections include the West Coast, South Coast and East Coast. Two site specific properties that can influence desalination cost are the inlet seawater temperature and quality (TDS). The seawater quality is very similar for the three coastal areas. The seawater temperature, however, differs greatly from as low as 9°C along the West Coast up to 22°C along the East Coast. Figure 21 indicates the location of the three coastline sections displayed in Table 3.

**Table 3: South African coastal seawater temperature and quality conditions (Swartz et al., 2006)**

| Location | Sea water temperature (°C) | TDS (mg/l) |
|---|---|---|
| West Coast | 9 | 36 000 |
| South Coast | 16 | 36 000 |
| East Coast | 22 | 36 000 |

Source: Swartz et al. (2006).

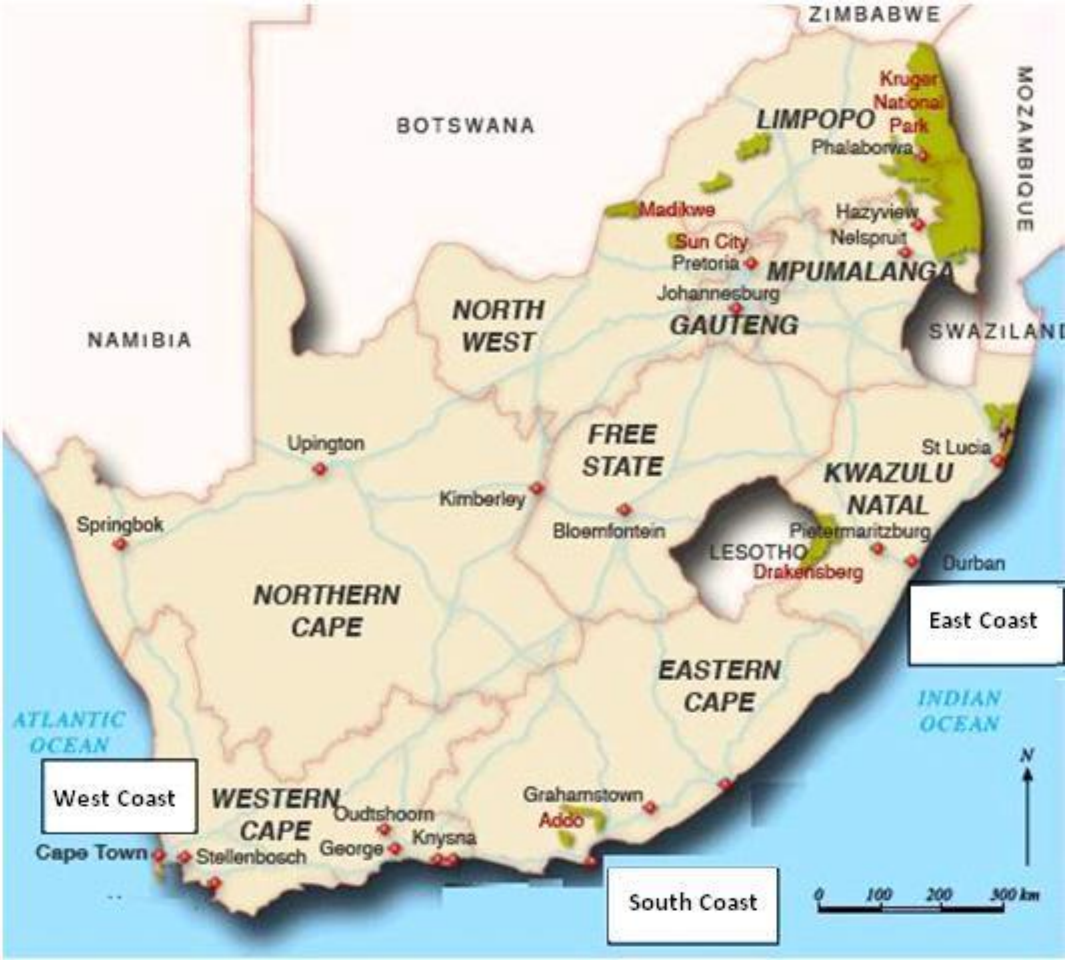



**Figure 21: The South African coast line ([http://dorsinindifferentcountry.blogspot.com/p/south-africa_18.html](http://dorsinindifferentcountry.blogspot.com/p/south-africa_18.html))**

In Chapter 2, three locations were identified that will experience freshwater supply shortages around 2025. As a result of urbanization and densification, these three locations are put under continuous freshwater availability pressure. The sites identified are:

- Cape Town : West Coast;
- Port Elizabeth (PE) : South Coast; and
- Durban : East Coast.

The three selected sites give a good representation of the entire South African coastline. The only seawater parameter which varies at the identified locations is the seawater temperature. As indicated in Chapter 2, a low inlet temperature is more advantageous for thermal desalination, whereas a high inlet temperature is more advantageous for membrane desalination. A higher water inlet temperature requires less pumping pressure by the RO process and, therefore, less electricity is consumed reducing operating cost. For distillation processes, the driving force for evaporation is the total temperature difference (i.e. the maximum process operating temperature minus the feed water temperature). The greater this temperature difference, the greater the amount of water that can be produced from the supply. Therefore, for two plants operating at the same top temperature, the one with the lower feed water temperature can produce more water. In addition, the cost of pumping the cooling water supply and its return to the feed water source will be less as the feed water temperature decreases (Watson et al., 2003). This means that RO should be more cost effective in the Durban area than in Cape Town, whereas MSF and MED should be more cost effective in Cape Town than in Durban.

Chapter 2 identified the different factors influencing desalination costs. The main factor influencing the economic viability, however, is often the running cost of the plant, and specifically the cost of the consumed energy. The selection of all feasible site specific energy/heats sources will, therefore, be evaluated.

## 3.4 Viable energy sources

Desalination remains an energy intensive process. Both thermal en membrane technologies use electricity, while only thermal desalination relies on heat as the main energy source for the distillation process. The main general energy sources available producing heat are coal, oil, natural gas, electricity, renewable energy and nuclear. All energy sources can be utilized as heat source in desalination. However, building new facilities producing heat from these energy sources are generally very costly. Large cost reductions can, therefore, be accomplished by avoiding the construction of a new plant producing heat (heat source) for the desalination plant.

One way to accomplish this, is the utilization of waste heat. Costs are further reduced by using waste heat of other facilities. Waste heat can be seen as free heat/energy; therefore, fuel cost is also excluded from the total cost. There are a variety of possible sources producing waste heat. The logical step is, therefore, to identify these potential sources/facilities from which waste heat could be potentially utilized as heat source by the desalination facility to produce fresh water and increase the affectivity. The production of electricity is typically a process which produces a sufficient amount of waste heat at sufficient temperatures to be utilized by all desalination technologies. However, the selection of possible processes and facilities producing waste heat is not limited to electricity production.

Off all the above mentioned heat sources, nuclear is seen as the most hazardous. Special care has to be taken when utilizing nuclear heat/energy. When coupling a desalination plant with a nuclear plant, the risk of radioactive contamination of the product water must be none. The desalination plant must produce water that meets well defined quality requirements as per end use. Design precautions must be taken to avoid product water contamination from radioactive materials during normal operation and accidents. These safety considerations include:

- One or more protective barriers, usually in the form of a leak tight intermediate heat transfer loop, are provided between the primary and desalination systems;
- The principle of pressure reversal where a higher pressure is maintained on the desalination plant side so that the direction of a potential leak is away from the desalination plant;
- The activity in the intermediate system and the desalination plant is continuously monitored;
- Condensate that is returned to the power plant from the desalination plant is also monitored for radioactivity; and
- Apart from gross radioactivity, the presence of specific radioisotopes such as cesium, strontium, tritium etc. are monitored periodically.

A schematic illustration of a nuclear reactor coupled to an MSF plant via an intermediate loop is illustrated in Figure 22.

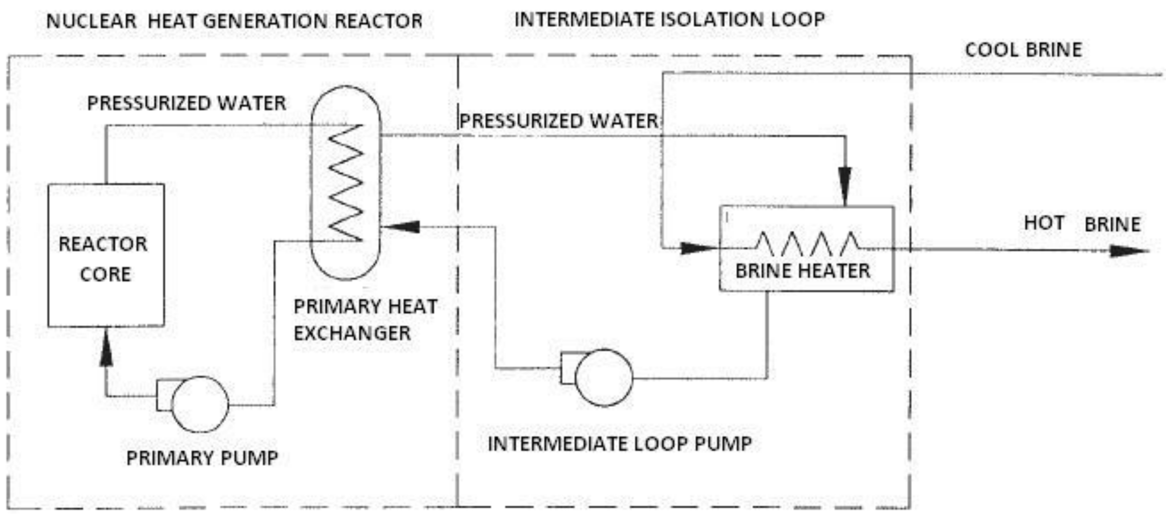



**Figure 22: Schematic diagram of a typical nuclear powered reactor coupled to an MSF plant via an intermediate loop (IAEA, 2000).**

Generally, the source water for a desalination plant co-located with a power plant is the cooling water discharge, which has already passed through screens similar to those used on surface water intakes for desalination plants. Therefore, a co-located desalination plant generally does not require the construction of a separate intake infrastructure, intake pipeline, screening facilities and outfall infrastructure. The cost of intakes and outfalls for a desalination plant is about 7 percent of the total capital costs (GWI, 2006). Generally, a permit is needed to install any type of intake and outfall pipelines in the sea. Power plants already have permits and, therefore, permit cost can be saved. The desalination plant can also use power direct from the power plant, avoiding grid transmission cost, which can lead to electrical cost savings. For the purpose of this study, only viable energy sources producing waste-heat at each location were selected.

Electricity as energy source was available at all selected locations. A stand-alone desalination plant, utilizing electricity as energy at Cape Town was therefore included in the evaluation. It should be noted that the one major advantage of utilizing electricity as energy not and heat is that the desalination plant can be located anywhere with an electric connection. All stand-alone plant configurations were, therefore, located at the selected cities. It was assumed that this site would not take credit for existing infrastructure. However, as the site is located in the city it was assumed that the water transport cost was zero (located as a water distribution point).

## 3.5 Cape Town

### 3.5.1 Viable waste heat co-location source

Cape Town, houses a large nuclear power plant, Koeberg (Figure 23), which can serve as a possible heat/energy source for the desalination plant. Koeberg is currently the only nuclear reactor producing electricity in South Africa. The facility contains two uranium pressurized water reactors based on a French design. Koeberg is rated at 1800 MWe; its average annual production is 13,668 GWh, and it has two large turbine generators (2× 900 MWe). The power plant can, therefore, produce more than enough waste heat to be utilised by the desalination technologies.

**Figure 23: Koeberg nuclear power station (Eskom.co.za).**

Co-location advantages at Koeberg:

- Situated on the coastline; placing the desalination plant at the sea will reduce the amount of piping needed and the distance to pump the feedwater from the sea to the desalination facility;
- Electricity is readily available from the Koeberg power plant and therefore no new distribution lines needs to be built;

- With the Koeberg nuclear facility located on the site, services and utilities needed to operate the desalination plant already exit thereby further reducing costs;
- There is existing water-intake and other general infrastructure reducing construction costs of the desalination facility;
- Reduction in personnel; personnel from the Koeberg facility can be used, which can reduce the number of workers needed on the plant (sharing of personnel);
- Close to highway; placing the desalination facility at an established road reduces the capital cost. A desalination facility placed far from any road means that new roads would have to been constructed before the desalination plant could be constructed. This also helps if any product needs to be transported by trucks;
- The low seawater temperature at Koeberg improves the efficiency of thermal desalination processes, which leads to a reduction of operating costs;
- Koeberg produces no $CO_2$ and, therefore, carbon tax is excluded; and
- No land cost; since the Koeberg site is large, no new land needs to be acquired for the desalination facility.

Co-location disadvantages:

- An intermediate loop needs to be constructed for process heat utilization;
- Licensing issues; the current nuclear installation licence (NIL) of Koeberg does not include nuclear desalination, therefore, a change for the current licence is needed. This requires Koeberg to submit a licence authorization change request (ACR) to the national nuclear regulator (NNR) to inform the regulator. A full revision of the safety assessment report (SAR) of the nuclear plant needs to be submitted with a full safety case of the desalination plant. The licensing process can be lengthy and expensive especially after the Fukushima accident;
- Some design modifications would be necessary on the power conversion unit to accommodate the desalination plant coupling (intermediate loop). The design modification makes part of the SAR and should, therefore, be included in the new licence application;
- Winning over public improvement; the public needs to be convinced and approve the usage of water produced by the desalination plant located at a nuclear power plant. This is not an easy feat, as incidents like Fukushima, Chernobyl and Three Mile Island tainted

the reputation of the whole nuclear industry for some individuals. Public perception can also be focused on localized issues associated with the siting of a desalination plant. Localized environmental degradation, co-location with power plants, barriers to beach access, and increased population growth and regional development are examples of concerns voiced by citizens about desalination plants. The public can also express concerns about environmental affects around Koeberg;

- Koeberg could have a shorter operation lifetime left than a new desalination plant, which can lead to early closure of the facility.

### 3.5.2 Coupling method

The main coupling methods between co-location desalination and power plant are:

- Extraction method;
- Low pressure steam; and
- Backpressure turbine.

An extraction/condensing turbine is suggested over a backpressure turbine when coupling a desalination plant to a power plant. A backpressure turbine implies the heat that is not going to be used in the desalination plant is going to be wasted instead of producing electricity. Since co-location at the Koeberg nuclear power plant was selected, an extraction coupling method was selected for all cost estimations.

### 3.5.3 Plant configuration

Both single and hybrid plant configurations were included and selected for the desalination cost evaluation at Koeberg. The single plant configuration included a RO, MED and MEF plant illustrated in Figure 24, while the hybrid configurations included a MSF-RO and MED-RO plant illustrated in Figure 25. The Hybrid plant configuration is in a parallel setup and not in series. Hybrid plants in parallel avoid potential production losses. If the thermal plant needs maintenance, the RO plant can still function, without having to rely on the thermal desalination plant for the inlet feedwater. Hybrid plants in a series setup generally use the outfall of the first plant as the inlet for second plant. If the first plant shuts down due to maintenance, the second plant does not receive any inlet water and can, therefore, not produce any product water.

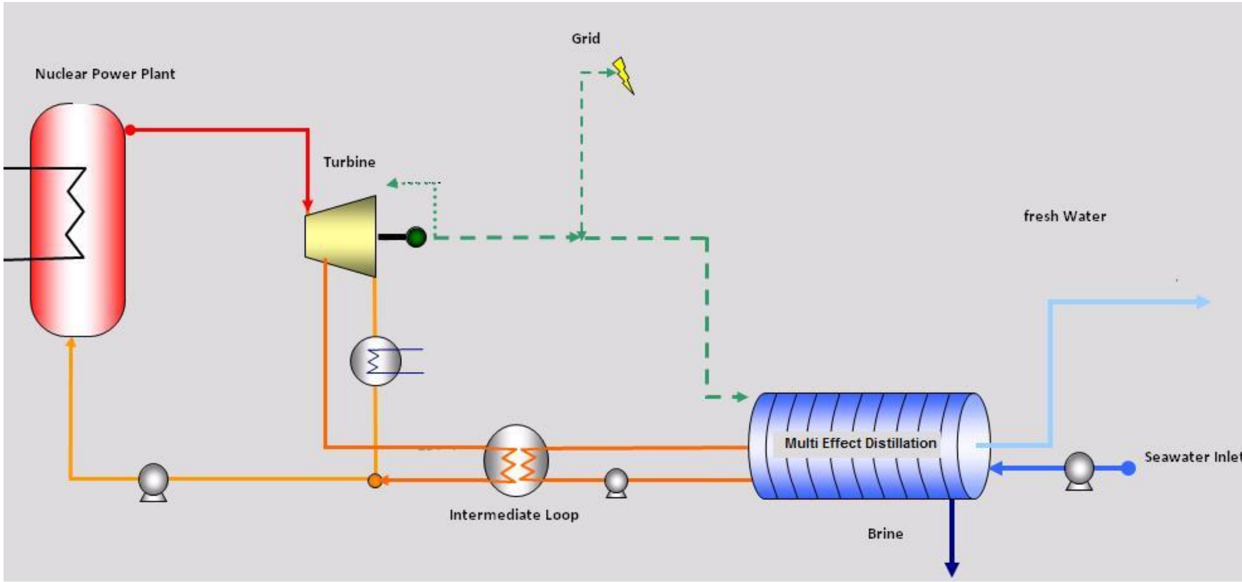



**Figure 24: DEEP 4.0 illustration of a single MED-nuclear power plant connection.**

The Hybrid plant configuration is in a parallel setup and not in series. Hybrid plants in parallel avoid potential production losses. If the thermal plant needs maintenance the RO plant can still function, without having to rely on the thermal desalination plant for the inlet feedwater. Hybrid plants in a series setup generally use the outfall of the first plant as the inlet for second plant. If the first plant shutdown due to maintenance, the second plant does not receive any inlet water and can, therefore, not produce any product water.

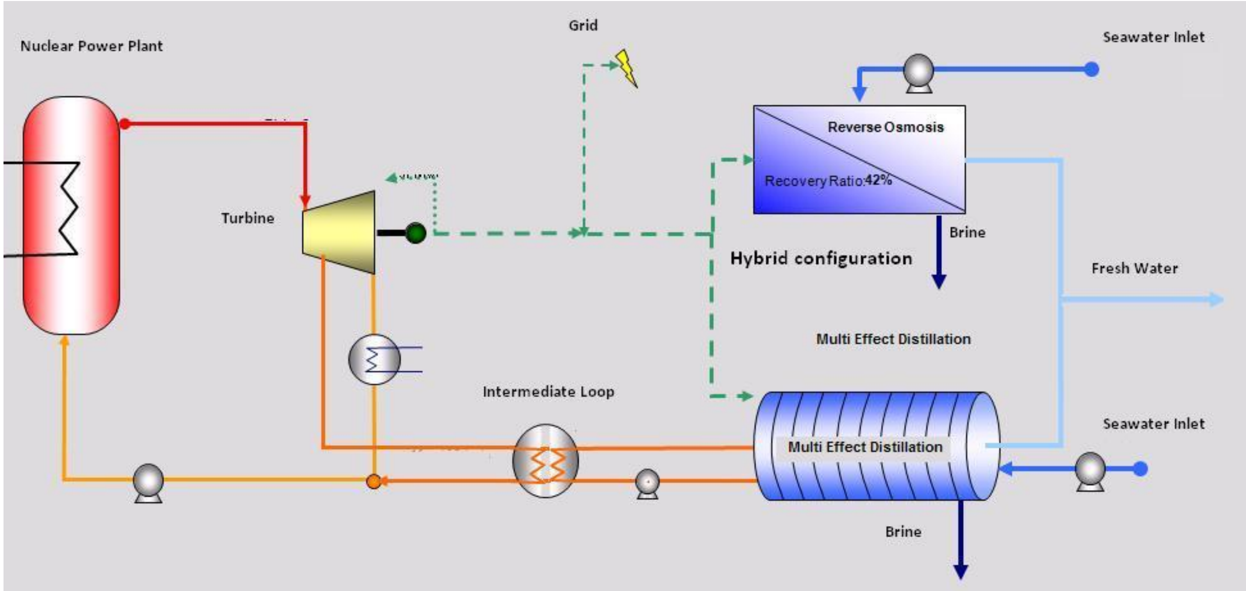



**Figure 25: DEEP 4.0 illustration of a hybrid-nuclear power plant connection.**

RO, MED, MSF MSF-RO and MED-RO plant configurations will be assessed at Koeberg with an extraction/condensing turbine coupling combined with an intermediate loop between the desalination plant and the nuclear power plant for safety. Water transport will be included as a site specific cost. Koeberg is approximately 30 km from Cape Town and, therefore, a distance of 30 km was selected for the pumping distance in the water transport calculations.

## 3.6 Port Elizabeth

### 3.6.1 Viable waste heat co-location source

Currently, the only viable energy source for desalination at PE is electricity. However, two potential co-location energy sources producing waste heat were identified. These energy sources include the planned nuclear power plant fleet at Thyspunt and an open cycle gas turbine (OCGT) upgraded to a combined cycle gas turbine (CCGT) planned at Coega in PE.

**THYSPUNT – NUCLEAR**

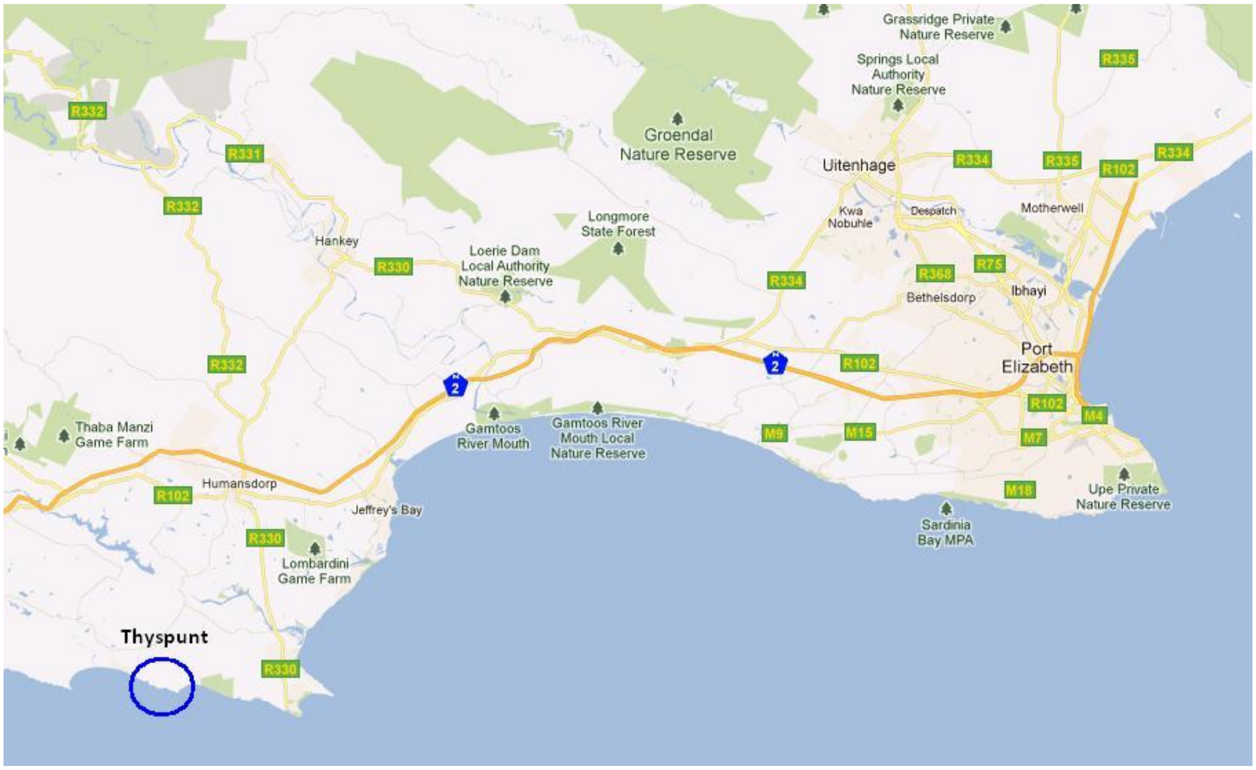



**Figure 26: Location of Thyspunt (Google Earth).**

Thyspunt is located a fair distance from PE, approximately 130 km (Figure 26).Thyspunt is the favorable site selected by ESKOM as the location of the Newbuild program consisting of six new nuclear power plants. The government indicated that the first plant should be operational around 2023. This date relates to the indicated water shortage for PE by the DWAF (2004).

Co-generation advantages at Thyspunt:

- Situated on the coastline; placing the desalination plant at the sea will reduce the amount of piping needed and the distance to pump the feedwater form the sea to the desalination facility;
- Electricity is readily available from the nuclear power plants and, therefore, no new distribution lines needs to be built;
- Utilization of utilities and facilities like intake and outfall infrastructure;
- Reduction in personnel; personnel from the nuclear power plants can share some responsibilities, which can reduce the number of workers needed on the plant;
- Close to highway;

- Carbon tax is excluded;
- Desalination co-location can be included in the original design of the nuclear facility, including the SAR and licence of the nuclear facility, which will prevent costly design changes to the nuclear plant layout;
- The EIA of the nuclear power plant can include that of the desalination plant, which will further reduce expenditures; and
- With the building of the nuclear fleet close to PE will accelerate population (transient population) and economic growth in the area. This may lead to a quicker than anticipated water shortage date in this area.

Co-location disadvantages:

- An intermediate loop needs to be constructed for process heat utilization;
- Gaining community support for a desalination plant coupled to the nuclear plant producing fresh water for the surrounding community; and
- Thyspunt is approximately 130 km from PE, which can lead to costly water transport costs.

**COEGA – COMBINED CYCLE GAS TURBINE**

The Coega industrial development zone (IDZ) covering 110 km² of land, is situated in the Nelson Mandela Municipality, within the Eastern Cape province of South Africa in the Nelson Mandela Metropolitan Municipality near Port Elizabeth. The initiative is a multi-billion dollar industrial development complex customized for heavy, medium and light industries, adjacent to a deep water port, Port of Naqura. The Coega development corporation (CDC) is the developer and operator of the Coega IDZ and is responsible for the land side infrastructure, while the deep-water port facility, Port of Naqura, is developed by the Transnet National Ports Authority (Wikipedia).

The total capacity of the Dedisa open cycle gas turbine (OCGT) facility will be around 335 MW, and the facility will comprise of two units (turbine and generator). Facility lay-out design allows for future change in primary fuel to gas and for future conversion to combined cycle gas turbine technology (CCGT) (Nersa, 2011). The facility will be upgrade to reach a maximum capacity of 2 400MW. The national energy regulator of South Africa (Nersa) has confirmed that it will host public hearings on July 13 2011 into applications for generation licences for the 335 MW facilities, which is proposed for the Coega industrial development zone (SAAEA, 2011).

The location of Coega relative to PE is indicated in Figure 27. Construction of the liquefied natural gas (LNG) terminal and the CCGT plant would take three years, but the power plant was expected to be completed before the terminal and would, therefore, run on diesel for the first two years of operation. The diesel would also be imported through the bulk liquids berth at the Port of Naqura (Creamer, 2011).

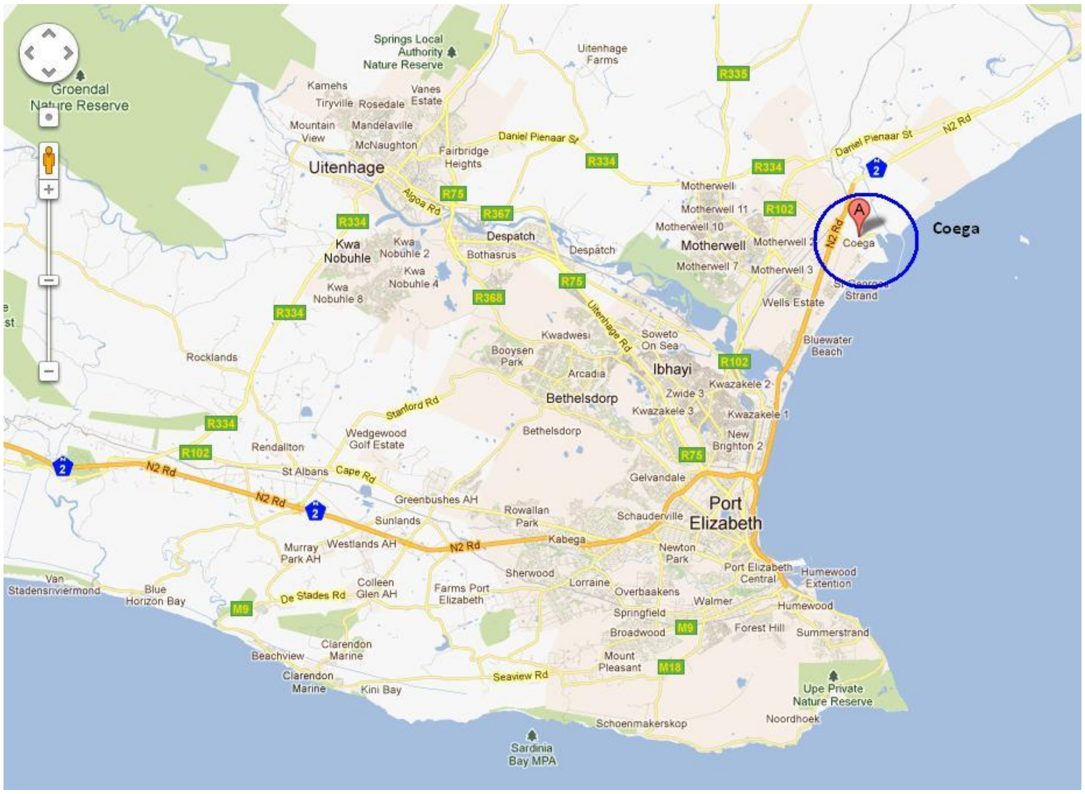



**Figure 27: Coega Industrial Development Zone (Google Earth).**

Co-generation advantages at Coega:

- Situated on the coastline; placing the desalination plant at the sea will reduce the amount of piping needed and the distance to pump the feedwater form the sea to the desalination facility;
- Electricity is readily available from the Dedisa substation and CCGT power plant, therefore, no new distribution lines need to be built;

- Reduction in personnel; personnel from the CCGT power plant facility can be used, which can reduce the number of workers needed on the plant (sharing of personnel);
- Close to highway; placing the desalination facility at an established road reduces the capital cost. A desalination facility placed far from any road means that new roads would have to been constructed before the desalination plant could be constructed. This also helps if any product needs to be transported by trucks;
- No land cost; since the Coega site is large, no new land needs to be acquired for the desalination facility;
- No intermediate loop needs to be constructed for process heat utilization; and
- No nuclear licensing issues.

Co-location disadvantages:

- There is no existing water-intake and other general infrastructure increasing construction costs of the desalination facility;
- $CO_2$ is produced by the power plant and, therefore, carbon tax would be included; and
- Winning over public improvement; the public needs to be convinced or approve the usage of water produce by the desalination plant located at a fossil fuelled power plant. Public perception can also be focused on localized issues associated with the siting of a desalination plant. Localized environmental degradation, co-location with power plants, barriers to beach access, increased population growth and regional development are examples of concerns voiced by citizens about desalination plants. The public can also express concerns about environmental impacts for Coega.

### 3.6.2 Coupling method

An extraction/condensing coupling method was selected for all cost estimations.

### 3.6.3 Plant configuration

The same plant co-location plant configurations were selected as described for Koeberg and Thyspunt. Both single and hybrid plant configurations were included selected for the desalination cost evaluation at Coega. Water transport will not be included as a site specific cost. Coega is located in PE, therefore, a distance of 0 km was selected for the pumping distance in the water transport calculations.

## 3.7 Durban

A potential co-location energy source producing waste heat was identified. This energy source includes the planned OCGT located at Shakaskraal north of Durban. Other possible waste heat options include the pulp and paper mill manufacturer, Mondi, near Richardsbay. They had achieved significant electricity savings of about 11 MW, adding that it is, overall, roughly 79% energy sufficient. A 27 MW gas turbine was installed in 2006, which resulted in significant savings. The average electrical import had been substantially reduced from 28 MW to 17 MW and, with some degree of internal load-shedding, the mill could operate with a full degree of electrical self-sufficiency (Lazenby, 2011). A desalination plant can be co-located at the mill and make use of the waste heat produced by the gas turbine, if available. However, Richardsbay is located far from Durban and, therefore, not considered.

### 3.7.1 Viable waste heat co-location source

**SHAKASKRAAL – COMBINED CYCLE GAS TURBINE**

The national energy regulator of South Africa (Nersa) has confirmed that it will host public hearings on July 13 into applications for generation licences for a 670 MW open-cycle gas turbine (OCGT). The Avon facility, 45 km north of Durban, is expected to begin operating from November 1, 2013, and comprises four OCGT units upgraded to CCGTs (Figure 28). The LNG terminal and the CCGT power plant were both expected to operate for a minimum of 35 years (Creamer, 2011).

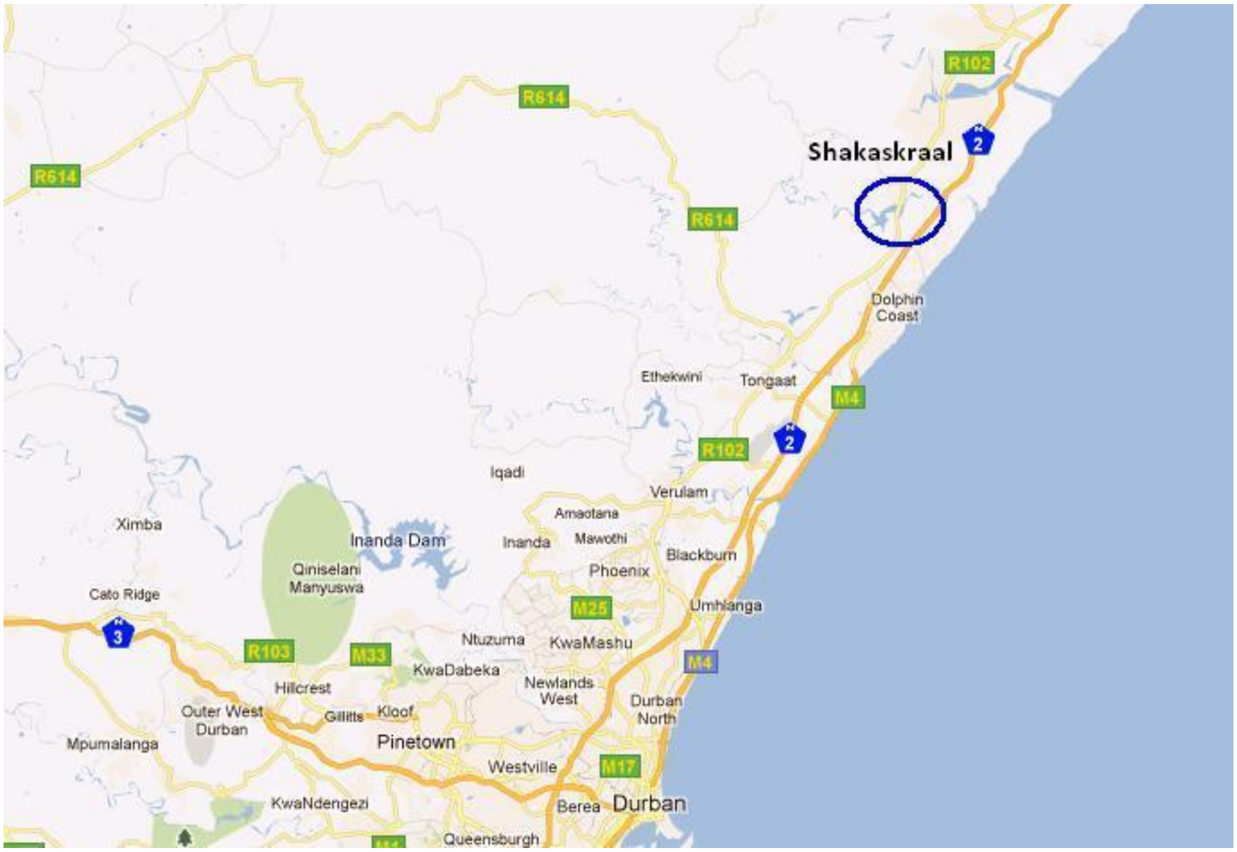



**Figure 28: Shakaskraal Industrial Development Zone (Google Earth).**

Co-generation advantages at Shakaskraal:

- Electricity is readily available from the Dedisa substation and CCGT power plant, therefore, no new distribution lines need to be built;
- Reduction in personnel; personnel from the CCGT power plant facility can be used, which can reduce the number of workers needed on the plant (sharing of personnel);
- Close to highway; placing the desalination facility at an established road reduces the capital cost. A desalination facility placed far from any road means that new roads would have to be constructed before the desalination plant could be constructed. This also helps if any product needs to be transported by trucks;
- Minimal land cost; since the Shakaskraal site is such a large site, no additional land need to be acquired for the desalination facility;
- No intermediate loop needs to be constructed for process heat utilization;
- No nuclear licensing issues.

Co-location disadvantages:

- Situated inland; placing the desalination plant inland increases the amount of piping needed and the distance to pump the feedwater from the sea to the desalination facility. Shakaskraal is situated approximately 5 km from the coast;
- There is no existing water-intake and other general infrastructure increasing construction costs of the desalination facility;
- $CO_2$ is produced by the power plant and, therefore, carbon tax would be included; and
- Winning over public improvement; the public needs to be convinced or approve the usage of water produce by the desalination plant located at a fossil fuelled power plant. Public perception can also be focused on localized issues associated with the siting of a desalination plant. Localized environmental degradation, co-location with power plants, barriers to beach access, and increased population growth and regional development are examples of concerns voiced by citizens about desalination plants. The public can also express concerns about environmental impacts on Shakaskraal.

### 3.7.2 Coupling method

An extraction/condensing coupling method was selected for all cost estimation.

### 3.7.3 Plant configuration

The same plant co-location plant configurations were selected as described for Koeberg, Thyspunt, and Coega. Both single and hybrid plant configurations were included selected for the desalination cost evaluation at Shakaskraal. Water transport was included as a site specific cost. Shakaskraal is located approximately 45 km north east of Durban and 5 km from the coast. The total pumping cost was determined by combining the pumping distance of the feedwater (5 km) and the pumping distance of the product water (45 km). The total water pumping distance of 50 km was selected to determine the total water transport cost.

## 3.8 Computer desalination economic models

Researchers, policymakers and planners generally make use of less accurate costing methods than process engineers, plant suppliers and consultants. Each makes use of different levels of costing accuracy. Usually they make use of their own developed costing methods, but there are also publicly available costing methods. DEEP and WTC cost are two publicly available programs used in most feasibility studies. The difference between the two is that WT cost is more detailed and has provisions to generate a user-defined flow sheet for commercial desalination processes in use including various pre- and post-treatment options. It estimates capital cost for each equipment module in the membrane desalination process considered and thus it should provide more accurate estimates than DEEP for membrane processes. However, for the purpose of this study, the interest is more in the trend between the different methods and locations. WTC and DEEP were, therefore, both used as costing models to validate the result of the study. A more detailed description of the process followed in DEEP 4.0 and WTC are given in Appendix A and Appendix B respectively.

### 3.8.1 DEEP

#### 3.8.1.1 General description

DEEP was originally developed by General Atomics under contract, and was used in the IAEA's feasibility studies. For further confidence in the software, it was validated in March 1998. After that, a user friendly version was issued under the name of DEEP at the end of 1998. DEEP output includes the levelised cost of water and power, a breakdown of cost components, energy consumption and net saleable power for each selected option. Specific power plants can be modeled by adjustment of input data including design power, power cycle parameters and costs. The DEEP main calculation sheet supports both nuclear and fossil power options, it considers heating and power plants as well as heat-only plants, distillation processes of MSF and MED and membrane process of reverse osmosis.

The spreadsheet methodology for co-generation/desalination economic evaluation is suitable for economic evaluations and screening analyses of various desalination and energy source options for several reasons. First, using spreadsheets is a commonly adopted way to cope with quite large calculations. These calculations include, in the case of DEEP, simplified models of several types of nuclear/fossil power plants, nuclear/fossil heat sources, and both distillation and membrane desalination plants. Current cost and performance data have already been incorporated so that the spreadsheet can be quickly adapted to analyse a large variety of options with very little new input data required. The spreadsheet output includes the levelised cost of water and power, breakdowns of cost components, energy consumption and net saleable power for each selected option. Specific power plants can be modelled by adjustment of input data including design power, power cycle parameters and costs (IAEA-TECDOC-1186, 2000).

DEEP serves three important goals:

1. It enables side-by-side comparison of a large number of design alternatives on a consistent basis with common assumptions;
2. It enables identification of the lowest cost options for providing specified quantities of desalinated water and/or power at a given location; and
3. It gives an approximate cost of desalinated water and power as a function of quantity and site specific parameters including temperatures and salinity.

The newest version available is DEEP 4.0, which was recently released in February 2011. The DEEP main calculation sheet supports both nuclear and fossil power options. It considers heat and power plants as well as heat only plants, distillation processes MSF and MED and Membrane process RO. The new features have also been added to DEEP 4.0, emphasizing its user friendliness. These features include (IAEA, 2011):

- Intuitive graphical user interface containing all basic reference coupling schemes in a single unified template;
- 'On-the-fly' comparison of different technologies and configurations. All parameter and factors can be modified instantly and users can quickly create their case and customize it step by step; and
- Versatile sensitivity analysis.

#### 3.8.1.2 Basic program function

In DEEP 4.0, all basic plant setups and configurations can be selected as indicated in Figure 29. The power plant configuration is selected in the top half and the desalination technology configuration is selected in the bottom half of the spreadsheet. RO, MSF, MED, MSF-RO and MED-RO are available for selection. The use of an intermediate loop, backup heat source, carbon tax and transport cost can also be selected.

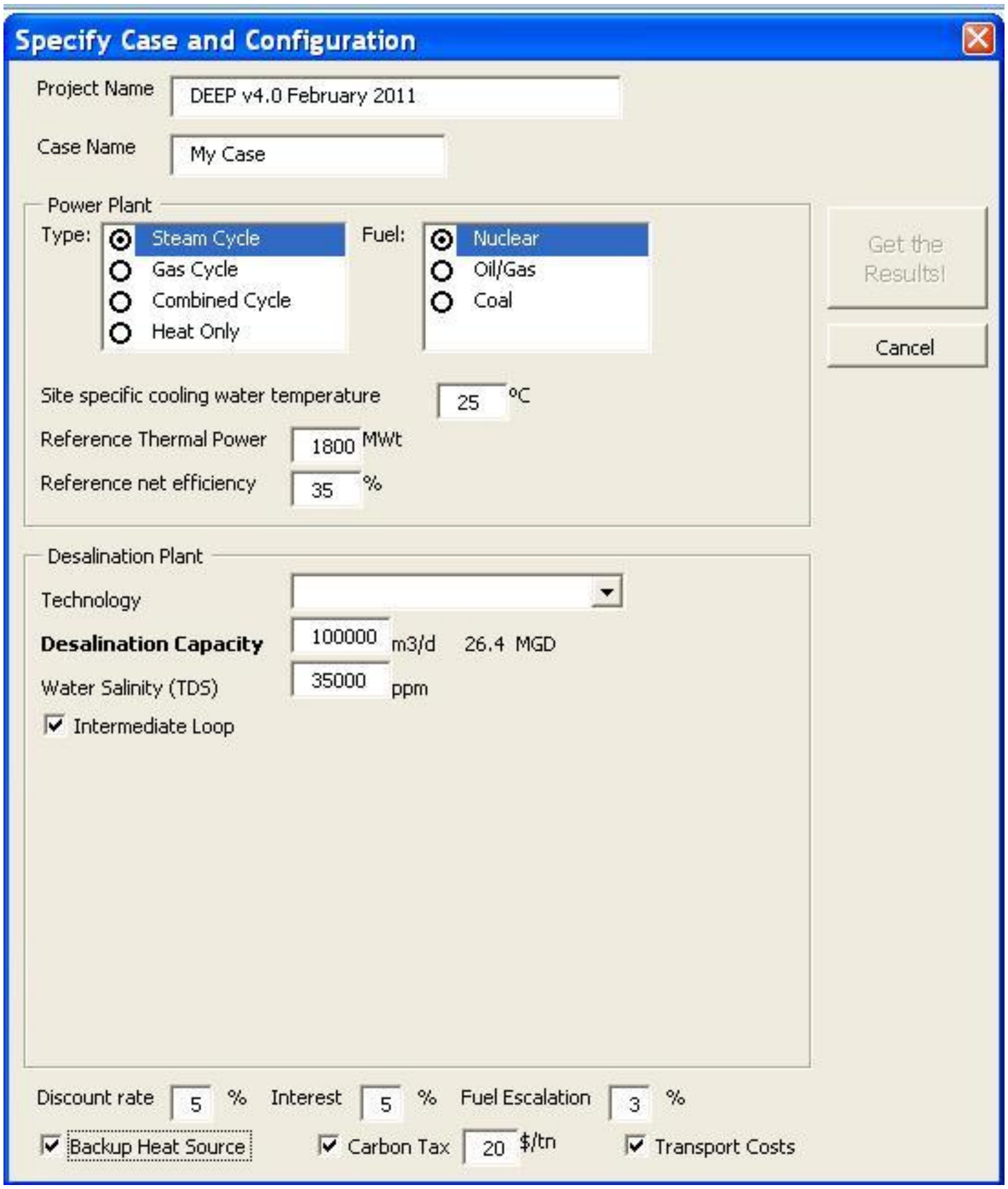



**Figure 29: Specific Case and Configuration.**

The results are shown in the following spreadsheet as indicated in Figure 30. This page lets the user choose the main economic and technical parameters for the desalination and power plant. An 'Expert Mode' can also be selected by the user to further refine the plant configurations (Figure 30).

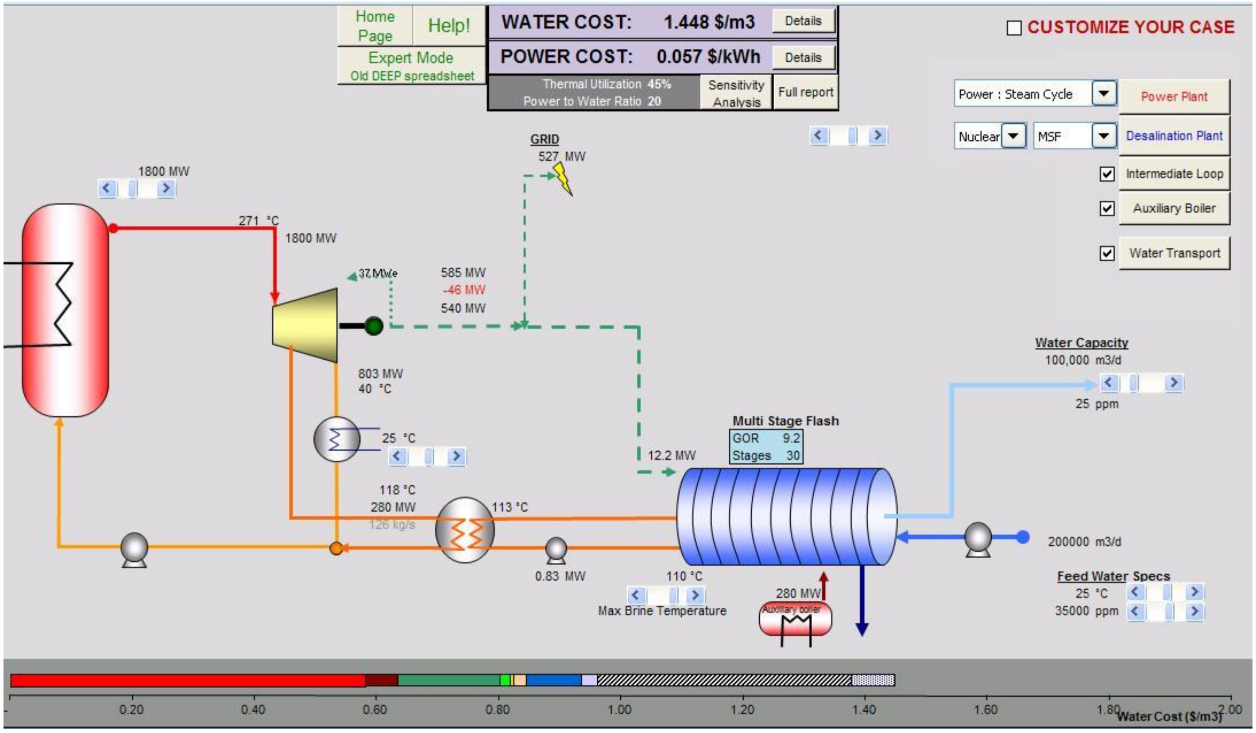



**Figure 30: DEEP Results spreadsheet.**

Figure 30 also displays the desalination and power plant co-location layout and setup. On this page, a more in-depth technical and economic power and desalination plant parameters can be selected and specified according to the user specific inputs.

The technical and economic parameters for the selected power plant are displayed in Figure 31, while the technical and economic parameters of the selected desalination plant are displayed in Figure 32.

POWER PLANT PARAMETERS

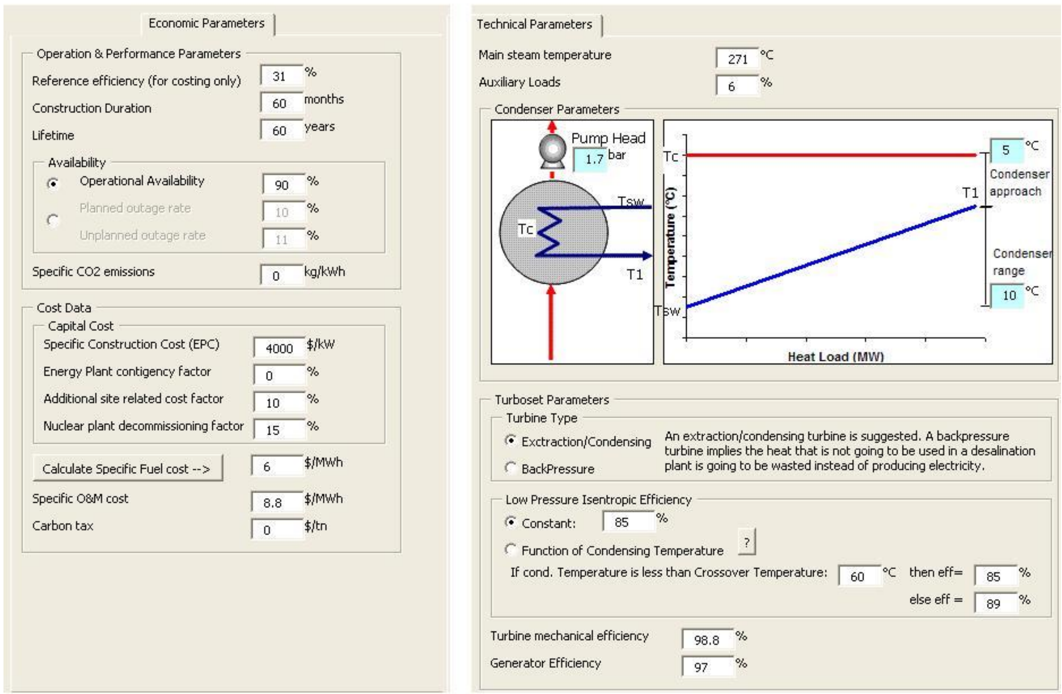



**Figure 31: Power plant variable parameters in DEEP 4.0.**

DESALINATION PLANT PARAMETERS

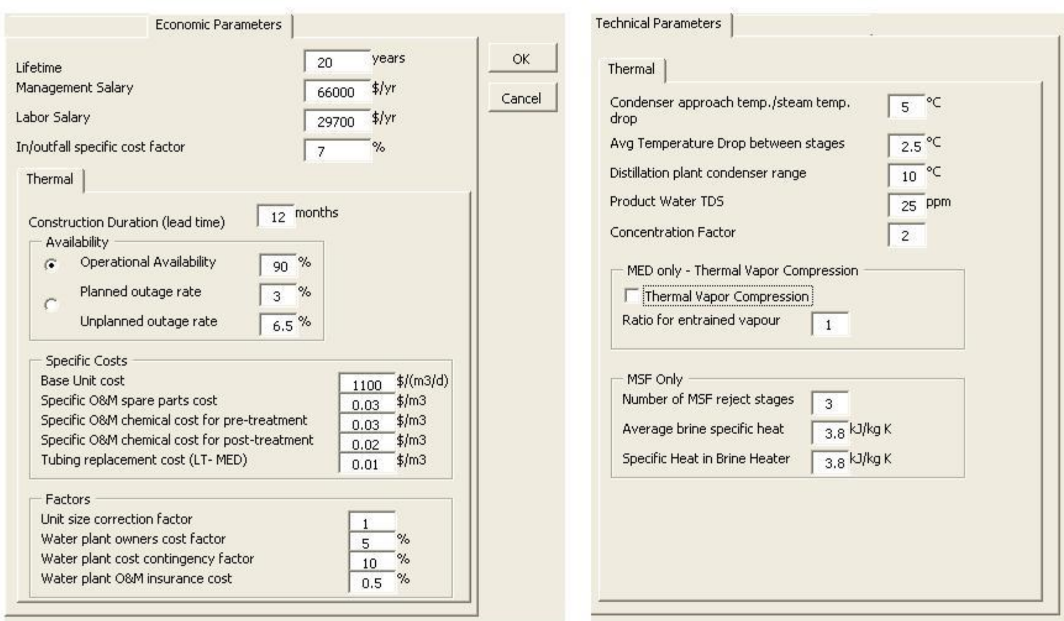



**Figure 32: Desalination plant variable parameters in DEEP 4.0.**

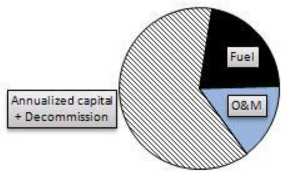
The general technical and economic parameters for the desalination processes are indicated in Figure 32. After all parameters have been changed to the user's specification the final results can be displayed by selecting the 'FULL REPORT' option. The 'FULL REPORT' gives the user a total cost result summary, which includes the power plant and the desalination plant associated costs as indicated in Figure 33.

## Summary of Cost Results

| | |
|---|---|
| Discount rate | 5% |
| Interest | 5% |
| Fuel Escalation | 3% |

### Power plant

| | |
|---|---|
| Type | Steam Cycle - Nuclear |
| ·erence thermal output | 1800 MW(th) |
| Reference electricity output | 558 MW(e) |
| Site Specific Electricity Production | 4614 GWh/yr |
| Availability | 90% |



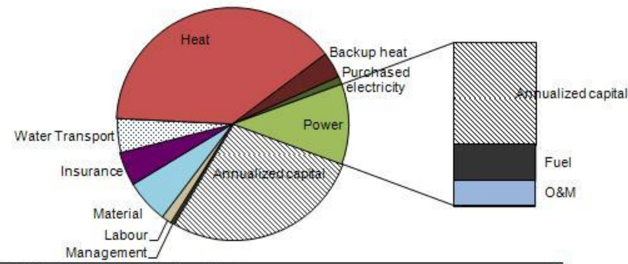

| Capital Costs of Power Plant | Total (M$) | Specific($/kW, | Share |
|---|---|---|---|
| Overnight EPC costs | 2,232 | 4,000 | 72% |
| Owners costs | 223 | 400 | 7% |
| Contigency cost | - | - | 0% |
| Interest during construction | 319 | 571 | 10% |
| Decommissioning costs | 335 | 600 | 11% |
| **Total Capital Costs** | 3,109 | 5,571 | |
| **Annualized Capital Costs** | 164 | 294 | |
| Sp. Annualized Capital Costs | | 0.036 | |

| Operating Costs of Power Plant | Total (M$) | Specific ($/kWI | Share |
|---|---|---|---|
| Fuel Costs | 58 | 0.013 | 59% |
| Operation & Maintenance cos | 41 | 0.009 | 41% |
| Carbon tax | - | - | 0% |
| **Annual Operating costs** | 99 | 0.021 | |

| | | |
|---|---|---|
| TOTAL ANNUAL COST | 263 | M$ |
| Power Cost | 0.057 | $/kWh |

### Desalination plant

| | | |
|---|---|---|
| Type | MSF | |
| Total Capacity | 100000 $m^3$/d | |
| Feed Salinity | 35000 ppm | |
| Combined Availability | 90% | |
| Water Production | 32.85 $Mm^3$/yr | |
| Power Lost | 45.5 MW(e) | *Extraction of 280 MW at 118°C (Power lost ratio=16.* |
| Power Used for desalination | 527 MW(e) | |




| Capital Costs of Desalination Plant | *MSF* | | *Total (M$)* | *Specific ($/m3 d)* | *Share* |
|---|---|---|---|---|---|
| Construction Cost | 133 | - | 133 | 1,331 | 69% |
| Intermediate loop cost | 11 | - | 11 | 111 | 6% |
| Backup Heat Source | 15 | - | 15 | 154 | 8% |
| Infall/Outfall costs | - | - | 8 | 77 | 4% |
| Water plant owners cost | 7 | - | 7 | 72 | 4% |
| Water plant contingency cost | 15 | - | 15 | 151 | 8% |
| Interest during Construction | 4 | - | 4 | 41 | 2% |
| **Total Capital Costs** | 186 | - | 194 | 1938 | |
| **Annualized Capital Costs** | | | 14 | | |
| Sp. Annualized Cap Costs | | | | **0.42** | $/m3 |

| Operating Costs of Desalination Plant | MSF | | Total (M$) | *Specific ($/m3)* | Share |
|---|---|---|---|---|---|
| ***Energy Costs*** | | | | | |
| Heat cost | 19 | | 19 | 0.58 | 61% |
| Backup heat cost | 1.8 | | 1.8 | 0.05 | 6% |
| Electricity cost | 5.5 | - | 5.5 | 0.17 | 17% |
| Purchased electricity cost | 0.5 | - | 0.5 | 0.02 | 2% |
| **Total Energy Costs** | 27 | - | 27 | 0.82 | 85% |
| ***Operation and Maintenance Costs*** | | | | - | 0% |
| Management cost | - | - | 0.20 | 0.01 | 1% |
| Labour cost | - | - | 0.68 | 0.02 | 2% |
| Material cost | 3.0 | - | 3.0 | 0.09 | 9% |
| Insurance cost | 0.8 | - | 0.8 | 0.03 | 3% |
| **Total O&M cost** | 4 | - | 5 | 0.14 | 15% |
| **Total Operating Costs** | 31 | - | 32 | **0.96** | |

| | | |
|---|---|---|
| **Total annual cost** | **45.26** | **M$** |
| Water production cost | 1.378 | $/m^3$ |
| Water Transport costs | 0.070 | $/m^3$ |
| **Total water cost** | **1.448** | **$/m^3$** |

**Figure 33: DEEP 4.0.FULL REPORT; cost breakdown summary.**

It should be noted that DEEP 4.0 does not include a cost evaluation for the feedwater preheat case including the selection of an intermediate loop configuration of RO.

### 3.8.2 WTC

#### 3.8.2.1 General description

WTC is the program selected to determine the economic feasibility of the different desalination processes. The program has been updated and new information added from the first version of the program. The revised program is a Visual Basic application that can run under Windows. The program calculates dose rates and cost estimates for a number of water treatment processes. In progressing through each process option, there are prompts for specifics such as preferred chemical dose, media filtration rate, membrane productivity, and rejection. The thermal processes, ion exchange, and electrodialysis have their own specific inputs and prompts. At the end, all information, imputed and calculated, is summarized on one screen followed by a window established to define indirect capital costs and possible land acquisition and/or feed water costs. The last screen contains a Table summarizing all the cost estimations capital, operations, and capital recovery. As an assist to the user, default values are offered throughout, but, if more definitive information is available, it can be entered, thus enhancing accuracy (Moch, 2008).

#### 3.8.2.2 Basic program function

Design parameters used to drive the cost estimates are calculated from the inputs. Indices from the engineering news record (ENR) are employed to update cost information to current values. Table 4 is a list of the indices and their value as of November 2011. In using this program, it is necessary that these indices be adjusted at any given time interval to account for inflation and country and site specific conditions.

**Table 4: Indices for Updating Costs***

| Indices for Updating Costs | |
|---|---|
| **Cost Indices Categories** | **November,2011** |
| ENR construction cost index | 9173.21 |
| ENR building cost index | 5113.37 |
| ENR skilled labor index | 8793.21 |
| ENR materials index | 2864.94 |
| ENR steel cost ($/cwt) | 49.21 |
| ENR cement cost ($/ton) | 105.03 |
| Electricity cost ($/kWh) | 0.823 |
| Water rate ($/kgal) | 0 |
| Interest rate (%) | 5.5 |
| Amortization time (years) | 30 |

* All ENR indices are from http://www.enr.com/features/coneco/subs/recentindexes.asp. The rest are defaults.

WTC includes all the following processes in the following order as illustrated in Figure 34:

- Desalting;
- Pre-treatment disinfection;
- Chemical feed systems;
- Filtration;
- De-chlorination;
- Post treatment; and
- Miscellaneous equipment.

More than one category may be selected. Click "Continue" at this point to go to forms for specifying the processes in more detail. The program progresses through the selected categories starting with Desalting, then Filtration, Pre-treatment disinfection, Chemical feed Systems, Decholrination, Post-treatment, and finally Miscellaneous Equipment and processes (Moch, 2008).

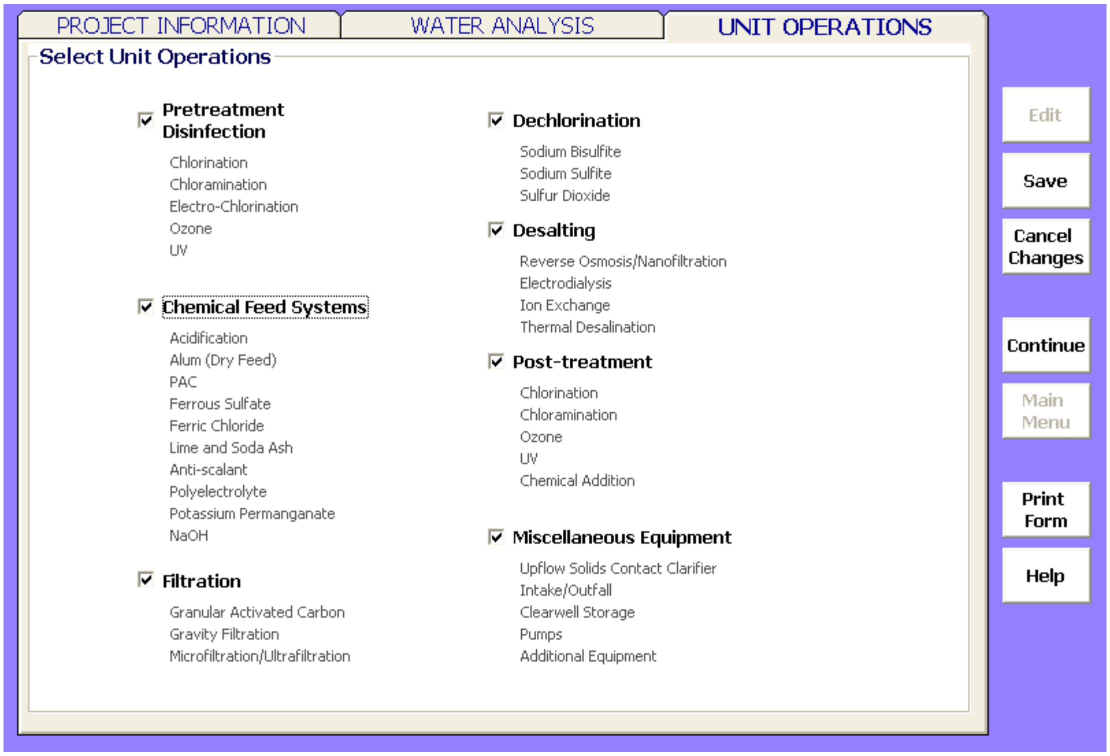



**Figure 34: Unit operations from WTCost II.**

All of the above is included in the project summary shown in Figure 35. This figure displays the project information, capacity and the processes chosen. In Figure 36 the Indirect Costs are added to the direct capital cost for the total project cost in a variety of units. Summarized costs are taken from the more detailed summary sheets for each category of process. The specific processes are listed on the project summary form (Moch, 2008).

The selection of the pre- and post-treatment methods plays a large part in the economics of the desalination plant. WTC provides default values for all chemicals used in the pre- and post-treatment sections. The majority of the set default values will be used to eliminate the current volatility in the chemical market. All site specific values included will be identified in Chapter 4.

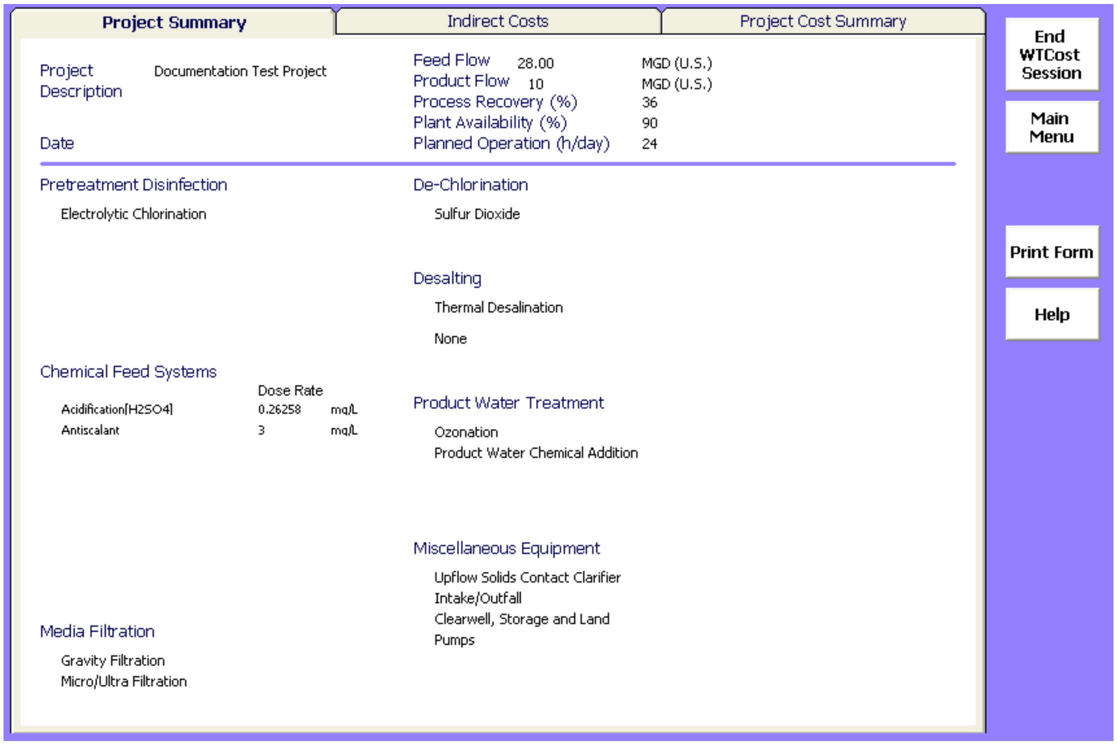
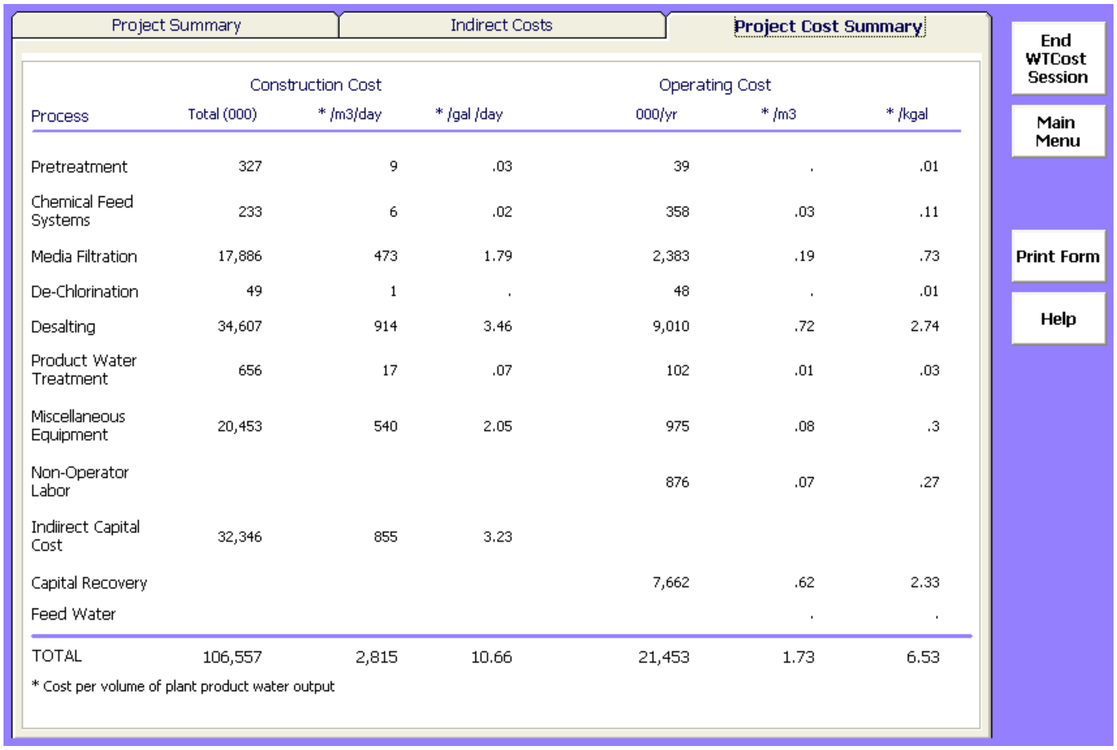



**Figure 35: Project summary.**

Finally, the project summary form is shown in Figure 35 and Figure 36. The first tab displays project information, capacity, and the processes chosen. The indirect costs are added to the direct capital cost for the total project cost, summarized in Figure 36 in a variety of units. Summarized costs are taken from the more detailed summary sheets for each category of process. The specific processes are listed on the Project Summary form.




| Process | Construction Cost Total (000) | * /m3/day | * /gal /day | Operating Cost 000/yr | * /m3 | * /kgal |
|---|---|---|---|---|---|---|
| Pretreatment | 327 | 9 | .03 | 39 | . | .01 |
| Chemical Feed Systems | 233 | 6 | .02 | 358 | .03 | .11 |
| Media Filtration | 17,886 | 473 | 1.79 | 2,383 | .19 | .73 |
| De-Chlorination | 49 | 1 | . | 48 | . | .01 |
| Desalting | 34,607 | 914 | 3.46 | 9,010 | .72 | 2.74 |
| Product Water Treatment | 656 | 17 | .07 | 102 | .01 | .03 |
| Miscellaneous Equipment | 20,453 | 540 | 2.05 | 975 | .08 | .3 |
| Non-Operator Labor | | | | 876 | .07 | .27 |
| Indiirect Capital Cost | 32,346 | 855 | 3.23 | | | |
| Capital Recovery | | | | 7,662 | .62 | 2.33 |
| Feed Water | | | | | . | . |
| TOTAL | 106,557 | 2,815 | 10.66 | 21,453 | 1.73 | 6.53 |

* Cost per volume of plant product water output

**Figure 36: Total Project Cost summary.**

One advantage of WTC over DEEP is the possibility of assessing stand-alone and co-generation desalination plant configurations and processes with an electricity fuelled heat source.

## 3.9 Costing program inputs

Since two desalination economic costing programs are used, the same set of selected parameter will be implemented in both programs as far as possible to ensure a confident amount of accuracy in comparing results. The costing trends shown by each program was compared and not the specific costing value, since the program operations and assumption differ from each other.

### 3.9.1 Input data and assumptions for DEEP 4.0 and WTC calculations

The studies carried out for this economic evaluation consisted of a set of detailed DEEP 4.0 and TWC calculations carried out for three broad geographical regions of South Africa. These regions include the West Coast, South Coast and East Coast. Within each region, the studies considered a viable co-location waste heat plant setup. Since only WTC can model thermal and

RO stand-alone desalination plant configurations and processes utilizing electricity as energy and heat source, these values were only compared to the co-generation WTC cost estimates. All stand-alone plant configurations utilizing electricity as heat/energy source modelled in WTC were assumed to be located in the identified city on a new site on the coast. This new site can be anywhere with an electricity connection, therefore, inlet and outfall infrastructure were included in all calculations while transport cost was excluded (inside city boundary).

On the West and South coast, a viable, nuclear co-location option was evaluated, while on the South Coast and East Coast a CCGT co-location plant setup was evaluated. Each power plant was coupled with five desalination processes, which included three different technologies. For each of these combinations, two different economic scenarios were considered. A sensitivity analysis was also carried out to permit evaluation of the impact of variations in a number of important input parameters affecting the overall total water cost. Calculations were carried out for three plant sizes (all at the same power level) in combination with the various desalination processes.

#### 3.9.1.1 Regional study

The approximate geographic area and specific site characteristics for each of these three regions are given in Table 5.

**Table 5: Input data assumptions for regional study**

| Region | Selected Site | Seawater temperature, (°C) | Seawater TDS, (ppm) | Personal Cost ($.year) |
|---|---|---|---|---|
| West Coast | Cape Town | 9 | 36 000 | Default |
| South Coast | Port Elizabeth | 15 | 36 000 | Default |
| East Coast | Durban | 22 | 36 000 | Default |

#### 3.9.1.2 Desalination options

This assessment was based on water demand. The sites were selected on the basis of identification by the WDAF as sites with large potential future water shortages. It was concluded that the three different plant production capacities should be evaluated. These plant sizes were small sized plants producing between 5 000 m³/d of potable water, medium sized plants producing 50 000 m³/d of potable water and large size plants producing 100 000 m³/d of potable water.

Based on recent desalination plant construction costs, the base unit cost for MSF was assumed to be $1 100 per m³/d of installed capacity, for MED $900 per m³/d and for RO $800 per m³/d for all calculations. It should be noted that the desalination base unit cost cannot be used as an input parameter in WTC. WTC utilises its own method by using the costing index indicated in Table 4 to determine the construction/capital cost of the different desalination processes. The desalination processes considered and their main characteristics are summarized in Table 6.

**Table 6: Desalination processes and their main characteristics**

| Desalination processes | Base Unit Cost ($/m³/d) | Plant Production Capacity (m³/d) |
|---|---|---|
| MSF | 1 100 | 5 000, 50 000 and 100 000 |
| MED | 900 | 5 000, 50 000 and 100 000 |
| RO | 800 | 5 000, 50 000 and 100 000 |
| MSF-RO | 1 100 - 800 | 5 000, 50 000 and 100 000 |
| MED-RO | 900 - 800 | 5 000, 50 000 and 100 000 |

#### 3.9.1.3 Heat and energy cost

**Electricity price**

The electricity price was selected from the data indicated in Table 2. In 2012/13 the cost of electricity will rise to 65.85 c/kWh. Assuming ZAR8 equals US$1 the electricity price selected was 0.0823 $/kWh.

**Nuclear fuel cost**

The price of the nuclear fuel was selected on the information stated by the world nuclear association (WNA) in 2011. The cost of nuclear fuel was estimated at 7.7 US $/MWh (WNA, 2011).

**Liquefied natural gas fuel price**

The historical relationship between the oil and gas price has an average of 10:1. Under the 10 to 1 rule, the natural gas price is one-tenth the price of oil. For, example, a $100 price for a barrel of WTI crude oil would indicate that natural gas should trade at $10 per million BTU at Henry Hub. The LNG price in November 2011 indicated by Bloomberg.com estimated the Henry Hob Spot price at 3.02 $/MMBtu. The LNG price was converted to $/bbl as DEEP 4.0 only allows the user to insert the price of gas in the unit form of $ per barrel of oil. The oil industry conversions show that LNG inter-fuel pricing equivalent (US currency) is:

ONE CENT PER MMBtu of LNG = 5.8 Cents per Barrel of crude oil.

Converting the inter-fuel pricing equivalent to $/MMBtu and incorporating the LNG Henry Hob Spot price at 3.02 $/MMBtu, the price of LNG equals 17.5 $/bbl. The LNG price was, therefore, selected at 17.5 $/bbl for all DEEP 4.0 calculations.

WTC allows the user to insert the LNG price in $\$/m^3$. One barrel of LNG equals $11, with the Henry Hob Spot price at 3.02 $/MMBtu. The price of LNG is, therefore, equal to 0.189 $\$/m^3$. LNG price was, therefore, selected at 0.189 $\$/m^3$for all WTC calculations.

#### 3.9.1.4 Interest/ discount rate and fuel escalation rate

**Interest and discount rate**

The benchmark interest rate in South Africa was last reported at 5.5 % in 2011 as indicated in

Figure 37. In South Africa, the interest rate decisions are taken by the South African Reserve Bank’s monetary policy committee (MPC). The official interest rate is the repo rate. This is the rate at which central banks lend or discount eligible paper for deposit money banks, typically shown on an end-of-period basis (TradingEconomics.com, 2011).

Figure 37 shows that the interest rate of South Africa varied significantly over the last decade peaking close to 14% in 2002/3. It was, therefore, assumed that a peak in the interest rate in the near future could occur especially with the current volatile global market. With fears of a second global recession, an interest rate increase up to 12% was selected for the sensitivity study.


**Figure 37: South Africa's interest rate over the last few years. (TraidingEconomics.com, Reserve Bank of South Africa).**

**Fuel escalation rate**

The fuel escalation rate was selected at 3%, which is the default DEEP 4.0 value.

**Carbon tax**

An article by Michael Cohen indicates that South Africa is weighing a charge of 75 rand to 200 rand ($9 to $25) per metric ton of carbon emitted. For this study a carbon tax of 20 $/ton of carbon emit was selected. This ensured conservative carbon tax estimations.

## 3.10 Sensitivity study

In addition to the site-by-site studies, sensitivity analyses were also carried out with variations of several important parameters that could potentially have significant influence on the final water cost. The parameters that were varied for these sensitivity analyses are listed in Table 7. These calculations were carried out to permit an evaluation and understanding of possible trends in the cost of water production to help understand which of the many input parameters are in fact important to the total cost of water production.

**Table 7: Parameters variation in sensitivity analysis**

| Parameter | Sensitivity |
|---|---|
| Interest Rate, %/year | 8% and 12 %, with 5.5% as the reference value |
| Discount Rate, %/year | 3% and 8 %, with 5.5% as the reference value |
| Fossil fuel price | 100% increase |
| Seawater TDS (Quality), ppm | 30 000 and 42 000, with 36 000 as reference value |
| Effect of an additional loop | % increase in water production cost evaluated |
| Electricity Price, $/kWh | -30%, -15%, 0%, 25%, 50%, 100%, 250% and 1 000% increase on the 2012/13 price of 0.0823 kW/h (0%) |
| Stand-Alone thermal desalination processes utilizing electricity as heat and energy source | % Influence on total water cost of different plant sizes |

## 3.11 Selected scenarios

### 3.11.1 Scenario 1

**Cape Town: Koeberg**

*Power source* : Koeberg Nuclear power station;

*Plant setup* : Co-generation;

*Technology* : RO, MED, MSF, MSF-RO and MED-RO;

*Inlet temperature* : 9ºC;

*Water quality* : 36 000 ppm;

*Production output* : 5 000, 50 000 and 100 000 m³/day;

*Transport distance* : 30 km;

*Carbon Tax* : n/a;

*Costing Program* : DEEP 4.0 and TWC.

*Intake and outfall* : Excluded.

### 3.11.2 Scenario 2

**PE: Thyspunt**

*Power source* Thyspunt Nuclear power station;

*Plant setup* : Co-generation;

*Technology* : RO, MED, MSF, MSF-RO and MED-RO;

*Inlet temperature* : 15ºC;

*Water quality* : 36 000 ppm;

*Production output* : 5 000, 50 000 and 100 000 $m^3$/day;

*Transport distance* : 130 km;

*Carbon Tax* : n/a;

*Costing Program* : DEEP and TWC;

*Intake and outfall* : Excluded.

### 3.11.3 Scenario 3

**PE: Coega**

*Power source* : CCGT;

*Plant setup* : Co-generation;

*Technology* : RO, MED, MSF, MSF-RO and MED-RO;

*Inlet temperature* : 15ºC;

*Water quality* : 36 000 ppm;

*Production output* : 5 000, 50 000 and 100 000 $m^3$/day;

*Transport distance* : n/a;

*Carbon Tax* : 20 $/ton;

*Costing Program* : DEEP 4.0 and TWC;

*Intake and outfall* : Excluded.

### 3.11.4 Scenario 4

**Durban: Shakaskraal**

*Power source* : CCGT;

*Plant setup* : Co-generation;

*Technology* : RO, MED, MSF, MSF-RO and MED-RO;

*Inlet temperature* : 22ºC;

*Water quality* : 36 000 ppm.;

*Production output* : 5 000, 50 000 and 100 000 $m^3$/day;

*Transport distance* : 50 km;

*Carbon Tax* : n/a;

*Costing Program* : DEEP 4.0 and TWC;

*Intake and outfall* : Included.

### 3.11.5 Scenario 5

**Cape Town**

*Power source* : Electricity;

*Plant setup* : Stand-Alone;

*Technology* : MED, MSF, MSF-RO and MED-RO;

*Inlet temperature* : 9ºC;

*Water quality* : 36 000 ppm;

*Production output* : 5 000, 50 000 and 100 000 $m^3$/day;

*Transport distance* : n/a;

*Carbon Tax* : n/a;

*Costing Program* : WTC;

*Intake and outfall* : Included.

## 3.12 Summary

The study performed included scenarios divided into three different site selections. These locations were selected on the basis of potential water shortages. The locations also give a good representation of the whole South African coastline. All desalination technologies and processes discussed in Chapter 2 were included in the cost estimation. The main output of the study was to determine which desalination technology, process and configuration is the most economically viable in South Africa.

Two desalination economic costing programs were used for the economic evaluation. The programs selected were DEEP 4.0 and WTC. Only the WTC costing program includes the option to model a stand-alone plant configuration utilizing electricity as heat source for all desalination processes, therefore, only WTC results were used to compare stand-alone plants utilizing electricity as heat source against nuclear and CCGT co-generation plant configurations.

To validate results, a trend analysis of the results were performed and compared in Chapter 4 where applicable. Sensitivity studies were included to identify the parameters that that are important to cost of water production.

# CHAPTER 4

Results

# 4 Results

Chapter 4 provides selected costing results obtained from DEEP 4.0 and WTC for each selected site. The results are displayed in the form of Tables and graphs containing the different estimated costs given by each program. The lowest and highest cost results were indicated in green and red respectively in each Table and Figure. The results provided by DEEP 4.0 include total operating cost, water production cost, water transport cost and total water cost (TWC). The selection of the most economically viable desalination technology will be based on the TWC. The results from WTC include the total operating cost. The sensitivity study results and a summary were displayed lastly.

It should be noted that small plants relates to 5 000 m³/d, medium plants to 50 000 m³/d and large plants to 100 000 m³/d. All co-located RO configurations did not include the effect of the waste heat only.

## 4.1 DEEP 4.0 regional study results

The “raw” results from DEEP 4.0 calculations carried out for each of the individual combinations of parameters on the site specific basis are presented in the following Tables and Figures. The results for co-location at Koeberg near Cape-Town are presented in Table 8 and Figure 38, those for co-location at Thyspunt near PE in Table 9 and Figure 39, for co-location at Coega in PE in Table 10 and

**Figure 40: Total Water Cost at Coega.**

and that for co-location at Shakaskraal near Durban in Table 11 and Figure 41.

### 4.1.1 Cape Town - Koeberg

**Table 8: Results of DEEP 4.0 calculations for Koeberg**

| Location & Heat-Source | Desalination Process | Desalination plant size (m³/d) | Total Operating Cost ($/m³/d) | Water Production cost ($/m³/d) | Water Transport Cost ($/m³/d) | Total Water Cost ($/m³/d) |
|---|---|---|---|---|---|---|
| Cape Town Koeberg | RO | 5 000 | 0.640 | 0.823 | 1.260 | 2.083 |
| | | 50 000 | 0.470 | 0.655 | 0.067 | 0.722 |
| | | ***100 000*** | ***0.460*** | ***0.643*** | ***0.063*** | ***0.706*** |
| | MED | 5 000 | 0.780 | 1.028 | 1.400 | 2.453 |
| | | 50 000 | 0.570 | 0.841 | 0.140 | 0.981 |
| | | 100 000 | 0.560 | 0.828 | 0.070 | 0.898 |
| | MSF | ***5 000*** | ***1.190*** | ***1.524*** | ***1.400*** | ***2.924*** |
| | | 50 000 | 1.010 | 1.337 | 0.140 | 1.477 |
| | | 100 000 | 0.990 | 1.324 | 0.070 | 1.394 |
| | MED-RO | 5 000 | 0.690 | 0.925 | 1.326 | 2.251 |
| | | 50 000 | 0.510 | 0.748 | 0.133 | 0.880 |
| | | 100 000 | 0.500 | 0.735 | 0.066 | 0.801 |
| | MSF-RO | 5 000 | 0.900 | 1.160 | 1.326 | 2.486 |
| | | 50 000 | 0.720 | 0.983 | 0.133 | 1.115 |
| | | 100 000 | 0.710 | 0.970 | 0.066 | 1.036 |

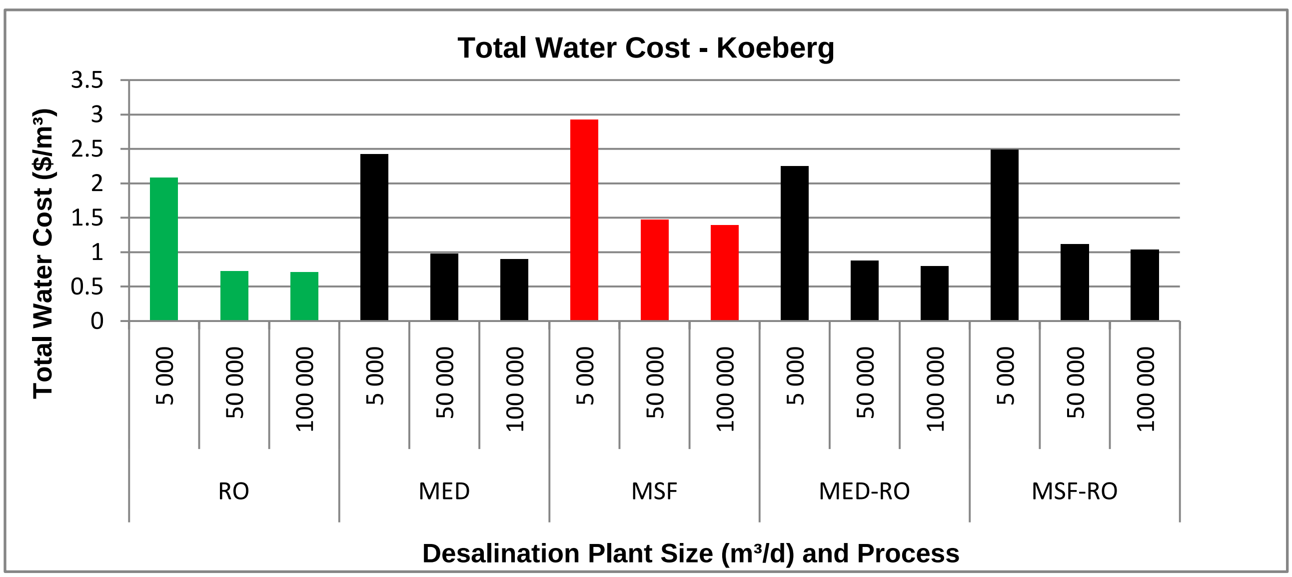



**Figure 38: Total Water Cost at Koeberg.**

**Table 9: Results of DEEP 4.0 calculations for Thyspunt**

| Location & Heat-Source | Desalination Process | Desalination plant size (m³/d) | Total Operating Cost ($/m³/d) | Water Production cost ($/m³/d) | Water Transport Cost ($/m³/d) | Total Water Cost ($/m³/d) |
|---|---|---|---|---|---|---|
| PE Thyspunt | RO | 5 000 | 0.610 | 0.819 | 4.055 | 4.874 |
| | | 50 000 | 0.450 | 0.650 | 0.406 | 1.056 |
| | | **100 000** | **0.440** | **0.635** | **0.203** | **0.838** |
| | MED | 5 000 | 0.780 | 1.053 | 4.506 | 5.559 |
| | | 50 000 | 0.590 | 0.867 | 0.451 | 1.318 |
| | | 100 000 | 0.580 | 0.853 | 0.225 | 1.078 |
| | MSF | **5 000** | **1.220** | **1.550** | **4.506** | **6.056** |
| | | 50 000 | 1.030 | 1.364 | 0.451 | 1.815 |
| | | 100 000 | 1.020 | 1.350 | 0.225 | 1.575 |
| | MED-RO | 5 000 | 0.690 | 0.926 | 4.269 | 5.195 |
| | | 50 000 | 0.520 | 0.749 | 0.427 | 1.176 |
| | | 100 000 | 0.500 | 0.736 | 0.213 | 0.949 |
| | MSF-RO | 5 000 | 0.900 | 1.161 | 4.269 | 5.430 |
| | | 50 000 | 0.720 | 0.984 | 0.427 | 1.411 |
| | | 100 000 | 0.710 | 0.971 | 0.213 | 1.184 |

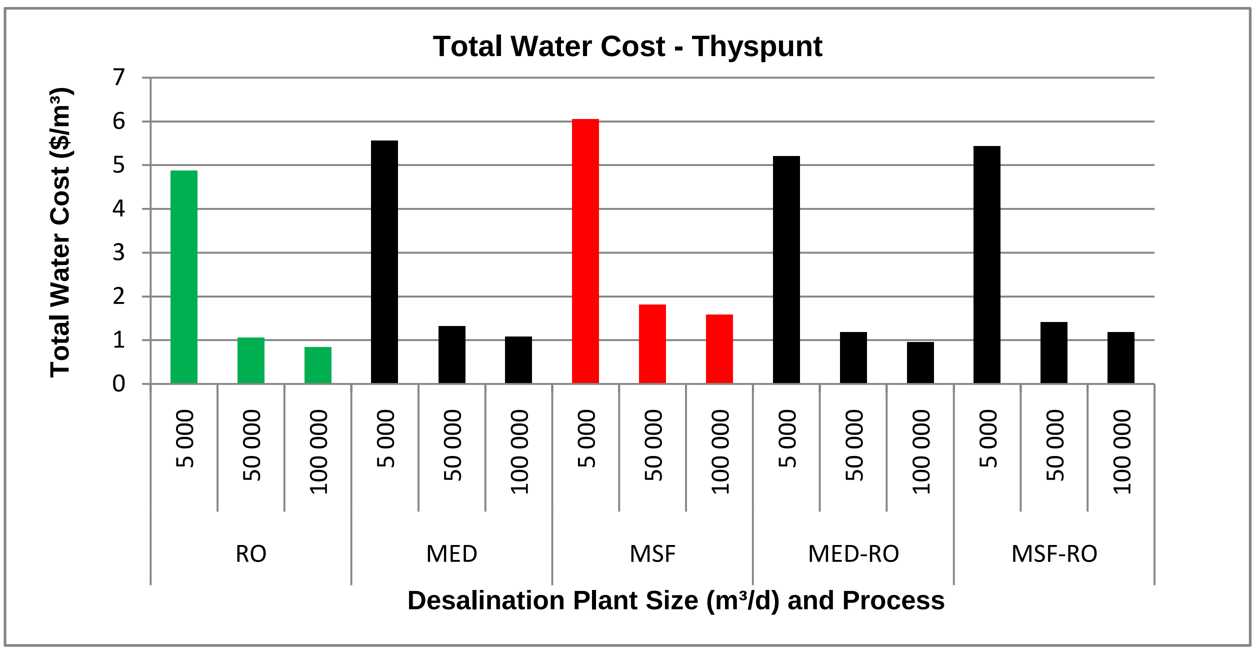



**Figure 39: Total Water Cost at Thyspunt.**

**Table 10: Results of DEEP 4.0 calculations for Coega**

| Location & Heat-Source | Desalination Process | Desalination plant size (m³/d) | Total Operating Cost (\$/m³/d) | Water Production cost (\$/m³/d) | Water Transport Cost (\$/m³/d) | Total Water Cost (\$/m³/d) |
|---|---|---|---|---|---|---|
| PE Coega | RO | 5 000 | 0.560 | 0.777 | 0.000 | 0.777 |
| | | 50 000 | 0.400 | 0.609 | 0.000 | 0.609 |
| | | ***100 000*** | ***0.380*** | ***0.597*** | ***0.000*** | ***0.597*** |
| | MED | 5 000 | 0.590 | 0.874 | 0.000 | 0.874 |
| | | 50 000 | 0.390 | 0.676 | 0.000 | 0.676 |
| | | 100 000 | 0.380 | 0.662 | 0.000 | 0.662 |
| | MSF | ***5 000*** | ***0.840*** | ***1.170*** | ***0.000*** | ***1.170*** |
| | | 50 000 | 0.630 | 0.972 | 0.000 | 0.972 |
| | | 100 000 | 0.610 | 0.958 | 0.000 | 0.958 |
| | MED-RO | 5 000 | 0.580 | 0.814 | 0.000 | 0.814 |
| | | 50 000 | 0.390 | 0.632 | 0.000 | 0.632 |
| | | 100 000 | 0.380 | 0.619 | 0.000 | 0.619 |
| | MSF-RO | 5 000 | 0.710 | 0.972 | 0.000 | 0.972 |
| | | 50 000 | 0.530 | 0.795 | 0.000 | 0.795 |
| | | 100 000 | 0.520 | 0.782 | 0.000 | 0.782 |

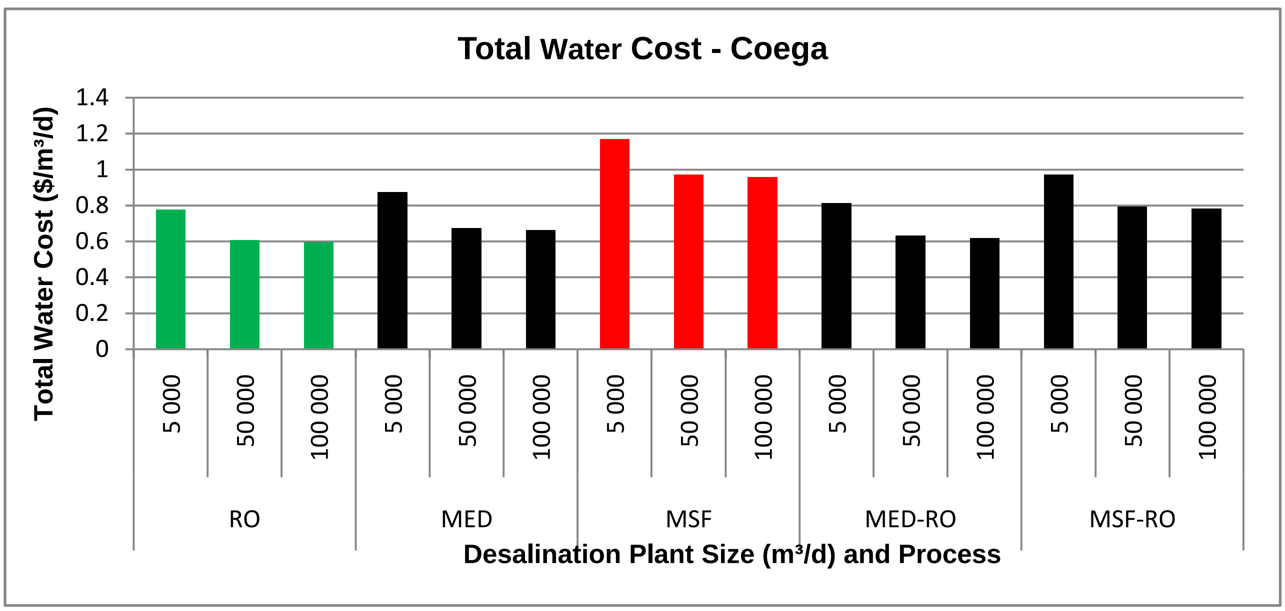



**Figure 40: Total Water Cost at Coega.**

**Table 11: Results of DEEP 4.0 calculations for Shakaskraal**

| Location & Heat-Source | Desalination Process | Desalination plant size (m³/d) | Total Operating Cost (\$/m³/d) | Water Production cost (\$/m³/d) | Water Transport Cost (\$/m³/d) | Total Water Cost (\$/m³/d) |
|---|---|---|---|---|---|---|
| Durban Shakaskraal | RO | 5 000 | 0.550 | 0.764 | 1.843 | 2.607 |
| | | 50 000 | 0.380 | 0.595 | 0.184 | 0.779 |
| | | ***100 000*** | ***0.370*** | ***0.583*** | ***0.092*** | ***0.675*** |
| | MED | 5 000 | 0.61 | 0.896 | 2.168 | 3.064 |
| | | 50 000 | 0.42 | 0.699 | 0.217 | 0.916 |
| | | 100 000 | 0.4 | 0.685 | 0.108 | 0.793 |
| | MSF | ***5 000*** | ***0.910*** | ***1.254*** | ***2.168*** | ***3.422*** |
| | | 50 000 | 0.710 | 1.052 | 0.217 | 1.269 |
| | | 100 000 | 0.700 | 1.042 | 0.108 | 1.150 |
| | MED-RO | 5 000 | 0.580 | 0.817 | 1.992 | 2.809 |
| | | 50 000 | 0.400 | 0.635 | 0.199 | 0.834 |
| | | 100 000 | 0.390 | 0.622 | 0.100 | 0.722 |
| | MSF-RO | 5 000 | 0.720 | 0.981 | 1.992 | 2.973 |
| | | 50 000 | 0.530 | 0.799 | 0.199 | 0.998 |
| | | 100 000 | 0.520 | 0.786 | 0.100 | 0.886 |

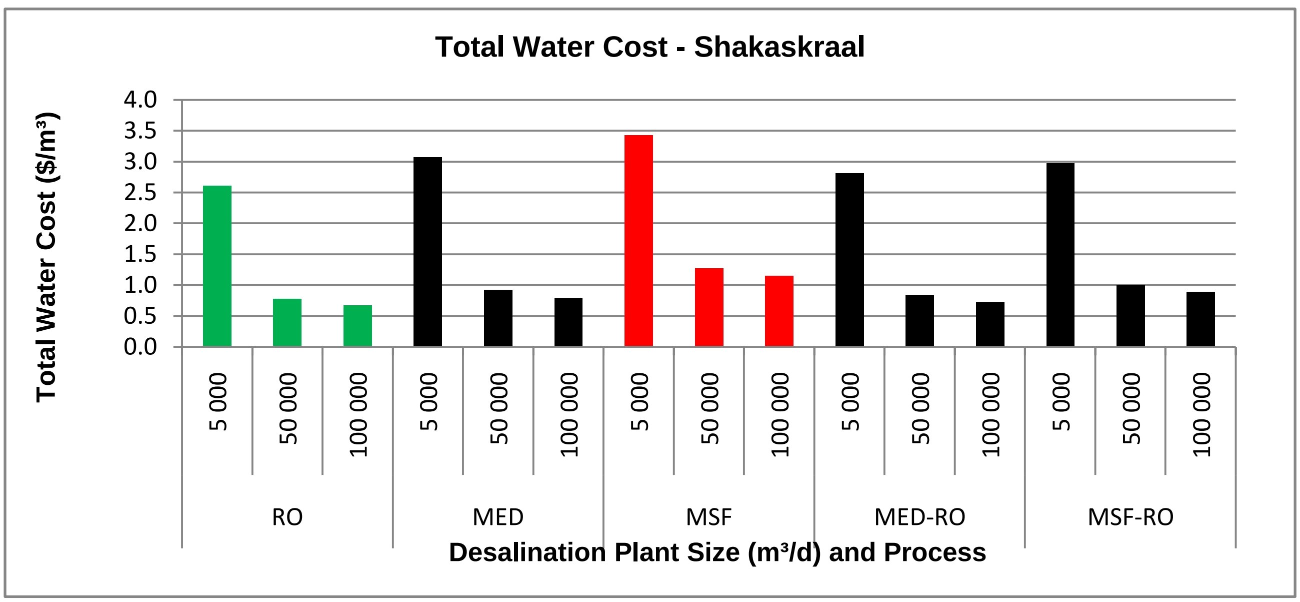



**Figure 41: Total Water Cost at Shakaskraal.**

### 4.1.2 General findings of DEEP 4.0 results

The desalination costs ranged between 0.597 $\$/m^3$ to about 1.254 $\$/m^3$ excluding water transport cost, while desalination cost ranged from 0.838 to about 6.056 $\$/m^3$ including water transport cost depending on the water plant type (desalination process), plant size energy source, specific region and economic scenarios.

Independent of the energy sources producing waste heat and the regions considered, in all investigated cases water production and total water cost from RO appear to be systematically lower than those from MED-RO, MED, MFS-RO and MSF. The TWC for MED-RO was on average only about 7% more than that of RO. The plant with the lowest cost at all evaluated sites out of all the configurations was the 100 000 $m^3/d$ RO plant for each location. MSF indicated the highest costs of all the processes. The plant with the highest water cost was the small 5 000 $m^3/d$ MSF plant for each location.

The processes are listed from the most cost effective to the least cost effective:

- RO;
- MED-RO;
- MED;
- MSF-RO; and
- MSF.

This costing trend was present in all plant sizes and locations.

### 4.1.3 Water cost

In the case of PE, the water production cost of the nuclear waste heat source and the fossil waste heat source (CCGT) were comparable. The water production cost of the CCGT co-located desalination plant was on average around 15% to 20% less than that of the nuclear co-generation plant (Table 9). However, the nuclear fuel price is more stable than the fossil fuel price, which in a short period of time can have a substantial negative impact on the water production cost of a desalination plant co-located at the fossil fuelled heat source.

Water costs for RO systems are typically lower than MED, MSF, MED-RO and MSF-RO. This gives RO an economic advantage even though its product water generally has a higher TDS than the other thermal desalination processes.

It should be noted that the water cost of RO is underestimated. It was assumed that the power plant would produce electricity for the RO plant for 90% of the year. However, power plant maintenance was not included which could lead to the scenario where the RO plant has to use power from the grid. This could lead to higher electricity prices increasing the water production cost of RO desalination processes. Section 4.4.3 in this chapter indicates that a small increase or decrease in electricity tariffs (15%), did not have a substantial effect on the RO water production cost.

The difference between the two thermal desalination processes was quite significant. MED production cost was around 20% less than that of MSF, while the RO costs were even less. The effect of economy of scale was predominant between the small and medium sized plants around 20%; whereas the higher capacity plants (between the medium and large sized plants) the economy of scale was only around 2%.

In general, nuclear power plants have a lower thermal efficiency than fossil fuelled power plants (Holbert, 2003). Thus, nuclear plants produce larger amounts of energy potentially available for desalination. A higher availability in steam can also be expected, since almost all of the rejected heat of a nuclear plant goes to the steam condenser. In the case of fossil fuelled power plants some of the rejected heat is directed to the atmosphere and therefore deemed useless. MED and MSF can, therefore, potentially produce a higher maximum amount of desalted water than other processes. This will, in turn, influence the economy of scale for MED and MSF, since a higher production potential could result in a further reduction in desalination production costs.

### 4.1.4 Effect of water transport

The water transport cost makes up a large part of the total water cost, especially in plants with a low production capacity. The higher the production capacity of the plant, the lower the influence of the water transport cost on the total water cost. Calculations showed the water transport cost to be directly related to the pumping distance and capacity. Furthermore, the water transport cost calculated for the different processes was very similar, thus indicating that the selection of the desalination technology/process did not play any significant role in the cost of water transport. This means that the cost of water transport is an additional cost added onto the production cost of the water irrespective of the technology used and can therefore be eliminated in the study of the most suitable technology, but it does influence the choice of location.

At Koeberg the water transport cost for a 5 000 $m^3$/d sized plant contributed 56% to the total water cost, whereas in Thyspunt the water transport cost contributed to 80% of the total cost as indicated in Table 12. A desalination plant located at Thyspunt can, therefore, only be justified if the cost advantage gained by co-location surpasses the cost of water transport. Even with a relatively short pumping distance and a large plant capacity of 100 000 $m^3$/d as in the case of Koeberg, the water transport cost still contributed 7% to the total water cost, which was still a significant contribution.

All small desalination plants should, therefore, be located as close as possible to a water distribution infrastructure or as close as possible to the end location of the product water.

**Table 12: Water transport cost contribution to total water cost**

| **Location** | **Koeberg** | **Thyspunt** | **Shakaskraal** |
|---|---|---|---|
| **Transport Distance** | 30 km | 130 km | 50 km |
| **Plant Size ($m^3$/d)** | **Average Contribution to Total Water Cost for all Processes** | | |
| **5 000 (Small)** | 56% | 80% | 69% |
| **50 000 (Medium)** | 10% | 33% | 22% |
| **100 000 (Large)** | 7% | 20% | 12% |

Since water transport cost played such an important role in the total water cost, this aspect of desalination economics should be included and investigated in the early siting phase of any desalination project identifying possible water connection points. This will prevent the situation where a site is selected only due to the possible reduction in costs obtained from co-location (waste heat, inlet and outfall infrastructure) and discarding all other sites with no co-location possibilities. The site with the possibility of co-location could result in a higher total water cost only due to the water transport cost and not the selection of the technology or plant configuration.

## 4.2 WTC regional study results

The results obtained from WTC calculations carried out for each of the individual combinations of parameters on the site specific basis are presented in the following Tables and Figures. The results for nuclear co-location at Koeberg near Cape Town are presented in Table 13 and Figure 42. The results for nuclear co-location at Thyspunt near PE, CCTG co-location at Coega in PE are presented in and Table 14 and Figure 43. The results of CCTG co-location at Shakaskraal near Durban are presented in Table 15 and Figure 44. It should be noted that all WTC costs presented in this study do not include water transport costs.

**Table 13: Cape Town WTC cost evaluation (excluding water transport)**

| **Cost Type** | **Total Operating Cost ($/m³)** | | |
|---|---|---|---|
| **Plant Configuration** | **Koeberg, Co-Generation** | | |
| **Plant Size (m³/d)** | **5 000** | **50 00** | **100 000** |
| RO | *2.300* | *1.370* | ***1.080*** |
| **MED** | 3.760 | 2.560 | 2.410 |
| ***MSF*** | ***3.960*** | *2.680* | *2.580* |
| **MED-RO** | 3.180 | 2.090 | 1.900 |
| **MSF-RO** | 3.290 | 2.210 | 1.960 |

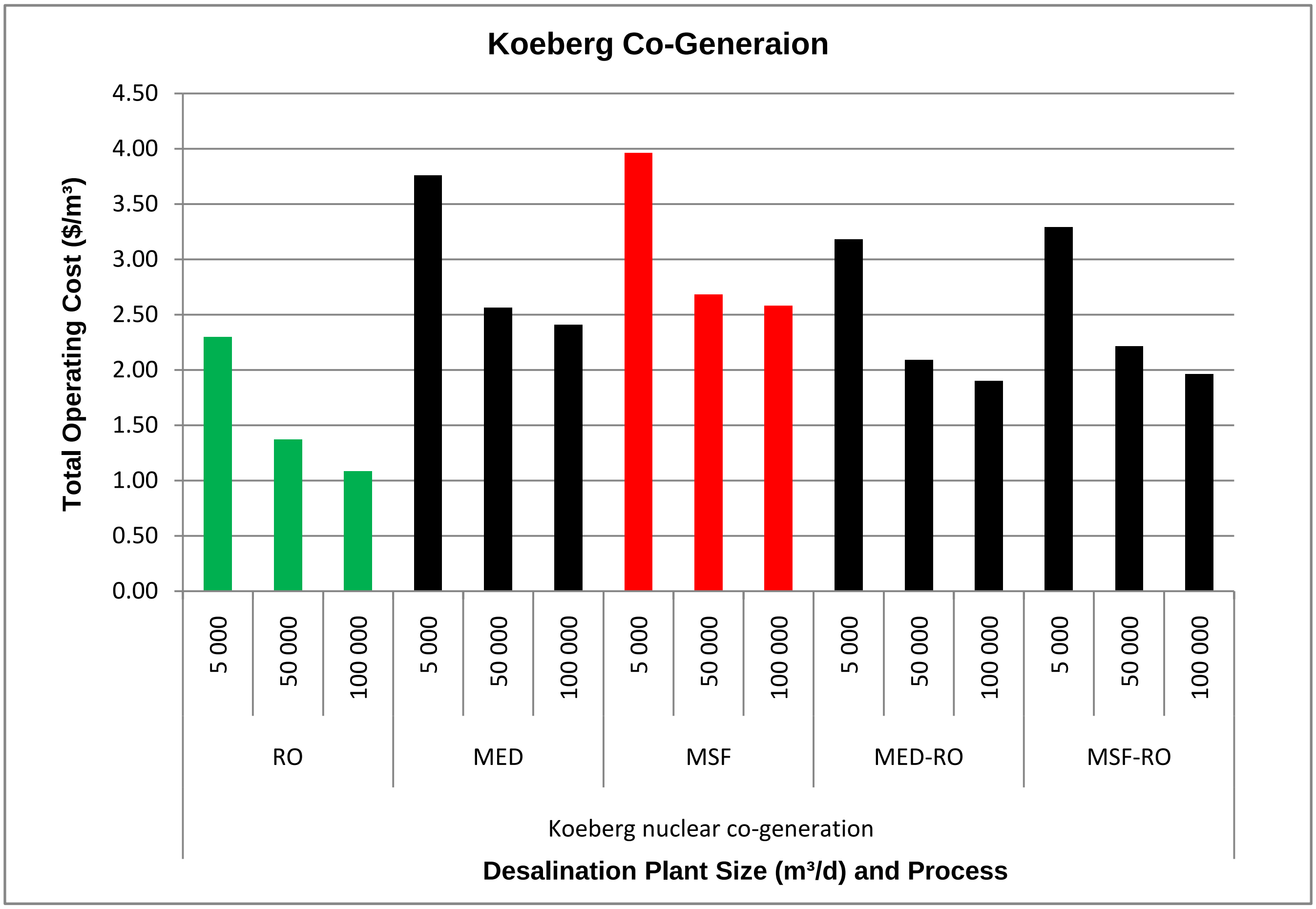



**Figure 42: Cape Town Total Operating Cost**

**Table 14: PE WTC cost evaluation (excluding water transport)**

| Cost Type | Total Operating Cost ($/m³) | | | | | |
|---|---|---|---|---|---|---|
| Plant Configuration | Thyspunt Co-Generation | | | Coega Co-Generation | | |
| PLANTSIZE (m³/d) | 5 000 | 50 000 | 100 000 | 5 000 | 50 00 | 100 000 |
| *RO* | *1.990* | *1.010* | ***0.900*** | *2.100* | *1.080* | *0.960* |
| MED | 3.760 | 2.530 | 2.610 | 3.690 | 2.620 | 2.650 |
| MSF | 3.960 | 2.710 | 2.710 | 3.840 | 2.760 | 2.790 |
| MED-RO | 3.180 | 2.110 | 1.890 | 2.990 | 1.830 | 1.800 |
| MSF-RO | 3.220 | 2.200 | 1.980 | 3.070 | 1.970 | 1.890 |

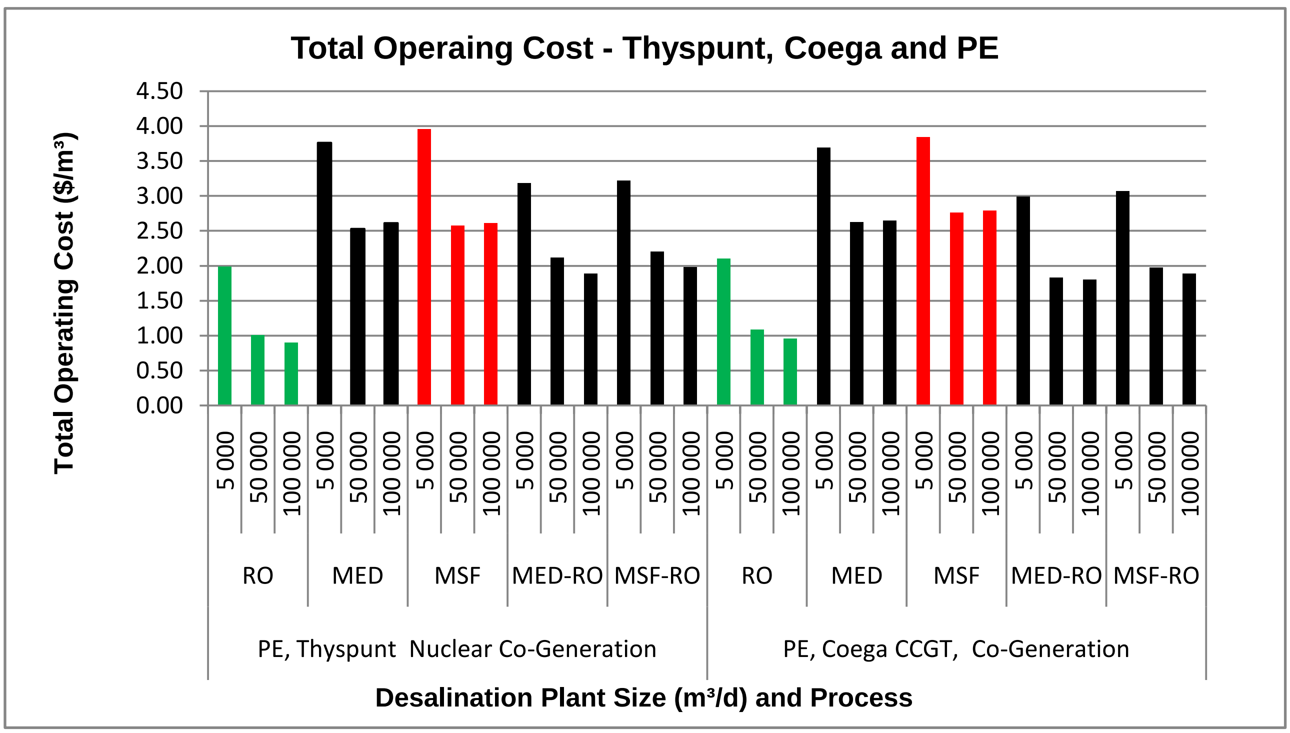



**Figure 43: PE Total Operating Cost**

**Table 15: Durban WTC cost evaluation (excluding water transport)**

| Total Operating Cost ($/m³) | | | |
|---|---|---|---|
| **Configuration** | **Shakaskraal, CO-GENERATION** | | |
| **Plant Size (m³/d)** | **5 000** | **50 00** | **100 000** |
| **RO** | 2.090 | 1.070 | **0.950** |
| **MED** | 3.680 | 2.620 | 2.650 |
| **MSF** | **3.831** | 2.760 | 2.790 |
| **MED-RO** | 2.990 | 1.900 | 1.810 |
| **MSF-RO** | 3.070 | 1.970 | 1.880 |

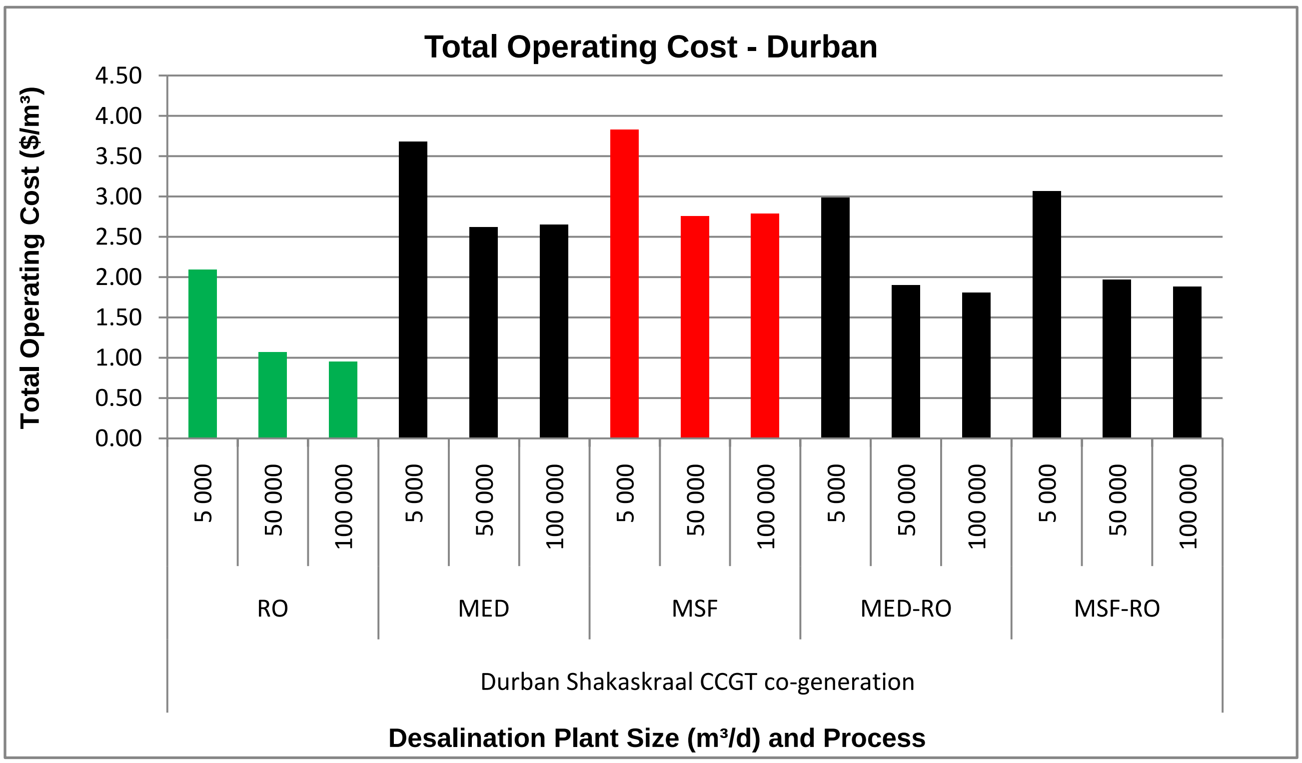



**Figure 44: Durban Total Operating Cost**

### 4.2.1 General findings of WTC results

The co-generation desalination costs ranged between 0.95 $/m^3$ to about 3.81 $/m^3$, depending on the water plant type (desalination process), plant size energy source, specific region and economic scenarios.

Independent of the energy sources producing waste heat and the regions considered, in all investigated cases water production and total water cost from RO appear to be systematically lower than those from MED-RO, MFS-RO, MED and MSF. The TWC for MED-RO was on average between 30 and 50% more than that of RO. The plant with the lowest cost at all evaluated sites out of all the configurations was the 100 000 $m^3$/d RO plant for each location. MSF indicated the highest costs of all the processes. The plant with the highest water cost was the small 5 000 $m^3$/d MSF plant. This was present in each location.

The processes are listed from the most cost effective to the least cost effective:

- RO;
- MED-RO;
- MSF-RO;
- MED;
- MSF.

This costing trend analysis was present in all plant sizes.

### 4.2.2 Water cost

In the case of PE, only the RO co-generation plant was more cost effective than the natural gas fuelled CCGT co-location plant. This small reduction in cost could be contributed to the inlet and outfall water infrastructure of the large nuclear power plants, since RO only utilised electricity as the energy source. For the single thermal desalination processes MSF and MED, the CCTG co-generation configuration was only more cost effective for the small 5 000 $m^3$/d plant. The nuclear co-location was more cost effective for the larger scale plants (50 000 $m^3$/d to 100 000 $m^3$/d). The co-location for the hybrid configuration was more cost effective for all plant sizes (Figure 43 and Table 14). The cost differences between the CCTG and nuclear co-location were small, only an average cost difference of between 3% and 6%. However, the nuclear fuel price is more stable than the fossil fuel price, which in a short period of time can have a substantial negative impact on the water production cost of a desalination plant co-located at the fossil fuelled heat source.

The water cost for RO systems are typically lower than MED, MSF, MED-RO and MSF-RO. This gives RO an economic advantage even though its product water generally has a higher TDS than all other thermal desalination processes. It should be noted that the water costs of RO are underestimated. It was assumed that the power plant would produce electricity for the RO plant for 90% of the year. However, power plant maintenance were not included which could lead to the scenario where the RO plant would have to use power from the grid. This could lead to higher electricity prices thereby increasing the water production cost.

The cost difference between the two thermal desalination processes was small. MED production cost was on average around 4% less than that of MSF. The effect of economy of scale was predominant between the small and medium sized plants (between 30% and 50%), whereas the higher capacity plants (between the 50 000 $m^3$/d and 100 000 $m^3$/d sized plants) the economy of scale was somewhat less (around 10% for nuclear co generation and around 2% for CCGT co-generation).

For all sites except Koeberg, an increase in water production cost was identified for MED and MSF between the 50 000 $m^3$/d and 100 000 $m^3$/d sized plants. The increase in cost was directly related to the large increase in the chemical feed costs. This indicated that the pre-treatment selection for thermal desalination processes was an important cost contributor to the total operating cost of large desalination plants.

In the case of the RO and hybrid configurations the contributions were still high, however, not as high as the single thermal plants. It should be noted that the treatment selections were the same for all processes to eliminate possible cost differences (this ensures apple to apple comparisons).

The final selection of the most economical site for PE was based on the inclusion of the possible water transport cost at Thyspunt, by assuming the same percentage cost increase as estimated in Table 12.

**Table 16: WTC RO costs estimates at PE including possible water tranport costs**

| Plant size (m³/d) | Total operating cost ($/m³) | | Water transport cost contribution | | Total cost ($/m³) | |
|---|---|---|---|---|---|---|
| **Site** | **Thyspunt** | **Coega** | **Thyspunt** | **Coega** | **Thyspunt** | **Coega** |
| **5 000** | 1.990 | 2.100 | 80% | 0% | 9.950 | *2.100* |
| **50 000** | 1.010 | 1.080 | 33% | 0% | 1.530 | *1.080* |
| **100 000** | 0.900 | 0.960 | 20% | 0% | 1.125 | ***0.960*** |

Table 16 showed that by including the possible water transport cost from Thyspunt to PE, the Coega co-location desalination RO plant configuration became more economical by a large margin.

## 4.3 Validation

Two different independent desalination economic costing programs were used to validate the outcome of this study. The following similarities in costing were identified:

- RO was identified as the most economically viable process for all plant sizes and all specified locations, therefore, making RO the most economically viable desalination process to be implemented in South Africa;
- MSF was identified as the desalination process with the highest cost out of all the processes, therefore, making MSF the least economically viable process to be implemented in South Africa;
- MED was identified as the most cost effective thermal desalination process;
- Substantial cost reductions were achieved by hybrid plant configurations rather than a single thermal desalination plant configuration. However, single RO plants were still the more cost effective of the hybrid configurations;
- The majority of the costing trends were very similar; and
- A small cost decrease in RO was identified with an increase in seawater inlet temperature and a small increase in cost was identified for all thermal desalination processes with an increase in cost due to an increase in seawater inlet temperature.

The following differences in costing were identified:

- At PE, DEEP 4.0 indicated Coega co-generation as more economical than nuclear co-generation at Thyspunt (excluding water transport cost). WTC indicated nuclear co-generation at Thyspunt more economical. However, the cost differences were marginal;
- WTC indicated that the pre-treatment cost played a larger part in the total cost in thermal desalination processes than RO and hybrid configurations. The water production cost increased slightly from 50 000 $m^3$/d up to 100 000 $m^3$/d, whereas DEEP 4.0 indicated a continuous decrease in water production cost from 5 000 $m^3$/d up to 100 000 $m^3$/d. However, DEEP 4.0 does not let the user specify any treatment process as in the case with WTC where all pre- and post-treatment processes can be selected, therefore, WTC is more sensitive to the treatment processes than DEEP 4.0;
- DEEP 4.0 indicated that only the MED-RO hybrid plants were more cost effective than the MED and MSF single co-located plants, whereas WTC indicated that both the MED-RO and MSF-RO plant were more cost effective than the MED and MSF single co-located plants; and
- The specific estimated costs from WTC were higher than that of DEEP 4.0 excluding the water transport cost. This was due to the fact that WTC lets the user define a large amount/selection of pre- and post-treatment options, which resulted in higher costs.

It should be noted that it was expected that the two costing programs would not yield the same quantitative results rather a qualitative indication, due to both program developers stating that the these programs should primarily be used to do a side by side comparison and not a cost specific evaluation.

Due to the similarities and differences identified in the data of both independent costing programs, the RO process was shown to be the most economically viable desalination process to be implemented in South Africa.

## 4.4 Sensitivity analysis

### 4.4.1 Interest rate

As expected, an increase in the interest rate led to an increase in the desalination production cost. The increase in production cost was not excessively high. The RO production cost was less effected by the increase of the interest rate than the MED process. The percentage increase in interest rate was more closely followed by the increase in production cost for MED than the RO process. The nuclear co-location indicated a larger production cost increase than the CCGT co-location, with the exception of the 8% MED CCGT plant. However, the cost increases were not very large.

**Table 17: Variation in interest rates (%)**

| **Water production cost impact** | | | | | |
|---|---|---|---|---|---|
| **Capacity (m³/d)** | **Interest Rate** | **Thyspunt Nuclear** | | **Coega - Fossil fuel** | |
| | | RO | MED | RO | MED |
| **50 000** | 5.50% | 0.609 | 0.676 | 0.650 | 0.867 |
| | 8.00% | 0.619 | 0.690 | 0.653 | 0.898 |
| | 12.00% | 0.632 | 0.713 | 0.658 | 0.909 |
| **Variation from 5.5% interest rate** | | | | | |
| **Capacity (m³/d)** | **Interest Rate** | **Thyspunt Nuclear** | | **Coega - Fossil fuel** | |
| | | RO | MED | RO | MED |
| **50 000** | 5.50% | - | - | - | - |
| | 8.00% | 1.57% | 2.09% | 0.54% | 3.57% |
| | 12.00% | 3.77% | 5.46% | 1.25% | 4.87% |

### 4.4.2 Discount rate

As expected, the discount rate is one of the factors that has the greatest effect on the water cost. A small reduction or increase in the discount rate resulted in a large increase and decrease in the water cost respectively.

A reduction in the discount rate from 5.5% to 3% (±45% reduction) led to a reduction in water cost of between 15% (RO) and 19% (MED) for the nuclear co-location and a reduction of 12% (RO) and 15% (MED) for the fossil co-location. This effect is more dominant for the nuclear co-location than for the fossil-based co-location and can be contributed to the high capital cost of nuclear power plants and their long construction periods as indicated in Table 18.

An increase in the discount rate from 5,5% to 8% (±45% increase) resulted in the same increase in production cost as the reduction obtained by the 2.5 reduction in percentage discount rate.

**Table 18: Variation in discount rate (%)**

| Water production cost impact | | | | | |
|---|---|---|---|---|---|
| **Capacity (m³/d)** | **Discount Rate** | **Thyspunt Nuclear** | | **Coega - Fossil fuel** | |
| | | RO | MED | RO | MED |
| **50 000** | 3.0% | 0.518 | 0.541 | 0.574 | 0.738 |
| | **5.5%** | 0.609 | 0.676 | 0.650 | 0.867 |
| | 8.0% | 0.807 | 0.974 | 0.809 | 1.146 |
| **Variation from 5.5%** | | | | | |
| **Capacity (m³/d)** | **Interest Rate** | **Thyspunt Nuclear** | | **Coega - Fossil fuel** | |
| | | RO | MED | RO | MED |
| **50 000** | 3.0% | -14.89% | -19.92% | -11.76% | -14.88% |
| | **5.50%** | - | - | - | |
| | 8.0% | 14.89% | 19.92% | 11.76% | 14.88% |

### 4.4.3 Electricity price increase – RO

With the current electricity price constantly increasing by 25% per year, RO production cost is coming under more and more pressure to outperform thermal desalination costs. Assuming that the nuclear fuel and fossil fuel price stay constant, RO production will become less cost effective with an increase of a 1 000% of the current electricity price as indicated in Table 22. This is not so farfetched when taking into account that the electricity price increase is actually a compound increase, since the electricity price increases 25% on the previous year's price. An increase of a 1 000% on the current price is about the same as a 10 to 11 year compound price increase.

The increase in the electricity price had no effect on the MED production cost, however, an increase in the fossil fuel price will greatly effect the operation cost of MED.

By decreasing the electricity price by 30%, only a 1.3% reduction in RO production cost was projected, showing that getting electricity directly from the power plant at a 30% lower price than grid power did not result in large cost reductions.

**Table 19: Electricity price increase (%)**

| % Increase in Electricity Price | Capacity ($m^3/d$) | Thyspunt Nuclear | | % RO Production Cost Increase |
|---|---|---|---|---|
| | | RO | MED | |
| **-30%** | 5 000 | 0.816 | 1.108 | -1.1% |
| | 50 000 | 0.648 | 0.961 | -1.2% |
| | 100 000 | 0.636 | 0.848 | -1.3% |
| **-15%** | 5 000 | 0.82 | 1.108 | -0.6% |
| | 50 000 | 0.652 | 0.961 | -0.6% |
| | 100 000 | 0.64 | 0.848 | -0.6% |
| **0** | 5 000 | 0.825 | 1.108 | -% |
| | 50 000 | 0.656 | 0.961 | -% |
| | 100 000 | 0.644 | 0.848 | -% |
| **25%** | 5 000 | 0.832 | 1.108 | 1.0% |
| | 50 000 | 0.664 | 0.961 | 1.0% |
| | 100 000 | 0.652 | 0.848 | 1.0% |
| **50%** | 5 000 | 0.832 | 1.108 | 1.0% |
| | 50 000 | 0.681 | 0.961 | 3.0% |
| | 100 000 | 0.659 | 0.848 | 2.0% |
| **100%** | 5 000 | 0.854 | 1.108 | 4.0% |
| | 50 000 | 0.686 | 0.961 | 3.0% |
| | 100 000 | 0.674 | 0.848 | 5.0% |
| **250%** | 5 000 | 0.869 | 1.108 | 5.0% |
| | 50 000 | 0.761 | 0.961 | 11.0% |
| | 100 000 | 0.689 | 0.848 | 7.0% |
| **1000%** | 5 000 | 1.091 | 1.108 | 32.0% |
| | 50 000 | 0.923 | 0.961 | 21.0% |
| | 100 000 | 0.911 | 0.848 | 41.0% |

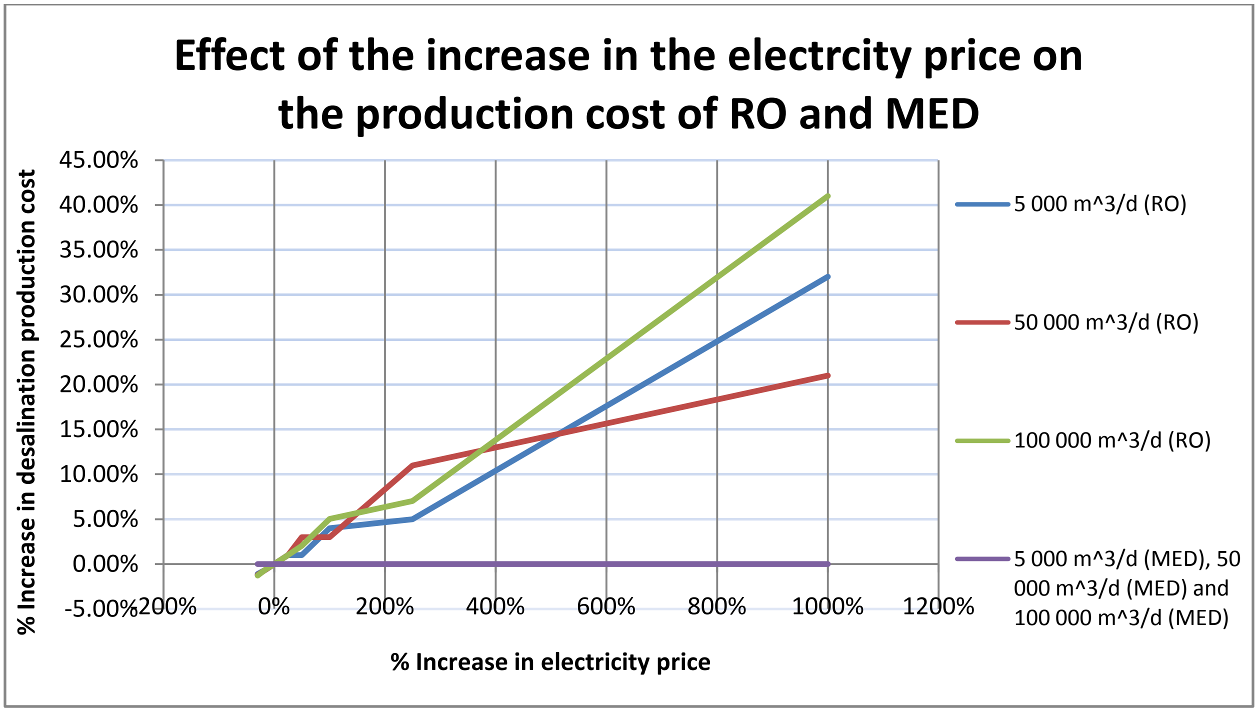



**Figure 45: Graphical illustration of the increase in electricity price on the production cost of RO and MED desalination (Table 19)**

### 4.4.4 Fossil fuel price

The water production cost from the fossil fuelled co-location is strongly influenced by the price of fuel, as indicated in Table 20. For the CCGT co-located 100 000 $m^3$/d MED plant, there is nearly an increase of 15% going from 17.7 \$/bbl to 35 \$/bbl with the 100 000 $m^3$/d RO plant indicating an increase of 8%.

For the nuclear power plant, the water production cost for MED and RO was not influenced by the increase in the fossil fuel price. If the MED process decided to include a backup boiler to be utilised as a heat source during a reactor shutdown there will be some influence on the production cost. However, the influence on the water production cost would be minimal since a high operation efficiency for the nuclear power plant was assumed.

**Table 20: Sensitivity of water production cost to the fossil fuel price**

| Total water cost excluding water transport ($/m³) | | | | | | |
|---|---|---|---|---|---|---|
| **LNG price ($/bbl)** | **MED** | | | **RO** | | |
| | **5 000** | **50 000** | **100 000** | **5 000** | **50 000** | **100 000** |
| **17.5** | 0.874 | 0.676 | 0.662 | 0.777 | 0.609 | 0.597 |
| **35** | 0.934 | 0.773 | 0.759 | 0.824 | 0.655 | 0.643 |
| **% Increase** | 7% | 14% | 15% | 6% | 8% | 8% |

### 4.4.5 Seawater TDS

Table 21 reflects the variation of TDS at a constant temperature. The costing results for MED and RO desalination processes are markedly different. As was expected for the distillation system (thermal desalination process), there was no change in the water cost with seawater TDS.

For the RO system there was a significant change in the production cost for changes in the seawater TDS. Here, an increase of 6 000 TDS resulted in an increase of around 5% in the production cost the RO.

**Table 21: Seawater TDS variation**

| **Plant Size** | **seawater TDS (ppm)** | **Production cost ($/m³)** | | **% increase in production cost - RO** |
|---|---|---|---|---|
| | | **RO** | **MED** | |
| **50 000** | 30000 | 0.881 | 0.861 | -5% |
| | **36000** | **0.923** | **0.861** | **-** |
| | 42000 | 0.96 | 0.861 | 4% |

The TDS can potentially have a more predominant role in the West Coast, due to the phenomena like red tide (harmful algal blooms) which predominantly appear in this region. The appearance of red tides has forced closures in seawater desalination plants. These closures were due to clogging of the intake filters, concerns that the bloom will foul RO membranes, possible operation problems and the concerns that toxins may end up in the final product water.

### 4.4.6 Effect of an additional/intermediate loop

The addition to the overall water production cost due to the inclusion of an intermediate loop was small, ranging from 2% to 6% for all desalination processes excluding RO. The average increase in cost for the desalination processes over all the plant sizes were 3% to 5% as indicated in Table 22.

**Table 22 : Percentage influence in cost due to an intermediat loop**

| **Desalination Process** | **% Increase in Water Production Cost** | | | **Average % Increase per Process** |
|---|---|---|---|---|
| **Plant Size** | **5 000** | **50 000** | **100 000** | **5 000 to 100 000** |
| **MED** | 5% | 6% | 6% | 5% |
| **MED-RO** | 4% | 4% | 4% | 4% |
| **MSF** | 3% | 3% | 3% | 3% |
| **MSF-RO** | 2% | 3% | 3% | 3% |

An intermediate loop is generally installed as a safety feature to meet the desired level of nuclear safety requirements. The NNR would, therefore, insist on the inclusion of an intermediate loop. The NNR would also ask for a full safety assessment and analysis since the intermediate loop is seen as part of the nuclear power plant. This would further increase the influence on the production of the thermal desalination processes. For Koeberg, this would entail an amendment of the current licence and some design changes, which could further increase costs. However, for Thyspunt the co-location could be included in the original SAR, licence application and power plant design reducing any extra costs.

DEEP 4.0 indicated that by increasing the seawater inlet temperature to the maximum allowable temperature of 40 °C, by utilizing waste heat (preheating of feedwater), an average production cost reductions of 8%, 6% and 4% were obtained for all RO plant sizes respectively (excluding intermediate loop costs). By adding the costs of the intermediate loop, the total reduction in production cost decrease from 8% to 4% at Koeberg and from 6% to 2% at Thyspunt.

By considering other costs, such as licensing, that are involved in an additional intermediate loop on the nuclear facility, the total water cost for a RO process utilizing waste heat may actually increase.

### 4.4.7 Stand-alone plants utilizing electricity as energy source

Utilizing electricity as energy source for the all thermal desalination processes increased the cost drastically as indicated in Table 23. The stand-alone thermal processes utilizing electricity as energy source indicated approximately on average 345% higher production costs, making this configuration unfeasible.

**Table 23:Stand-alone operating cost vs. Koeberg co-location operating cost**

| Cost Type | Total Operating Cost ($/m³) | | | | | |
|---|---|---|---|---|---|---|
| | Co-Generation at Koeberg | | | Stand-Alone anywhere in the West Coast | | |
| **Plant Size ($m^3/d$)** | **5 000** | **50 00** | **100 000** | **5 000** | **50 00** | **100 000** |
| **RO** | 2.300 | 1.370 | 1.080 | 2.490 | 1.420 | 1.180 |
| **MED** | 3.760 | 2.560 | 2.410 | 12.730 | 11.200 | 11.090 |
| **MSF** | 3.960 | 2.680 | 2.580 | 12.800 | 11.240 | 11.120 |
| **MED-RO** | 3.180 | 2.090 | 1.900 | 7.830 | 6.410 | 6.210 |
| **MSF-RO** | 3.290 | 2.210 | 1.960 | 7.890 | 6.570 | 6.250 |

## 4.5 Hidden costs

There is a cost that has not been included in either programs. This is the licensing cost. Generally, not a lot of attention is given to licensing; however, this should be seen as one of the most important factors in any project involving nuclear. Without a licence from the national nuclear regulator (NNR) nothing can be done. To obtain a licence from the NNR in South Africa is not an easy task. The NNR is a non prescriptive regulator. This makes the licensing process a tedious task to complete. The nuclear energy corporation of South Africa (Necsa) has a whole department only handling licensing matters. A licence of a nuclear facility generally involves the submission of a safety analysis report (SAR) and any documentation which the NNR requests.

A review of submitted licensing documentation to the NNR can take longer than anticipated, which can increase the cost of any project. Since the desalination plant is not a nuclear facility one would assume that the NNR would not be involved in the project, however, the desalination is connected to the nuclear power plant and, therefore, the NNR would insist on certain documentation to show compliances to all safety regulations.

The licensing burden is, therefore, part on the desalination facility and not just on the nuclear power plant, since the desalination facility would not be entitled to be constructed and operate without a licence.

## 4.6 Summary

Both the independent costing programs indicated RO as the most economically viable desalination process to be implemented in Cape Town, PE and Durban. The MSF desalination process was identified as the least economically viable desalination process. This was the case for all plant sizes. The plant size with the lowest total water cost was the large 100 000 $m^3$/d sized plant. Even with the large co-location cost decreases gained by the thermal desalination processes, RO was still the most economically viable process. The MED-RO hybrid configuration plant costs were the closest to the RO costs.

All hybrid plant configurations were more cost effective than the single thermal desalination plants with the MED-RO configuration more cost effective than the MSF-RO plant configuration. Of the thermal desalination processes, MED were more cost effective than MSF desalination.

The sensitivity study identified the discount rate and fossil fuel price that had the largest influence on the water production cost. However, the nuclear co-located desalination costs were not influenced by an increase in the fossil fuel price. This indicates that nuclear co-location would provide a stable cost in water production even with the current volatility in fossil fuel prices. Assuming all fuel costs stay constant, RO would only become less economical with an increase in electricity price of approximately 1 000%, which relates to around a compound growth rate of 25% over approximately 10 years.

The other factor which was identified in this study was the influence of the water transport cost on the TWC. The results indicated that the water transport cost contributed extensively to the total water cost in small scale desalination plants, coming to the conclusion that small desalination plants should be located as close as possible to the location of the product water's final destination. In the case of Thyspunt where water a transport distance of 130 km was selected, the water transport cost contributed approximately 80% to the TWC of the 5 000 $m^3$/d plant capacity.

The cost of water transport was very similar for all desalination processes. The parameters influencing the water transport cost were the capacity and distance of the water transported. The only other factor which will influence the cost of water transport is the transport technology (type) used or selected. Examples of different water technologies includes pipelines, road transport (trucks), canals, tunnels etc and therefore falls beyond the scope of this study. However, water transport played such a large role in the TWC in some scenarios it is advised that future studies specifically on water transport cost in South Africa should be conducted. The study should include existing site specific water transport infrastructure (piping, canals, water connection hubs, etc) and the effect of utilizing different types of transport technologies on water transport costs.

Co-locating RO at a nuclear power plant and installing an intermediate loop to utilize waste heat (preheat feed water) may actually result in a higher TWC than a RO plant co-located at a nuclear power plant not utilizing the waste heat and only the available inlet and outfall infrastructure, if all possible cost are included.

Stand-alone thermal desalination processes utilizing electricity as heat source were the most uneconomical. The water production costs were on average 345% more than the co-located plants utilizing waste heat.

# CHAPTER 5

## Conclusion and Recommendations

# 5 Conclusion and recommendations

This chapter provides an overview of the research project. It also discusses problems identified during the execution of the project and the use of the costing programs. It concludes with recommendations and for future research in this field of this study.

Due to the highly site specific nature of many factors influencing the total cost of desalination and due to the state of the assumptions and estimations used in the two independent desalination economic costing programs, it is not the intent of this study to provided a definitive cost of seawater desalination, rather a relative comparison of the different desalination technologies (processes). The results are therefore expected to be a source of information and guidance for business leaders and decision makers in South Africa considering seawater desalination as one of the potential solutions of future fresh water shortages.

## 5.1 Summary of the dissertation

The main purpose of this study was to identify which desalination technology (process) is the most economically viable to be implemented in South Africa to address current and future fresh water shortages.

The literature study indicated three sites on the South African coast that will face fresh water shortages in the near future. These sites are Cape Town, Port Elizabeth (PE) and Durban. Subsequently, every site is located in a different coastal region with Cape Town on the West Coast, PE on the South Coast and Durban on the East Coast. Since there are many proven desalination technologies available commercially in the world, seawater desalination offers good potential for producing fresh water to sustain the current and future economic and population growth in these areas.

The most popular seawater desalination technologies and processes were researched and identified. These processes included reverse osmosis (RO), multi-stage flash distillation (MSF) and multi-effect distillation (MED). The selection of the desalination processes for this study was based on the fact that these processes have been used in numerous countries for many years in large to small scale commercial desalination plants and is industrially mature. It was established that co-locating the desalination plant at the heat/energy source and utilizing available waste heat resulted in large cost reduction potential. Possible co-locating facilities for each site were also identified.

A number of factors influencing desalination economics were identified. The main factors influencing the desalination production costs are the selection of the desalination technology, energy source, plant size and certain site specific factors such as seawater temperature and TDS.

All co-location configurations included an extraction coupling method. This coupling method was selected as this enables the desalination plant to be permanently supplied with expanded steam, independently of power load of the power plant. All nuclear co-location configurations, in addition, included an intermediate loop to ensure no possibility of radiation contamination of the product water produced by the desalination plant. The intermediate loop was also included due to strict nuclear safety regulations and requirements.

Two independent desalination economic costing software programs were identified and selected to determine the results in Chapter 4. The two selected programs included DEEP 4.0 and WTC. The results of obtained from the two programs were evaluated individually to determine which desalination technology was the most economically viable for implementing in South Africa. The costing trends and results from the two independent cost programs were compared to validate the results. As an addition to the regional studies, a sensitivity analysis was carried out to permit the evaluation of desalination options as a function of credible variation in key parameters.

RO was identified as the most economically viable process to be implemented in South Africa.

## 5.2 Main findings

A large number of calculations, using DEEP 4.0 and WTC, were made. The calculations included a wide range of desalination processes from different technologies and possible co-location facilities producing waste heat. The results, based on the input data provided, would lead to the following conclusions.

Independent of the energy source, location and regions considered, in all investigated cases RO water production and total water costs appeared to be systematically lower than all other desalination processes. The water production costs calculated using DEEP 4.0 ranged between 0.706 $\$/m^3$ and 1.254 $\$/m^3$ depending on the desalination process, plant size, energy source, specific region and economic scenario. The water production cost calculated using WTC ranged between 0.950 $\$/m^3$ and 3.831 $\$/m^3$ depending on the desalination process, plant size, energy source, specific region and economic scenario. The costing results obtained with WTC were systematically higher than the results obtained DEEP 4.0.

Both DEEP 4.0 and WTC identified the large 100 000m$^3$/d capacity RO desalination plant with the lowest water production cost of all the plant sizes. The RO process also indicated the lowest production and total water cost for all evaluated plant sizes at all sites, therefore, RO is identified as the most economically viable desalination technology to implement in South Africa regardless of the location.

The hybrid plant configurations (combining a thermal process with a membrane process) indicated lower water cost than the single thermal desalination plants. Independent of the energy source, location and regions considered, in all investigated cases MSF water production costs appeared to be systematically higher than all other desalination processes and, therefore, the least economically viable desalination process.

A relatively significant economy of scale was identified at all sites as plant capacities increased. This effect was more pronounced increasing the capacity from 5 000 m$^3$/d to 50 000 m$^3$/d (lower sized plants). Only a small cost reduction was identified by increasing the capacity from 50 000 m$^3$/d to 100 000 m$^3$/d, which suggest that no large cost benefits are gained by increasing the desalination plant capacity beyond 50 000 m$^3$/d. This economy of scale was identified in both DEEP 4.0 and WTC, except with the WTC results in the case of the single thermal co-location plant configurations located at PE and Durban. WTC results actually indicated an increase in water production cost with an increase the plant capacity from 50 000 m$^3$/d to 100 000 m$^3$/d for these plant configurations at PE and Durban. The increase in production cost was directly related to the large increase in chemical feed cost. However, this was not the case in Koeberg. A possible explanation could be that since the seawater temperature was the only parameter which differed from the other sites, a larger amount or concentration of the specified chemical feed was needed to treat the feedwater with the higher temperatures.

In the case of PE, two possible co-location facilities producing waste heat was identified and evaluated. The one co-location candidate was the planned nuclear power plant at Thyspunt and the other was planned for the liquid natural gas (LNG) fuelled combined cycle gas turbine (CCGT) located at Coega. The water production cost results from DEEP 4.0 and WTC indicated that a RO plant located at the nuclear power plant at Thyspunt was more cost effective than locating the plant at the fossil fuelled CCGT power plant at Coega. This was due to the possibility of the desalination plant utilizing the large seawater inlet and outfall infrastructure of the nuclear power plant. However, the water production cost results from DEEP 4.0 and WTC indicated that all thermal desalination processes (MED, MSF, MED-RO and MSF-RO) co-located at the fossil fuelled CCGT at Coega was more cost effective than co-locating at the nuclear power plant at Thyspunt. Since the sensitivity analysis indicated that nuclear co-located desalination costs were not influenced by an increase in the fossil fuel price, it was concluded that nuclear co-location would provide a stable cost in water production even with the current volatility in fossil fuel prices. Therefore, on the basis of water production cost and taking into account the volatility in the current fossil fuel prices, nuclear co-location plants are suggested rather that fossil fuelled co-location plants. The total water cost results indicated the co-location at Coega was more cost effective than co-location at Thyspunt. This was due to the contribution of the water transport cost at Thyspunt.

The water transport cost is a site/location specific cost and not a dependant type of energy source of the desalination technology. The water transport cost predominantly depends on the pumping distance from the desalination plant to the final location. The further the pumping distance, the higher the water transport costs. The water transport cost from DEEP 4.0 played a significant role in the total water cost, especially in a desalination plant with a small capacity. In the case of Koeberg Thyspunt and Shakaskraal, the water transport cost contributed 56%, 80% and 69% respectively to the total water cost of the 5 000 $m^3$/d sized plant. For the 100 000 $m^3$/d sized plant, the water transport cost contribution to the total water cost decreased significantly to about 7%, 20% and 12% respectively. This indicates that the smaller the desalination plant, the larger is the contribution of the water transport cost to the total water cost, which suggests that water transport cost plays a more prominent role in the economic viability of small scale seawater desalination projects, than for large scale seawater desalination projects. Small desalination plants should, therefore, be located as close as possible to a water connection point or the final water location. The siting process for small scale desalination projects is, therefore, more important than for larger scale desalination plants.

The sensitivity study identified the discount rate and fossil fuel price had the largest influence on the water production cost. Assuming all fuel costs stay constant, RO would only become less economical than thermal desalination processes with an increase in the electricity price of approximately 1 000%, which relates to around a compound growth rate of 25% per annum over 10 years. However, this is highly unlikely to occur. RO is, therefore, still recommended above all other desalination technologies to be implemented in South Africa.

Stand alone thermal desalination processes utilizing electricity as the heat source indicated a much higher water production cost. On average all stand alone thermal desalination plants indicated a 345% higher production costs than the co-located plants. This confirms that the economic viability of seawater desalination is drastically improved by co-locating the desalination plant at a heat source producing waste heat for all thermal desalination processes.

The RO process described uses electricity as a power source. Preheating the water marginally increases efficiency and reduces the cost of the process but integration (or co-location) with the nuclear power facility is challenging and may involve additional nuclear regulatory approvals, which could be a costly prolonged process. In the case of nuclear co-location, it is suggested that a RO plant should only make use of the existing seawater inlet and outfall infrastructure and not include an intermediate loop. This makes RO a prime candidate to be implemented with a renewable energy source that can provide constant electricity to the desalination plant.

The public perception should be included in the overall site considerations. Issues such as environmental degradation, co-location with power plants, barriers to beach access and regional developments are examples of concerns that could be raised by the public and should be addressed early in the site phase.

## 5.3 Overall conclusion

The study identified the RO desalination process as the most economically viable desalination process to implement in South Africa, even with the anticipated annual electricity price increases. Water transport costs play a major role in the total economics of desalination, especially in smaller scale desalination plants. The final decision on selecting a viable site for seawater desalination should not only be based on the process with the lowest production cost but should include the water transport costs, since it could have an impact on the total water cost.

Co-locating a RO desalination plant does result in a decrease of production cost. However, co-locating at a nuclear power facility and utilizing an intermediate loop for feedwater preheat applications is challenging and may involve additional nuclear regulatory approvals, which could be a costly prolonged process. It is, therefore, suggested that RO plants co-located at nuclear power plants should only make use of the existing seawater inlet and outfall infrastructure and not include an intermediate loop for feedwater preheating.

## 5.4 Recommendations

Various site specific studies should be researched. These studies should include:

- Research identifying all other viable industrial facilities which could be utilised for desalination co-location purposes at Cape Town, PE and Durban;
- Research to identify all the licensing processes, regulatory requirements and costs involved in including an intermediate loop at Koeberg should be conducted. This should include all the specific licensing applications and safety analyses requested by the NNR for the desalination plant as well as for that of the nuclear power plant;
- Research into if a RO nuclear co-location plant incorporating an intermediate loop is actually more cost effective than a plant without an intermediate loop. This study should include all cost associated with licensing to the total water cost;
- Research identifying the current location, state and viable connection points of the available water transport infrastructure of Cape Town, Port Elizabeth and Durban should be carried out. This would ensure more accurate water transport costs for future desalination projects, since water transport cost plays a prominent role in desalination economics and siting. This study should also research if it is possible to connect to the current infrastructure;
- Research to better understand the environmental impact of desalination and development approaches to minimize this impacts relative to the other water supply alternatives, and develop approaches to lower the financial cost of desalination so that it is a more attractive option relative to other alternatives in a location where traditional sources of water are inadequate;
- Research into implementing wave power as a possible energy source for a RO desalination plant in South Africa should be pursued. A wave powered plant would be able to provide a constant power output to ensure optimal desalination production and operating time;
- Field studies to assess environmental impacts of seawater intakes. Measurements and modelling of the extent of mortality of aquatic or marine organisms due to impingement is needed;
- Research into utilizing brine as a possible income. This should include options such as salt harvesting, irrigation, aquaculture, solar ponds and integrated value-adding and

disposal. The economic and environmental viability of these options should be assessed according the South African environmental regulations;

- Develop and improve a zero discharge system for each coastal region; and
- Develop improved intake methods at coastal facilities to minimize the impingement of larger organisms and entrainment of smaller ones.

Studies improving the economic viability of RO desalination must be conducted, so that it is a more attractive option relative to other alternative in the locations where traditional sources of fresh water supply are inadequate. These technology specific studies should include:

- Research to improve the pretreatment process is needed that would develop alternative, cost effective approaches. Research is also needed on alternative formulations or approaches to reduce the chemical requirements of the pretreatment process, both to reduce overall cost and to decrease the environmental impacts of desalination;
- More research is necessary in order to optimize the pretreatment membranes for more effective removal of foulants to the RO system, to reduce the fouling of the pretreatment membranes, and to improve configuration of the pretreatment membranes to maximize cost reduction; and
- The development of membranes that are more resistant to degradation from exposure to cleaning chemicals will extend the useful life of a membrane module. The ability to clean membranes more frequently can also decrease energy usage because membrane fouling results in higher differential pressure loss through the modules. By extending the life of membrane modules, the operating and maintenance cost will be reduced by the associated reduction in membrane replacements required.

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# APPENDIX A

**Scenario 1: MED co-location at Koeberg, 100 000 m$^3$/d, intermediate & loop transport cost**

**First spreadsheet**

The first spreadsheet lets the user select case specific parameters and configurations as indicated in Figure 46.

*Step 1:*

Power Plant – Steam cycle

Fuel – Nuclear

*Step 2:*

Seawater Temperature – 9°C

*Step 3:*

Desalination Technology – Distillation

Desalination Capacity – 100 000m$^3$/d

Seawater Salinity (TDS) – 36 000 ppm

*Step 4:*

Intermediate Loop - Included (nuclear power plant)

*Step 5:*

Desalination Process – MED

Maximum Brine Temperature – 70 °C

*Step 6:*

Discount Rate - 5.5%

Interest rate - 5.5%

Fuel escalation rate - 3%

Water transport cost - Included (130 km)

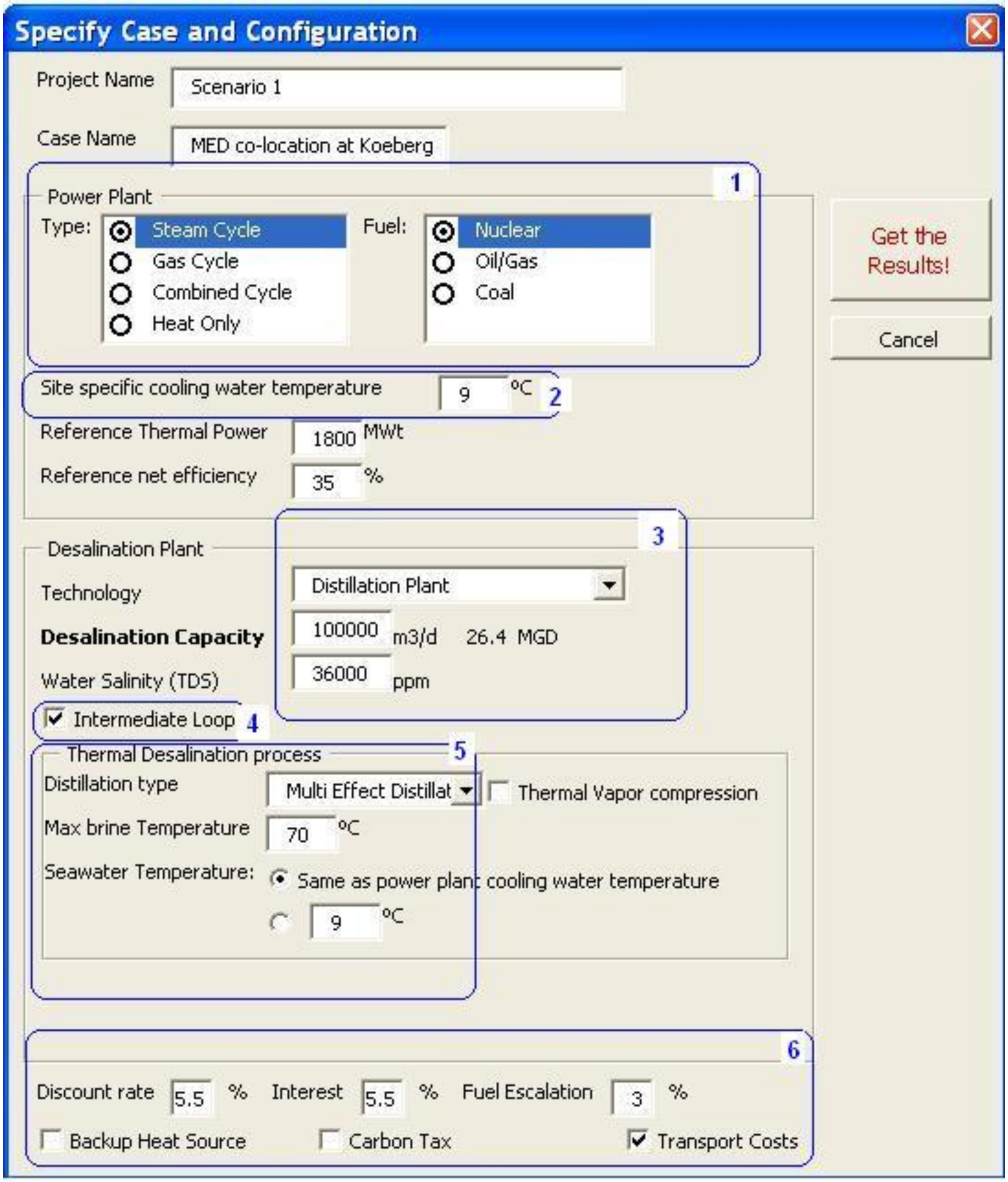



**Figure 46: First spread sheet.**

### Second spreadsheet

The second spreadsheet lets the user select all technical and economic parameter of the power plant and desalination plant as indicated in Figure 47.

*Step 7:*

Power Plant Technical - Extraction /condensing coupling method

Power Plant Economical - Fuel specific cost, Nuclear 7.7 $/MWh

Desalination Plant Technical - Default values

Desalination Plant Economical - Life time 30 years, inlet/outfall 0%, base unit cost 900 $/m^3/d (Figure 48)

*Step 8:*

Intermediate Loop - Default values

Water Transport - Pipe length 30 km, operation life 30 years, construction lead time 12 months (same as desalination plant) (Figure 48)

*Step 9:*

Electricity Price - 0.0823 $/kWh

*Step 10:*

Full Report - States all the determined values of the evaluation (Table 24)

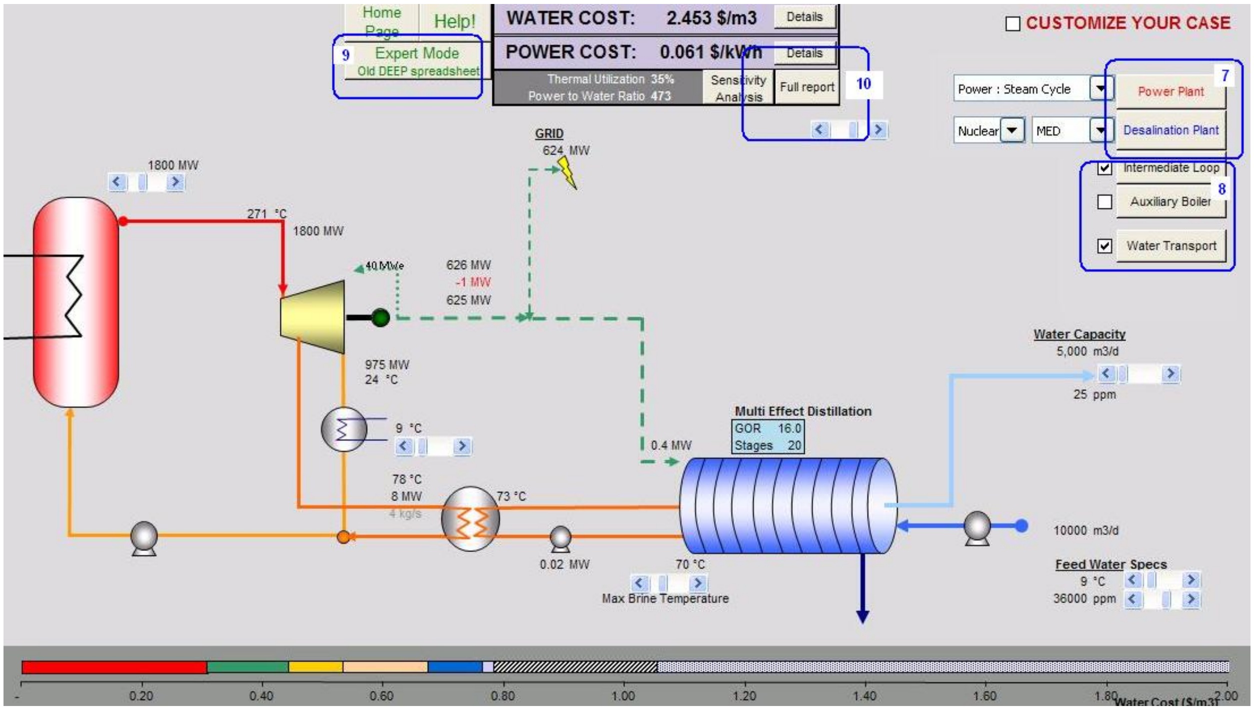



**Figure 47: Second spreadsheet.**

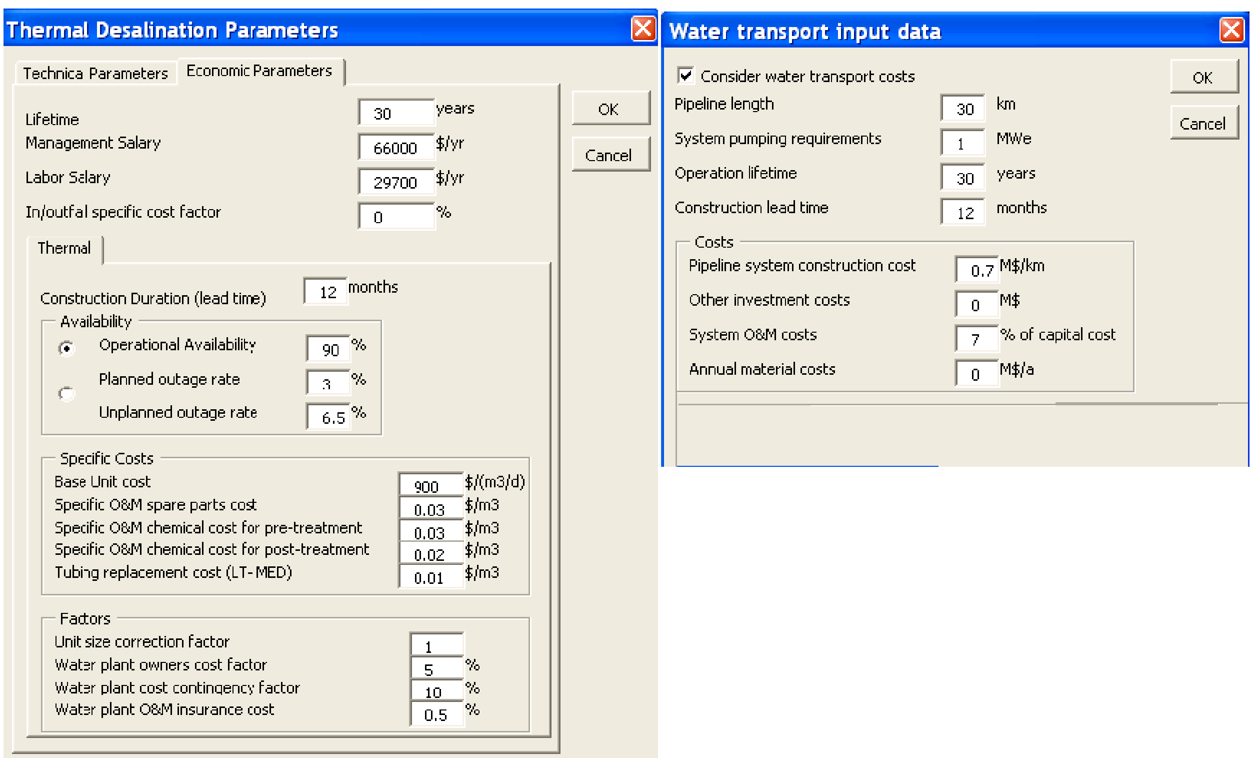



**Figure 48: Desalination plant economic parameters and water transport parameters.**

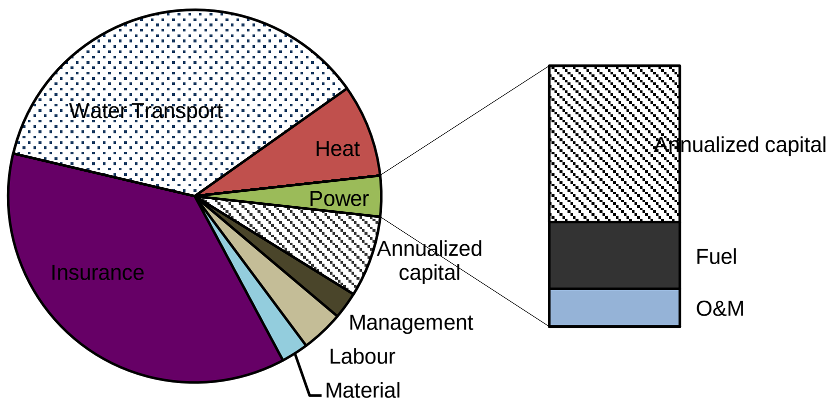
**Table 24: Summary of costs**

# Summary of Cost Results

| | |
|---|---|
| Discount rate | 6% |
| Interest | 6% |
| Fuel Escalation | 3% |

## Desalination plant

| | | | |
|---|---|---|---|
| Type | MED | | |
| Total Capacity | 5000 | $m^3/d$ | |
| Feed Salinity | 36000 | ppm | |
| Combined Availability | 81% | | |
| Water Production | 1.48 | $Mm^3/yr$ | |
| Power Lost | 1.1 | MW(e) | *Extraction of 8 MW at 78°C (Power lost ratio=12.5%)* |
| Power Used for desalination | 468 | MW(e) | |




| **Capital Costs of Desalination Plant** | | | | | X |
|---|---|---|---|---|---|
| | *MED* | | *Total (M$)* | *Specific ($/m3 d)* | *Share* |
| Construction Cost | 5 | - | 5 | 900 | 77% |
| Intermediate loop cost | 0 | - | 0 | 80 | 7% |
| Backup Heat Source | - | - | - | - | 0% |
| Infall/Outfall costs | - | - | - | - | 0% |
| Water plant owners cost | 0 | - | 0 | 49 | 4% |
| Water plant contingency cost | 1 | - | 1 | 103 | 9% |
| Interest during Construction | 0 | - | 0 | 31 | 3% |
| **Total Capital Costs** | 6 | - | 6 | 1162 | |
| **Annualized Capital Costs** | | | 0 | | |
| Sp. Annualized Cap Costs | | | | **0.27** | $/m3 |

| Operating Costs of Desalination Plant | | | | | |
|---|---|---|---|---|---|
| | MED | | Total (M$) | *Specific ($/m3)* | Share |
| ***Energy Costs*** | | | | | |
| Heat cost | 0 | | 0 | 0.31 | 39% |
| Backup heat cost | - | | - | - | 0% |
| Electricity cost | 0.2 | - | 0.2 | 0.14 | 17% |
| Purchased electricity cost | - | - | - | - | 0% |
| **Total Energy Costs** | 1 | - | 1 | 0.44 | 57% |
| ***Operation and Maintenance Costs*** | | | | - | 0% |
| Management cost | - | - | 0.13 | 0.09 | 11% |
| Labour cost | - | - | 0.21 | 0.14 | 18% |
| Material cost | 0.1 | - | 0.1 | 0.09 | 12% |
| Insurance cost | 0.0 | - | 0.0 | 0.02 | 2% |
| **Total O&M cost** | 0 | - | 1 | 0.34 | 43% |
| **Total Operating Costs** | 1 | - | 1 | **0.78** | |

| | | |
|---|---|---|
| **Total annual cost** | **1.56** | **M$** |
| Water production cost | 1.053 | $\$/m^3$ |
| Water Transport costs | 1.400 | $\$/m^3$ |
| **Total water cost** | **2.453** | $\mathbf{\$/m^3}$ |

# APPENDIX B

**Scenario 3: MSF-RO hybrid co-location at Coega, 100 000m$^3$/d (excluding transport cost)**

**Spreadsheet 1 (Figure 49)**

The first spreadsheet lets the user select case specific parameters, general project information, water analysis and unit operations.

*Step 1:*

Desired Product Water Flow Rate – 100 000 m$^3$/d

Planned operating Hours – 24 h

*Step 2:*

Seawater Temperature – Steam cycle –- 9°C

Seawater Salinity (TDS) – 36 000 ppm

*Step 3:*

Unit operations – the selection included pre-treatment disinfection, chemical feed system, filtration, decholrination, desalting, post-treatment and miscellaneous equipment.

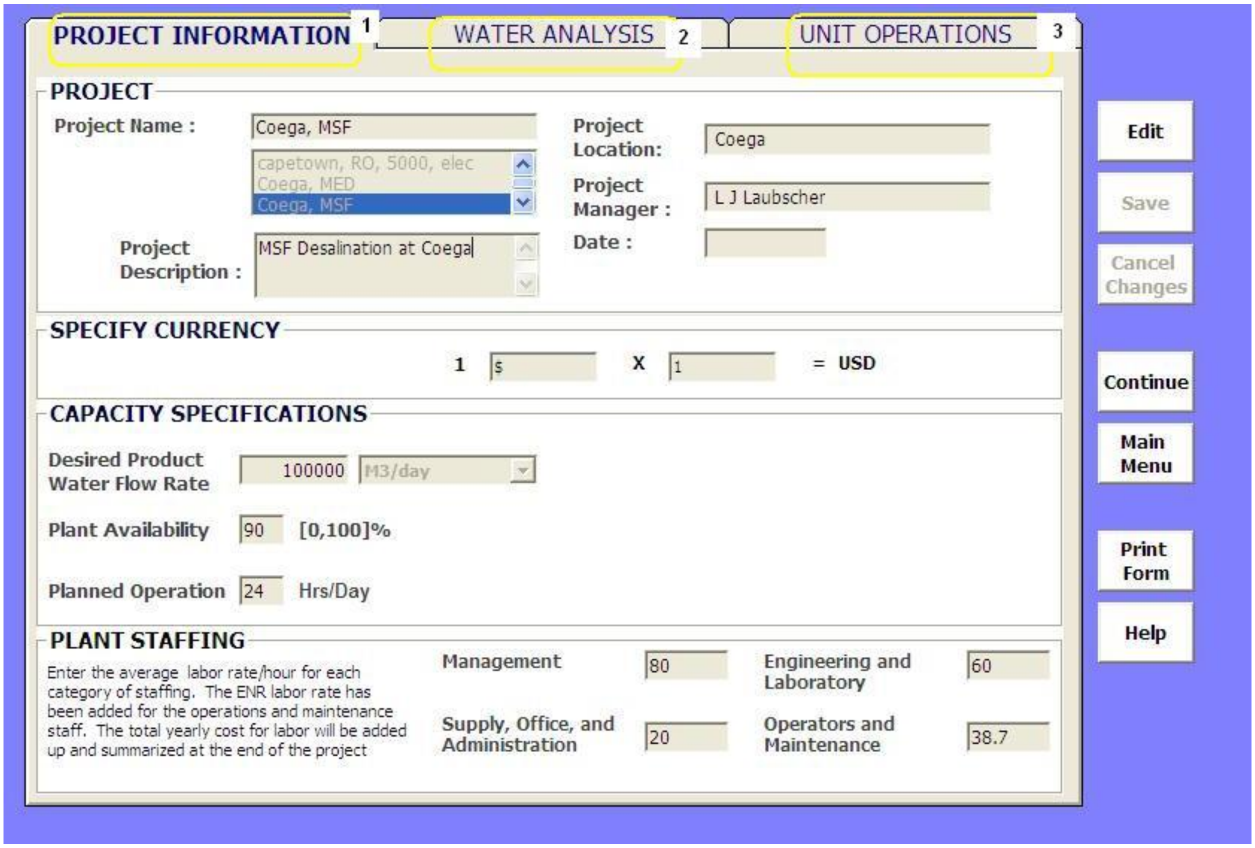



**Figure 49: Spreasheet 1.**

**Spreadsheet 2 – separation process options**

*Step 4:*

Plant configuration –- Hybrid dual MSF-RO plant

Desired flow rate –- 50% MSF and 50% RO

**Spreadsheet 3 – RO specific selections**

*Step 5:*

Membrane selection –- seawater membrane

Number of trains –- 3 (requires only sectional shutdown for maintenance)

**Spreadsheet 4 – thermal desalination specific selections**

*Step 6:*

| | | |
|---|---|---|
| Thermal Desalting Process | –- | MSF |
| Select Configuration | –- | Co-location |
| Select Fuel | –- | Natural gas |
| Fuel Price | –- | 0.189 $/kg |
| Fuel Heat Value | –- | 37 000 kJ/kg |
| Select Power Cycle | –- | CCGT |

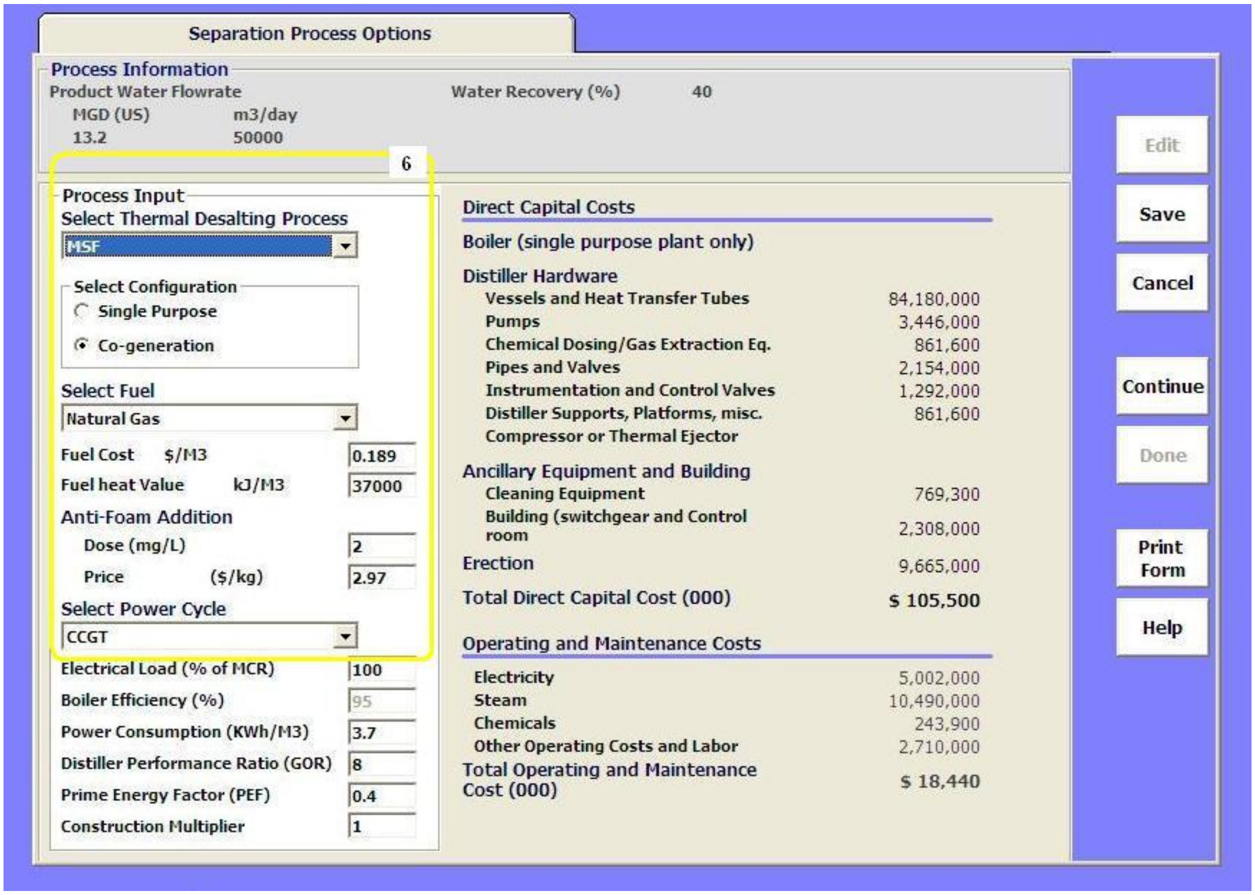



**Figure 50: Separation process option.**

**Spreadsheet 5 to 8 – Pre-treatment processes**

*Step 7:*

Filtration method –- Activated carbon filter bed (remove color, odor, organic chemicals ,disinfection byproducts, and chlorine from water through the process of adsorption)

Pre-treatment disinfection –- Chlorination

Chemical feed –- Antiscalants, Polyelectrolyte (suited for both membrane And thermal processes)

**Spreadsheet 9 to 10 – Post-treatment processes**

*Step 8:*

Decholrination Method –- $NaHSO_3$, $Na_2SO_{3,}$ and$SO_2$

Product water Disinfectant –- Chlorination use same system as pre-treatment for Cost saving

**Spreadsheet 11 – Miscellaneous equipment (Figure 51)**

*Step 9:*

Equipment Selection –- Pump, upflow solids contact clarifier (UFSCC), intake and outfall, water storage and other equipment

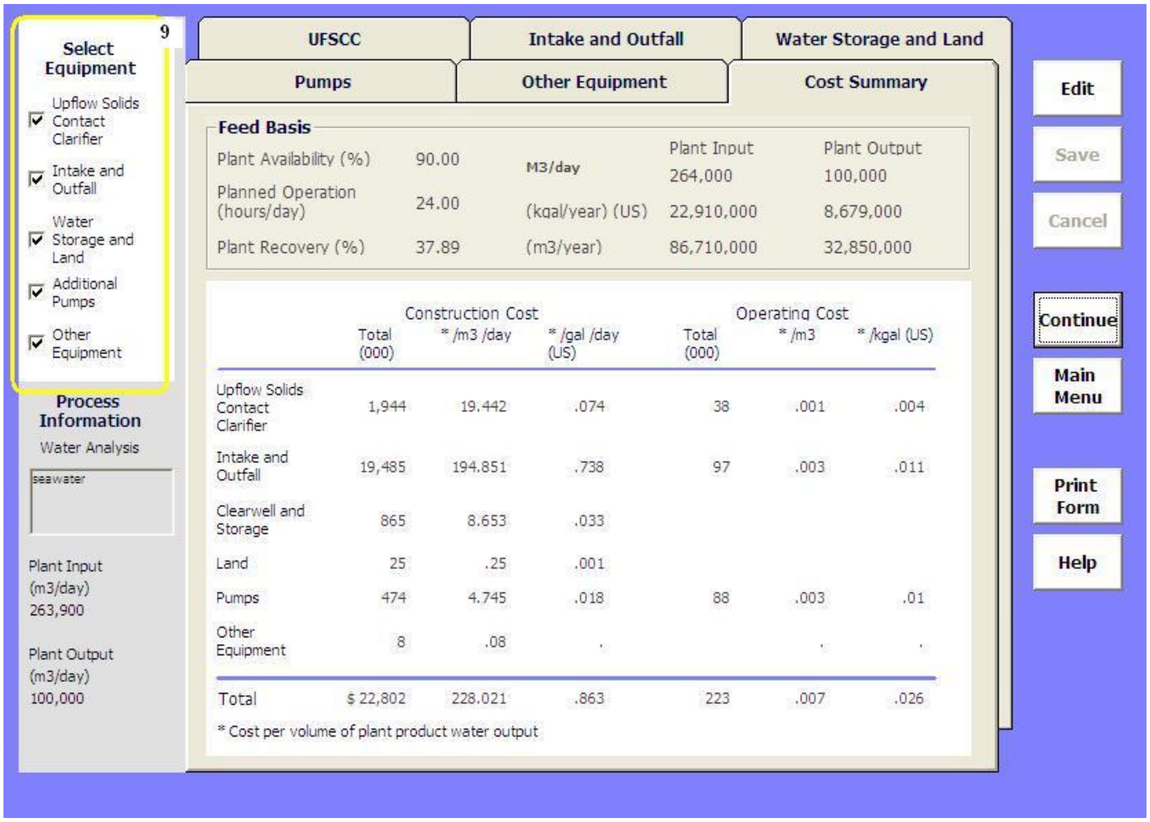



**Figure 51: Miscellaneous equipment.**

**Spreadsheet 12 – Program summation of processes (Figure 52)**

*Step 10:*

Summary include –- Process summary, indirect costs and project cost summary


| Process | Construction Cost Total (000) | * /m3/day | * /gal /day (US) | Operating Cost 000/yr | * /m3 | * /kgal (US) |
|---|---|---|---|---|---|---|
| Pretreatment | 84 | 1 | . | 198 | .01 | .02 |
| Chemical Feed Systems | 21,850 | 219 | .83 | 8,953 | .27 | 1.03 |
| Media Filtration | 43,520 | 435 | 1.65 | 11,550 | .35 | 1.33 |
| De-Chlorination | 276 | 3 | .01 | 261 | .01 | .03 |
| Desalting | 116,300 | 1,163 | 4.4 | 19,640 | .6 | 2.26 |
| Product Water Treatment | 34 | | . | 13 | . | . |
| Miscellaneous Equipment | 22,780 | 228 | .86 | 223 | .01 | .03 |
| Non-Operator Labor | | | | 1,120 | .03 | .13 |
| Indirect Capital Cost | 89,150 | 891 | 3.37 | | | |
| Capital Recovery | | | | 20,030 | .61 | 2.31 |
| Feed Water | | | | | . | . |
| TOTAL | 294,000 | 2,940 | 11.13 | 61,990 | 1.89 | 7.14 |

* Cost per volume of plant product water output

**Figure 52: Project cost summary.**