DEEP 5 User Manual

2013

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A. Introduction

A.1. Purpose and use of software

The Desalination Economic Evaluation Program (DEEP) is a spreadsheet tool originally developed for the IAEA by General Atomics and later expanded in scope by the IAEA, in what came to be known as the DEEP-2 version. These models have been thoroughly reviewed and upgraded and a new version, DEEP-3.0, has been released. After years of update and model reviews the version DEEP -4 offered a major interface upgrade. The program allows designers and decision makers to compare performance and cost estimates of various desalination and power configurations. Desalination options modeled include MSF, MED, RO and hybrid systems while power options include nuclear, fossil and renewable sources. Both co-generations of electricity and water as well as water-only plants can be modeled. The program also enables a side-by-side comparison of a number of design alternatives, which helps identify the lowest cost options for water and power production at a specific location. Data needed include the desired configuration, power and water capacities as well as values for the various basic performance and costing data.

Technological advances of the last decade have helped desalination to spread faster and to become a reliable way for the supply of water and consequently for sustainable development. Yet minimizing the cost of seawater desalination is recognized as one of the most important technology challenges. With rising energy costs and water demands, the energy consumed and subsequently the costs involved in any desalination plant play an important role in any economic feasibility and optimization studies.

In the last decade, the total contracted desalination capacity has almost tripled. The desalination technology with the greatest share is 60% for RO, 30% for MSF and 10% for MED. The average capacity per project has also dramatically increased. Consequently, the energy needs of each project have become significantly larger creating the necessity for larger and more reliable energy sources. Moreover, the increase in energy costs and the uncertainty in fossil fuel prices have multiplied the expenditures of constructing and operating a desalination plant.

The economics of desalination could improve through cogeneration: the use of dual purpose plants (i.e. for electricity generation and water production). Sustainability, environmental considerations, and large-scale economic aspects have made nuclear energy a promising energy source candidate for desalination. Currently, there is a growing interest in the use of nuclear energy for various non-electrical applications such as desalination, hydrogen production, and process heat applications. Among other drivers for this interest are cheaper energy, less uncertainty on energy costs, higher load factor of the desalination plant, better load factor of the nuclear unit, utilization of nuclear plant’s free land, and reduction of the desalination carbon footprint.

The DEEP software is usually used for the following:

- Calculation of the levelized cost of electricity and desalted water as a function of quantity, site specific parameters, energy source, and desalination technology.
- Side-by-side comparison of a large number of design alternatives on a consistent basis with common assumptions.
- Quick identification of the lowest cost options for providing specified quantities of desalted water and/or power at a given location.

However, the user is cautioned that the spreadsheet is based on simplified models. For planning an actual project, final assessment of project costs should be assessed more accurately based on substantive information including project design and specific vendor data.

A.2. Software requirements and installation

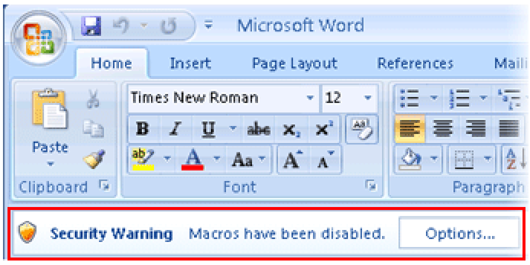
DEEP is implemented as an enhanced Microsoft Excel spreadsheet. DEEP has been developed and successfully tested in the following versions of software:

Operating system: Microsoft Windows XP and above

Application: Microsoft Excel 2007 and above

DEEP can run in previous versions of Office e.g. in MS Excel 2003 but a trouble-free experience can be guaranteed only with the recommended versions. DEEP can also run in Office for Mac OS, however the responses to some commands will be rather slow, and the graphics will not appear as designed.

The user should have sufficient rights to have the macros enabled. Despite the fact that most calculations do not require macros to run, they are necessary for the execution of the friendly user interface that was implemented in the latest version. To enable the macro click **Options** on the Message Bar, a security dialog box opens. Then select "**Enable this content**" and press OK.



For more information about macros, please visit MS office help page (http://office.microsoft.com/en-us/excel-help/enable-or-disable-macros-in-office-documents-HA010031071.aspx)

A.3. Latest improvements in DEEP software

The new version, DEEP 5, released in 2013, adds some new features that enhance the economic analysis of desalination plants supported by a new modern user friendly interface.

The highlights of DEEP 5 are:

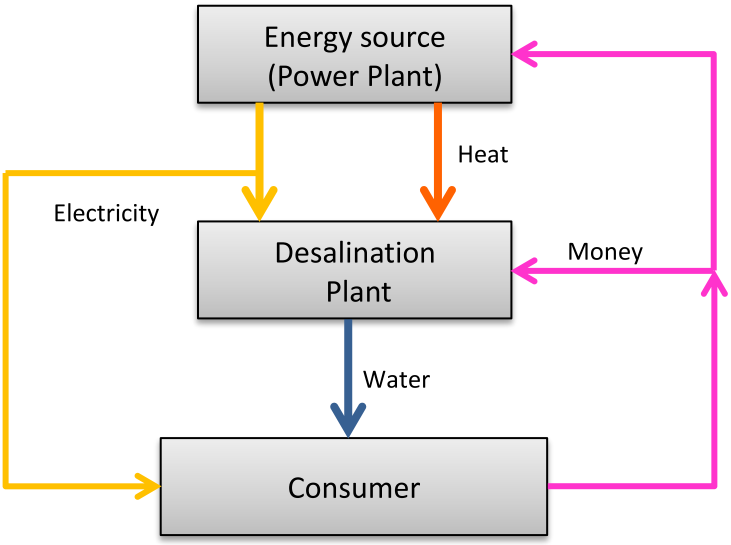
- Overall visual improvement for easier navigation between the input, analysis and the results
- Detailed cash flow analysis of any dual purpose desalination plant, showing a detailed overview of the project financing. This analysis is appropriate for use in 'bankable' feasibility studies
- Scenario manager screen, for comparing scenarios and importing/exporting to files.
- All features introduced in previous versions, such as sensitivity analysis and case comparison have been reworked and optimized for faster and easier access. The default parameters have been also updated to reflect generic cases according to latest developments.

DEEP is suitable for analysis among different plant types (steam, gas, combined cycle and heat only plants), different fuels (nuclear, oil, coal) and various desalination options including Multi-Effect Distillation (MED), Multi-Stage Flash (MSF), Reverse Osmosis (RO) and hybrid options. It also includes formulation of different alternatives such as different turbines configurations, backup heat, intermediate loop, water transport costs and carbon tax.

B. Technologies covered by DEEP

B.1. General

Every desalination process requires energy. The heat energy required for distillation can be extracted from the steam cycle of a fossil fired or nuclear power plant, from a heating plant or from suitable waste heat sources. Electricity, which is required for all desalination processes, can be taken from a power plant or from the electrical grid. DEEP is designed to calculate these energy inputs and the water (and electricity, if applicable) production costs.

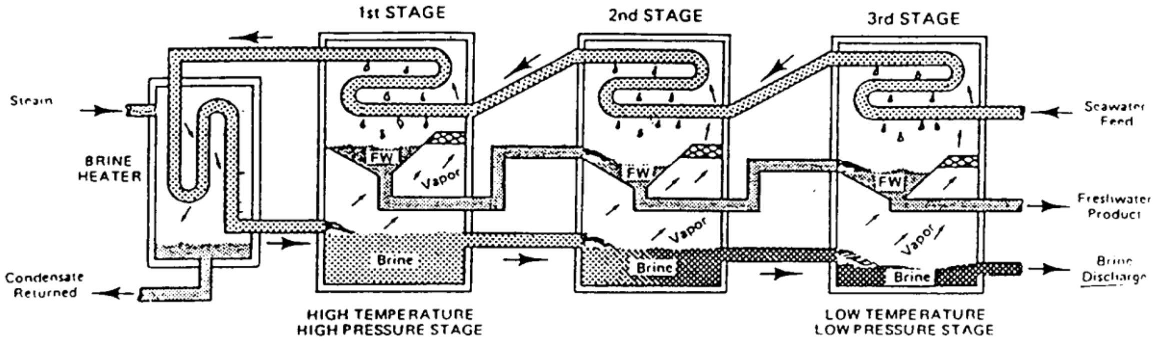


The energy conversion and water desalination technologies are described here as far as necessary for the user for preparing input data, basically understanding the calculations, and interpreting the results of DEEP.

B.2. Desalination processes

Desalination systems fall into two main design categories, namely thermal and membrane types. Thermal designs including multi-stage flash (MSF) and Multi-effect distillation (MED), use flashing and evaporation to produce potable water while membrane designs use the method of Reverse Osmosis (RO). With continuing improvements in membrane performance, RO technology is increasingly gaining markets in seawater desalination and hybrid configurations, combining RO with MED or RO with MSF have also been considered.

B.3. Multi stage flash (MSF) distillation



FW = Freshwater

The Figure above shows the schematic flow diagram of an MSF system. Seawater feed passes through tubes in each evaporation stage where it is progressively heated. Final seawater heating occurs in the brine heater by the heat source. Subsequently, the heated brine flows through nozzles into the first stage, which is maintained at a pressure slightly lower than the saturation pressure of the incoming stream. As a result, a small fraction of the brine flashes forming pure steam. The heat to flash the vapour comes from cooling of the remaining brine flow, which lowers the brine temperature. Subsequently, the produced vapour passes through a mesh de- mister in the upper chamber of the evaporation stage where it condenses on the outside of the condensing brine tubes and is collected in a distillate tray. The heat transferred by the condensation warms the incoming seawater feed as it passes through that stage. The remaining brine passes successively through all the stages at progressively lower pressures, where the process is repeated. The hot distillate flows as well from stage to stage and cools itself by flashing a portion into steam which is re-condensed on the outside of the tube bundles.

MSF plants need pre-treatment of the seawater to avoid scaling by adding acid or advanced scale-inhibiting chemicals. If low cost materials are used for construction of the evaporators, a separate deaerator is to be installed. The vent gases from the deaeration together with any non-condensable gases released during the flashing process are removed by steam-jet ejectors and discharged to the atmosphere.

B.4. Multiple effect distillation (MED)

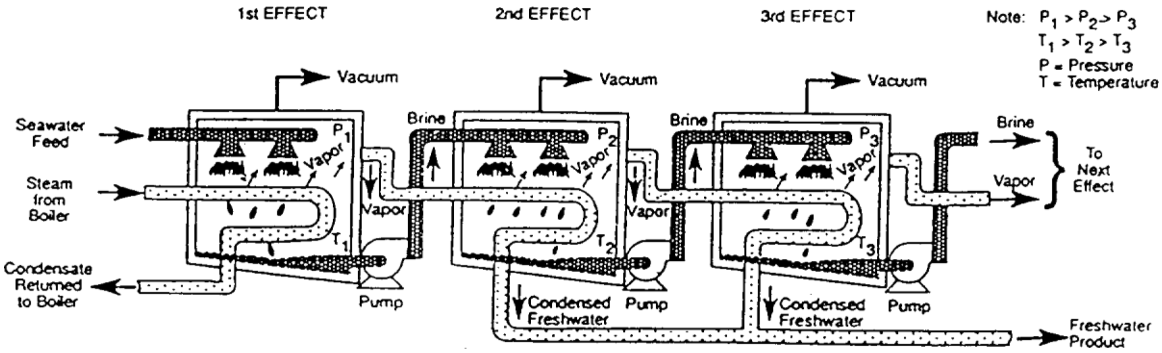


Diagram of a multiple effect plant.

The Figure above shows the schematic flow diagram of MED process using horizontal tube evaporators. In each effect, heat is transferred from the condensing water vapour on one side of the tube bundles to the evaporating brine on the other side of the tubes. This process is repeated successively in each of the effects at progressively lower pressure and temperature, driven by the water vapour from the preceding effect. In the last effect at the lowest pressure and temperature the water vapour condenses in the heat rejection heat exchanger, which is cooled by incoming seawater. The condensed distillate is collected from each effect. Some of the heat in the distillate may be recovered by flash evaporation to a lower pressure. As a heat source, low pressure saturated steam is used, which is supplied by steam boilers or dual-purpose plants (co-generation of electricity and steam).

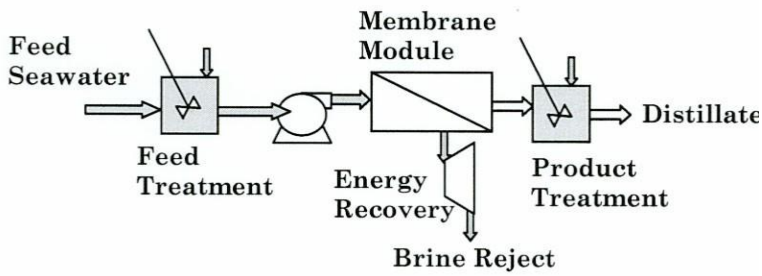
Currently, MED processes with the highest technical and economic potential are the low temperature horizontal tube multi-effect process (LT-HTME) and the vertical tube evaporation process (VTE).

In LT-HTME plants, evaporation tubes are arranged horizontally and evaporation occurs by spraying the brine over the outside of the horizontal tubes creating a thin film from which steam evaporates. In VTE plants, evaporation takes place inside vertical tubes.

B.5. MED plants with vapour compression (VC)

In some MED designs, a part of the vapour produced in the last effect is compressed to a higher temperature level so that the energy efficiency of the MED plant can be improved (va- pour compression). To compress the vapour, either mechanical or thermal compressors are used.

B.6. Reverse osmosis (RO)



Reverse osmosis is a membrane separation process in which pure water is “forced” out of a concentrated saline solution by flowing through a membrane at a high static transmembrane pressure difference. This pressure difference must be higher than the osmotic pressure between the solution and the pure water. The saline feed is pumped into a closed vessel where it is pressurised against the membrane. As a portion of the water passes through the membrane, the salt content in the remaining brine increases. At the same time, a portion of this brine is discharged without passing through the membrane.

RO membranes are made in a variety of modular configurations. Two of the commercially successful configurations are spiral-wound modules and hollow fibre modules. The membrane performance of RO modules such as salt rejection, permeate product flow and mem- brane compaction resistance were improved tremendously in the last years. The DEEP performance models cover both the effect of seawater salinity and the effect of seawater temperature on recovery ratio and required feedwater pressure.

A key criterion for the RO layout is the specific electricity consumption, which should be as low as possible. That means, the recovery ratio has to be kept as high as possible and the accompanying feedwater pressure as low as possible fulfilling the drinking water standards as well as the design guidelines of the manufactures. Since the overall recovery ratios of current seawater RO plants are only 30 to 50%, and since the pressure of the discharge brine is only slightly less than the feed stream pressure, all large-scale seawater RO plants as well as many smaller plants are equipped with energy recovery turbines.

C. User manual

This section describes the use of the software and how to navigate through its different sheets.

C.1. Starting with DEEP and navigating through the program

To perform a simple water cost analysis of any dual or single purpose plant, perform the following steps:

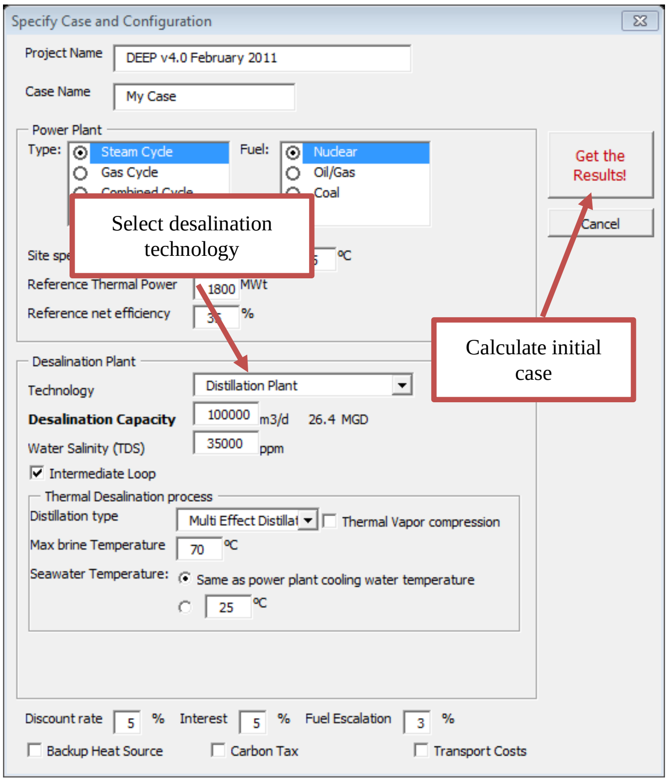
Select the *New Case* button.

In this form the user has to select basic parameters to create his own custom case. The parameters shown here are limited to the necessary ones so that the user is not overfed with information. Further customization is possible after the first results.

The first from contains information about the power plant. More specifically the user has to select the type of power plant as defined by its thermodynamic cycle and its fuel. Then he has to enter the size, its reference efficiency that is used and the site specific temperature.

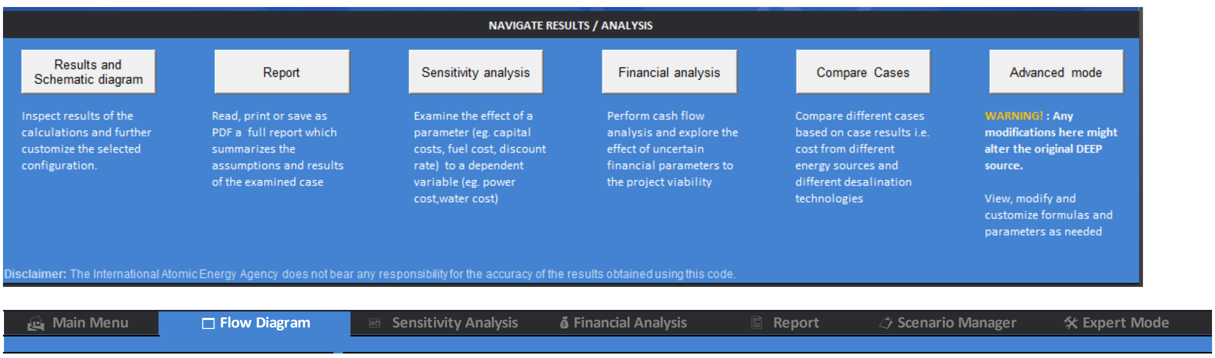
The second form frame contains information about the desalination plant. Two thermal plants (MED,MSF) and one electric plant (RO) are available for selection as well as any combination between them (hybrid). Other basic parameters include:

- **Seawater TDS:** Feed water salinity, defined according to the total dissolved solids (TDS).
- **Top brine temperature:** Maximum temperature at which the brine is heated up in the brine heater of a MSF plant or the first effect of a MED plant.
- **Seawater temperature:** If it is different than the sweater temperature that is used in the power plant
- **Option for intermediate loop:** This is usually necessary for nuclear power plants coupled to a distillation plant. An intermediate loop, which could either be a hot water loop (for MSF) or a flash loop (for MED). DEEP calculates the performance and cost impacts of it.



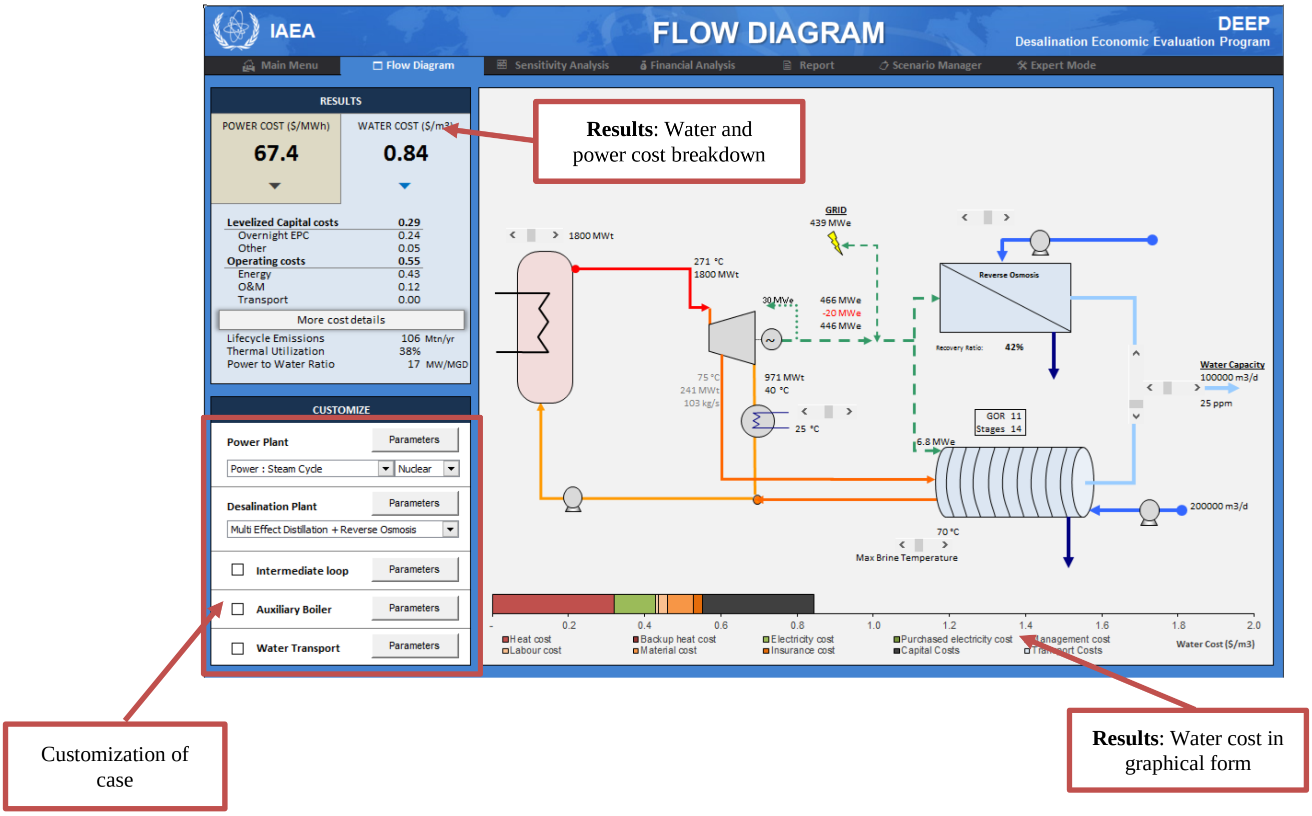
After accepting or customizing the default values you can proceed by clicking the *Get the results* button. The following options are available for selection when the calculations finish:

- Results and schematic diagram: Inspect results of the calculations and further customize the selected configuration
- Report: Read, print or save as PDF a full report which summarizes the assumptions and results of the examined case
- Sensitivity analysis: Examine the effect of a parameter (eg. capital costs, fuel cost, discount rate) to a dependent variable (eg. power cost,water cost)
- Financial analysis: Perform cash flow analysis and explore the effect of uncertain financial parameters to the project viability
- Compare Cases: Compare different cases based on case results i.e. cost from different energy sources and different desalination technologies
- Advanced mode: View, modify and customize formulas and parameters as needed. Similar to the old DEEP spreadsheet (version 3).



The main modes and functionalities of each one of them are presented in the following sections. The user can navigate either from the buttons in the home screen, or from the top menu that can be found on each screen. It is not necessary to go through them on a specific order.

C.2. Results and schematic diagram



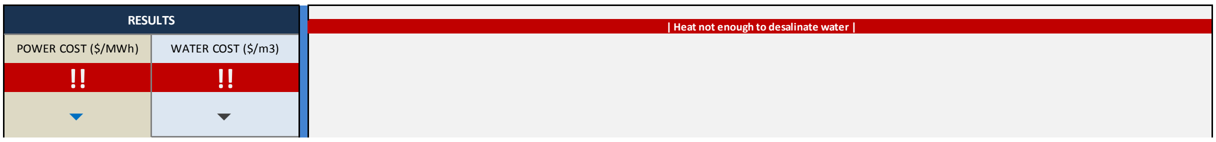
In this screen the user can inspect their results and further customize them. Three main sections can be identified:

- *Schematic diagram*: On the center of the screen the conceptual flow diagram of the designed case is presented. The information that can be seen is: energy flows, temperatures, capacities etc. The most crucial parameters can be modified by moving the scrollbars and all other values are modified accordingly.
- *Results*: On the top left of the screen the user can see the water ($/m3) and power cost ($/MWh) of the defined case. The power or water cost breakdown can be seen by hovering the mouse on each one of them. The same information regarding the water costs can be found at the bar chart at the bottom of the screen. All values are interactive and change automatically with any modification that the user does. By clicking the "More cost details" button a window is hovered above the flow diagram showing all the details of the cost estimation.
- *Customize case*: From these menus all calculation modules can be further customized. The main options are as follows:
    - Selection of power plant type. The dropdown menu is the same as the one that existed in the 'New Case' form which defined the power plant's thermodynamic cycle and fuel. The parameters button includes two tabs in which all technical and economic parameters can be overviewed and modified.
    - Selection of desalination plant. The dropdown menu is the same as the one that existed in the the 'New Case' form which defined the desalination plant type. The

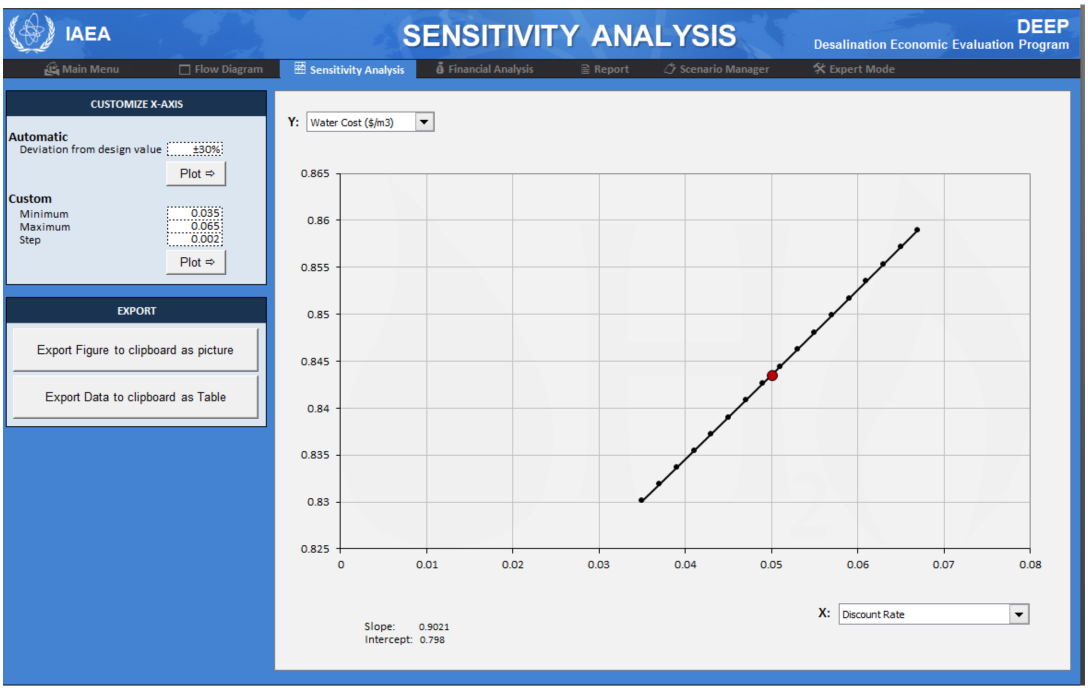
parameters button includes two tabs in which all technical and economic parameters can be overviwed and modified.

- Intermediate loop. By clicking the checkbox the user has the option to include or not an intermediate loop to its system. The costs and diagram are modified accordingly. The parameters button contains more information regarding the temperature differentials efficiencies and costs of this loop.
- Auxiliary boiler
- Water transport

In the software there are many error checking routines that inform the user of any possible logical mistakes of his inputs. As an example, there is a case that the power plant is not big enough to provide energy to the defined desalination plant. In that case the user will receive an alert message informing him of that error, so that he can take the required action.



C.3. Sensitivity analysis of main parameters



In this screen the user can easily examine the effect of one variable to another. The user can select the parameters that want to examine from the drop-down menus in the x and y-axis.

The independent parameters (x-axis) are the following:

- Water Capacity (m3/d)
- Max Brine Temperature (°C)
- RO feed pressure (bar)
- Power plant - Sp. Construction Cost ($/kW)
- Interest Rate
- Discount Rate

- Fuel Escalation
- Power Plant Availability
- Condensing Temperature (°C)
- Specific fuel cost ($/MWh)
- Carbon tax ($/tn)

The dependent variables (y-axis) are the following:

- Water Cost ($/m3)
- Power Cost ($/kWh)
- Thermal Utilization (%)
- Net Electricity Output (MWe)
- Lost Electricity (MWe)

Any combination of the above is possible. In case of a variable not having an effect to another, a straight line with zero slope will be created (eg. Discount rate effect on thermal utilization).By default the range of the independent parameter is ±30% of its design value. That can be changed by the first option in '*Customize x-axis'* menu (*Automatic*) if a wider or narrower range is desired. For custom range the minimum, maximum value as well as the increment between these two points.

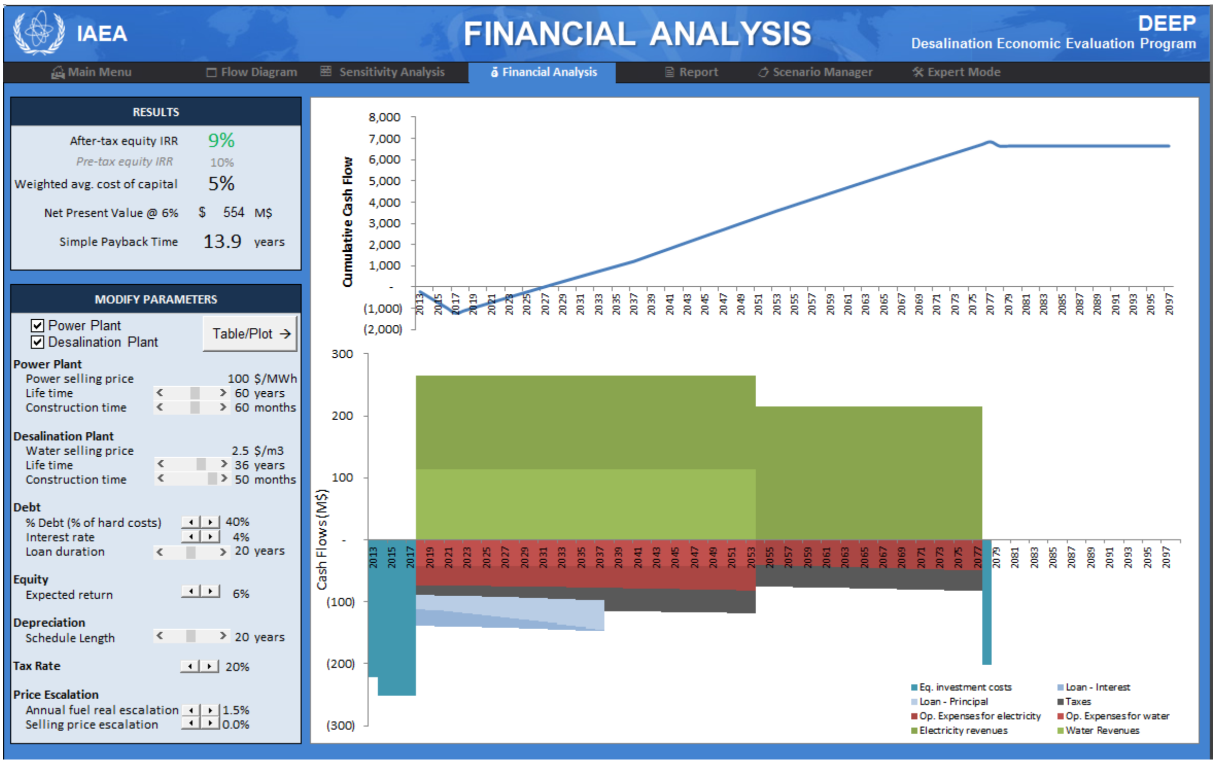
Linear regression is also done to the generated points and the slope and intercept of the predicted line are shown under the figure.

The results can be exported with the two buttons on the left column:

- The '*Export Figure to clipboard as picture'* copies the generated figure to memory that can be pasted to any other file that accepts pictures (document, presentation, etc)

- The '*Export Data to clipboard as table'* copies the x-y points of the generated figure that can be pasted for further analysis in any spreadsheet software.

C.4. Financial analysis



This screen is the newest feature of DEEP 5. The user can see the detailed cash flow analysis throughout the life time of his project. In the center of the screen the user can see two graphs. The top graph is the cumulative net cash flow throughout the lifetime of the project. The second graph gives a more detailed breakdown of all the cashflows. The categories estimated are summarized below:

- Equity investment costs: The initial investment cost that
- Revenues from selling electricity or water
- Operating expenses for electricity and water
- Loan payment: principal and interest
- Taxes

On the top left side of the screen the user can see some important economic indices related to his case. More specifically:

- Internal rate of return of his equity both pre-and after-tax
- Weighted average cost of capital. It is shown here for a quick comparison with the IRR
- Net present value at the equity discount rate
- Simple payback time of the project

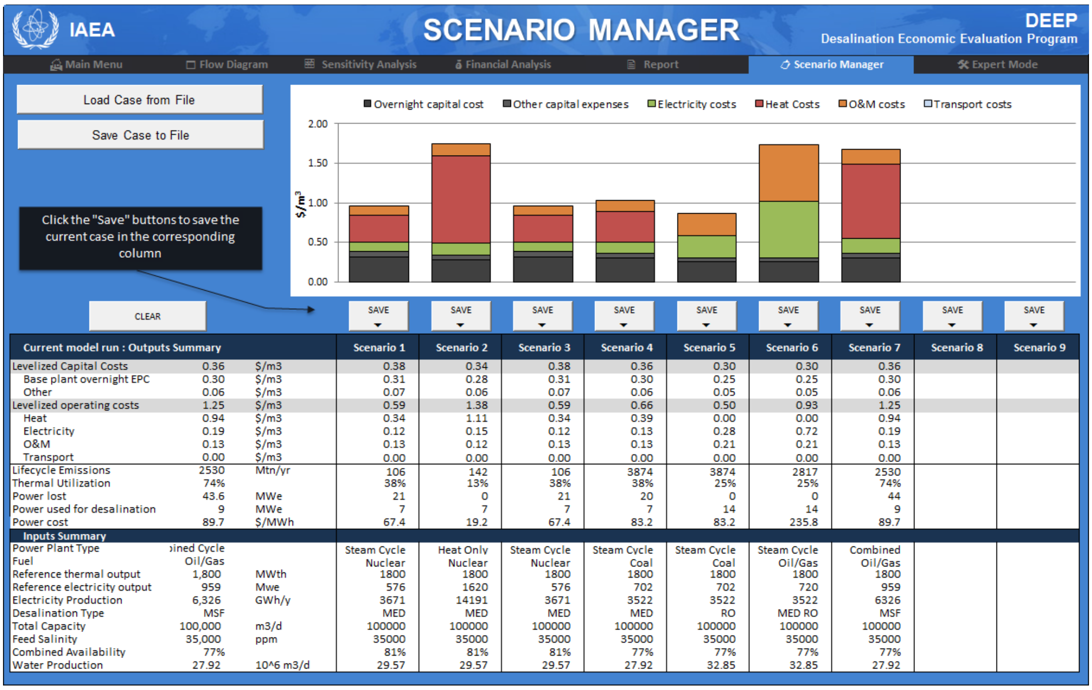
On the bottom left side of the screen the user can modify the most crucial economic parameter related to his case:

- Selling price of electricity and water
- Estimated lifetime of power and water plant
- Estimated construction time
- Percentage of debt related to total investment cost (without the financing costs). As an extreme case the following example is made.If the deb ration is 0%, it means that there is not loan and the whole project is financed with equity. If it is 100% then the whole project is financed through a loan
- Duration and interest rate of the loan

- Expected return of the equity, which is used for the calculation of the weighted average cost of capital and the net present value.
- Duration of depreciation of the assets, which is used for the estimation of the taxable income
- Tax rate applied on the taxable income
- Escalation factors that are applied above inflation. Usually this factor applies only on fuel.

Similar to the other screens any modification on the above parameters will immediately cause a recalculation of the model the update of the diagrams and results.

C.5. Compare cases



This screen offers the possibility to the user to store a temporarily case in order to compare it with another one. Once a case has been defined and customized from the first two steps as described above, the user can save its main results to a column in this screen by pressing the corresponding "*Save*" button. Then he can modify any parameters that he wants from the "Flow Diagram" screen, such as power plant or desalination plant type, capacities, temperatures etc. By returning to this screen and storing the results to another column he can directly compare these two cases. Alternatively, the current case can be saved into an external file (e.g AP1000MED.deep) which can be loaded again to DEEP either by this screen ("Load Case from file") or from the home page. The "*Clear*" button clears the information of all stored cases.

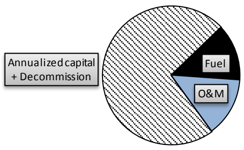
C.6. Export and inspect results

Summary of Cost Results

Project Name	DEEP v5 2013
Case Name	My Case
Discount rate	5%
Interest	5%
Fuel Escalation	2%

Power plant

Type	Steam Cycle - Nuclear
Reference thermal output	1052 MW(th)
Reference electricity output	336.64 MW(e)
Site Specific Electricity Production	2145 GWh/yr
Availability	90%



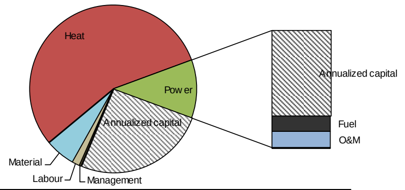
Capital Costs of Power Plant	Total (M$)	Specific($/kW)	Share
Overnight EPC costs	1,347	4,000	72%
Owners costs	135	400	7%
Contigency cost	-	-	0%
Interest during construction	192	571	10%
Decommissioning costs	202	600	11%
Total Capital Costs	1,875	5,571	
Annualized Capital Costs	99	294	
Sp. Annualized Capital Costs		0.046	

Operating Costs of Power Plant	Total (M$)	Specific ($/kWh)	Share
Fuel Costs	18	0.008	49%
Operation & Maintenance cos	19	0.009	51%
Carbon tax	-	-	0%
Annual Operating costs	37	0.017	

TOTAL ANNUAL COST	136	M$
Power Cost	**0.063**	**$/kWh**

Desalination plant

Type	MSF	
Total Capacity	154000 m^3/d	
Feed Salinity	35000 ppm	
Combined Availability	81%	
Water Production	45.53 M m^3/yr	
Power Lost	67.1 MW(e)	*Extraction of 819 MW at 75°C (Power lost ratio=8.2%)*
Power Used for desalination	14 MW(e)	



Capital Costs of Desalination Plant	*MSF*		*Total (M$)*	*Specific ($/m3 d)*	*Share*
Construction Cost	181	-	181	1,177	74%
Intermediate loop cost	-	-	-	-	0%
Backup Heat Source	-	-	-	-	0%
Infall/Outfall costs	-	-	12	77	5%
Water plant owners cost	9	-	9	59	4%
Water plant contingency cost	19	-	19	124	8%
Interest during Construction	22	-	22	145	9%
Total Capital Costs	232	-	244	1582	
Annualized Capital Costs			14		
Sp. Annualized Cap Costs				**0.31**	$/m3

Operating Costs of Desalination Plant	MSF		Total (M$)	*Specific ($/m3)*	Share
Energy Costs					
Heat cost	30		30	0.66	73%
Backup heat cost	-		-	-	0%
Electricity cost	6.1	-	6.1	0.13	15%
Purchased electricity cost	-	-	-	-	0%
Total Energy Costs	36	-	36	0.80	87%
Operation and Maintenance Costs				-	0%
Management cost	-	-	0.20	0.00	0%
Labour cost	-	-	0.80	0.02	2%
Material cost	3.2	-	3.2	0.07	8%
Insurance cost	1.0	-	1.0	0.02	3%
Total O&M cost	4	-	5	0.11	13%
Total Operating Costs	41	-	42	**0.91**	

Total annual cost	**55.52**	**M$**
Water production cost	1.219	$\$/m^3$
Water Transport costs	-	$\$/m^3$
Total water cost	**1.219**	$\$/m^3$

In this screen a report is generated showing the main results for the defined case. This report contains the most detailed cost breakdown of of both water and power costs. Two possibilities are given to the user by the buttons on the top of the screen:

- Print Report: A report that fits in three A4 sized papers is printed
- Export as PDF: A separate PDF file is created that can be stored separately and printed in a later time.

D. DEEP models (Calculation structure)

DEEP includes models for 8 power plants; 3 nuclear, 5 fossil, and 5 desalination plants; 2 thermal, one electrical and 2 hybrid (Table 1). There are 36 possible configurations between energy sources and desalination plants as formulated on equal numbered DEEP templates. DEEP input variables can be split in the following categories:

- User input data: Case specific input such as power and desalination plant capacity, discount rate, interest, fuel escalation etc.
- Technical parameters: Technology specific parameters such as efficiencies, temperature intervals etc. which depend only on the technology used and are subject to physical constraints
- Cost parameters: specific costs of various components (eg. construction, fuel etc), cost factors and other operational parameters (lifetime, availability etc).

Table 1: Power and desalination plants formulated in DEEP

Energy Sources		**Power**	**Heat**
NSC	Nuclear Steam Turbine (PWR,PWHR,SPWR)	✔	✔
NBC	Nuclear Gas Turbine (GTMHR)	✔	✔
NH	Nuclear Heat (HR)		✔
COAL	Steam Cycle – Coal (SSB)	✔	✔
OIL	Steam Cycle – Oil	✔	✔
GT	Gas Turbine/HRSG	✔	✔
CC	Combined Cycle (Steam Turbine – Gas Turbine)	✔	✔
FH	Fossil Heat (Boiler)		✔
Desalination Plants			
MED	Multi Effect Distillation	✔	✔
MSF	Multi Stage Flash	✔	✔
RO	Reverse Osmosis	✔	

The benefits of the coupling of an energy source and a desalination plant are shown by using the 'power credit' method. This method is based on the comparison between the proposed dual purpose plant and an imaginary reference single purpose plant. The cost of electricity delivered to the desalination plant, is valued based on the cost of that product from alternative imaginary power plant. The cost of heat is taken to be the revenue that would have accrued from lost electricity generation (due to the delivery of heat). As a result, water is credited with all of the economic benefits associated with the plant being dual purpose. For dual purpose heat only plants that are coupled with a thermal desalination process, the levelized (heat) energy costs are calculated with the same procedure as for single purpose electricity only plants. An option for fossil fueled-backup heat is also available so that heat can be provided for desalination even if the power plant is unavailable.

DEEP structure is presented in a modular form in Figure 1.

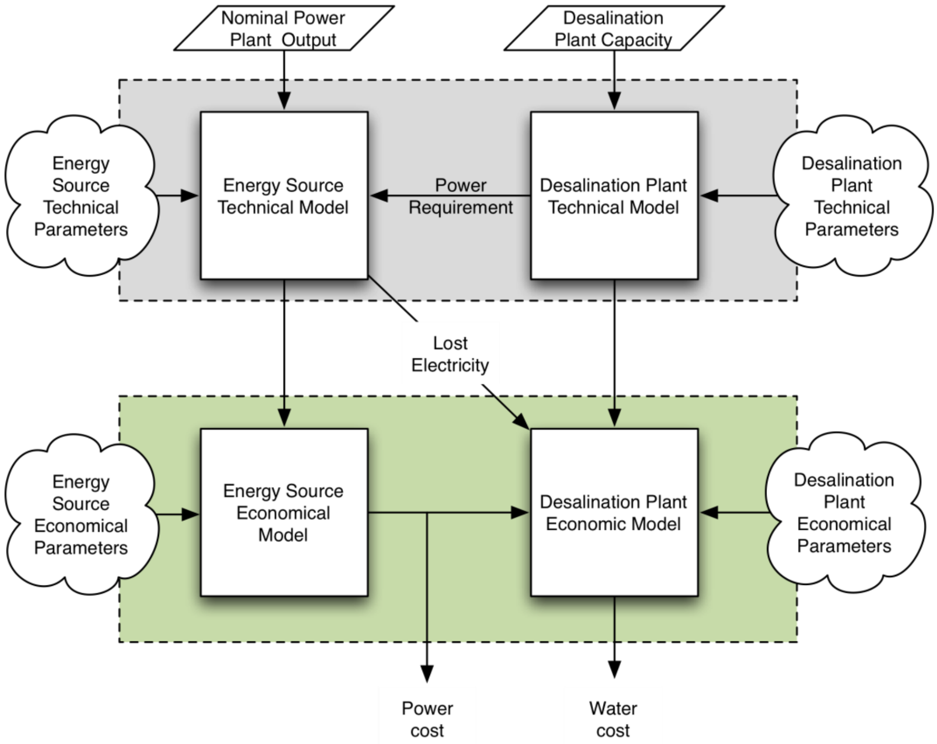


Figure 1 Modular Representation of DEEP software

D.1. Technical models

Technical models are based on simple thermodynamic cycle calculations and empirical expressions in order to estimate the required figures needed in the economic model.

D.1.1. Power Plant Model

The 9 energy sources that were formulated in previous DEEP versions can actually be simplified in the following three configurations:

1. Steam turbine plant: NSC, COAL, OIL, FH, RH
2. Gas turbine plant: NBC, GT
3. Combined Cycle (steam and gas) plant: CC

The structure and models are exactly the same for each one of the above categories and it is based on simple thermodynamic cycle calculations. A combination of a set of both technical and economic parameters is used to define a unique configuration. All parameters are user-adjustable and can be tuned in order to determine a specific case tailored in any user needs.

Steam-cycle based power plants (NSC, OIL, COAL)
Model Description

The thermodynamic performance of dual purpose steam-cycle based plants is modelled as follows:

1. Required power output (*Pen*) and thermal base plant (*Qtp*) are entered as inputs
2. The reject heat load of single purpose plant (*Qcr*) is calculated for the site specific average condensing temperature (*Tc*)
3. For the dual purpose plant the following figures are estimated:

    a. Required heat for the operation of the desalination plant with a capacity *Wdrc* and a max brine temperature
    b. Available reject heat in modified temperature level (*Tmb*) required for the desalination, assuming a hypothetical Carnot or Rankine cycle between *Tcm* and *Tc*
4. The lost work caused by the extraction of heat in a higher temperature is estimated as follows:
    a. With a back pressure turbine all the heat must be extracted in the new temperature level
    b. With an extraction/condensing turbine only the heat needed for the desalination plant is extracted in the new temperature level.
5. Lost electricity is equal to the electricity that could be produced if the heat extracted for the desalination plant would be extracted in the lowest available temperature (*Tc*).

Single Purpose Plant

$Peg = Pen + Pal$	Base power plant net output
$Qcr = Qtp - Peg$	Condenser reject heat load
$Tc = Tsw + Tca + Dtcr$	Average condensing temperature
$Fcc = \dfrac{Qcr}{Dtcr \cdot 4.187}$	Condenser cooling water flow
$Fte = \dfrac{Qcr}{2300}$	Turbine exhaust flow
$qcc = \dfrac{Fcc \cdot DPcp}{Ecp \cdot Eem \cdot 9866}$	Cooling water pump power

Concept of Power lost

The benefits of the coupling of an energy source and a desalination plant are shown by using the 'power credit' method. This method is based on the comparison between the proposed dual purpose plant and an imaginary reference single purpose plant. The cost of electricity delivered to the desalination plant, is valued based on the cost of that product from alternative imaginary power plant. The cost of heat is taken to be the revenue that would have accrued from lost electricity generation (due to the delivery of heat). As a result, water is credited with all of the economic benefits associated with the plant being dual purpose. For dual purpose heat only plants that are coupled with a thermal desalination process, the levelized (heat) energy costs are calculated with the same procedure as for single purpose electricity only plants. An option for fossil fueled-backup heat is also available so that heat can be provided for desalination even if the power plant is unavailable.

Shaft work that could be acquired by a theoretical cycle between the condensing temperature of the desalination plant (*Tcm*) and the lower available cooling temperature (*Tc*) is calculated as follows:

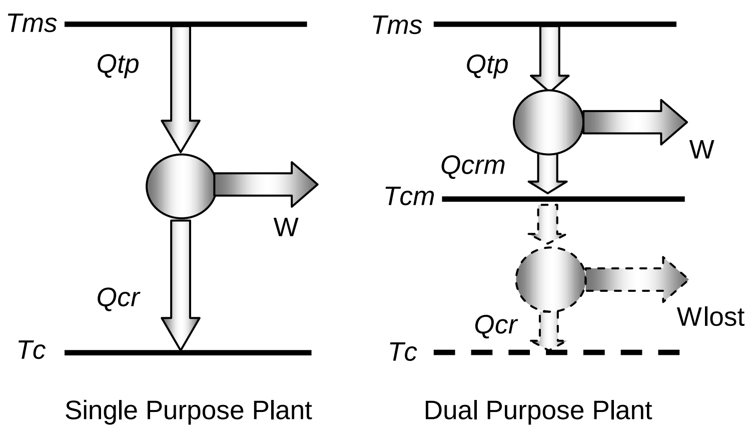


Figure 2 Comparison of heat engine analog between two plants

$$Qcrm = \frac{Qcr}{1-\eta}$$

$$Wlost = Qcrm \cdot \eta$$

For the **Carnot Cycle** efficiency is calculated by means of:

$$\eta = 1 - \frac{Tc}{Tcm}$$

For the **Rankine Cycle** efficiency is calculated by means of:

$$X = \frac{S_v(Tcm) - S_l(Tc)}{S_v(Tc) - S_l(Tc)}$$

$$H2 = H_l(Tc) + X \cdot \left(H_v(Tc) - H_l(Tc)\right)$$

$$\eta = \frac{H_v(Tcm) - H2}{H_v(Tcm) + H_l(Tc)}$$

Where *X* is the steam quality in turbine outlet, *Hv(T)* is the enthalpy of saturated vapour in temperature *T*, *Hl(T)* is the enthalpy of saturated liquid in temperature *T*, *Sv(T)* is the entropy of saturated vapour in temperature *T* and *Sl(T)* is the entropy of saturated liquid in temperature *T*.

For the **Carnot Cycle** efficiency is calculated by means of:

$$\eta = 1 - \frac{Tc}{Tcm}$$

For the **Rankine Cycle** efficiency is calculated by means of:

$$X = \frac{S_v(Tcm) - S_l(Tc)}{S_v(Tc) - S_l(Tc)}$$

$$H2 = H_l(Tc) + X \cdot \left(H_v(Tc) - H_l(Tc)\right)$$

$$\eta = \frac{H_v(Tcm) - H2}{H_v(Tcm) + H_l(Tc)}$$

Where *X* is the steam quality in turbine outlet, *Hv(T)* is the enthalpy of saturated vapour in temperature *T*, *Hl(T)* is the enthalpy of saturated liquid in temperature *T*, *Sv(T)* is the entropy of saturated vapour in temperature *T* and *Sl(T)* is the entropy of saturated liquid in temperature *T*.

According to the above the efficiencies of two cycles versus the temperature of the sink (cold) are presented in the following figures.

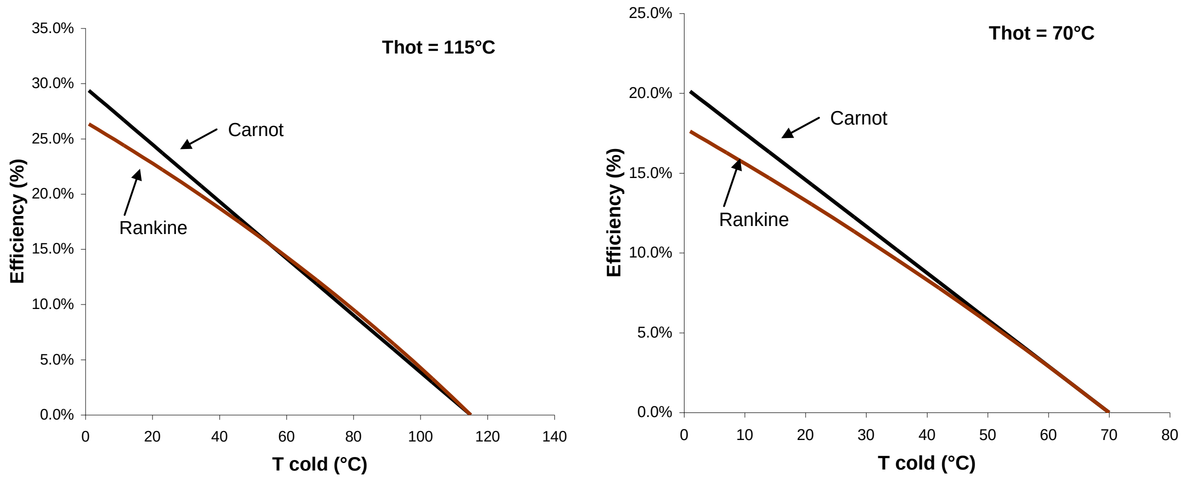


Figure 3 Efficiencies of theoretical cycles as calculated in DEEP

Gas-cycle based power plants (GT, NBC)

Gas cycle based power plant calculations are similar with the steam cycle, but Brayton cycle is supposed instead of Carnot (or Rankin). The following equations are used for the performance calculations of single purpose plants. Performance for dual purpose plants are calculated in the exact same way as steam plants. The only difference is that lost electricity is equal to zero. Gas turbine based plants are offering virtual free heat because the heat recovered could not be used for further extraction and electricity production.

Model Description

$Ebpgg = 34.205 - 0.024 \cdot Tair - 0.0007 \cdot Tair^2$	Gross efficiency of GT
$Texg = 528.9 + 0.725 \cdot Tair$	Exhaust gas temperature of GT
$Ebl = \begin{cases} \dfrac{Texg - 130}{Texg - Tair} & Tmb + DTht \leq 130 \\ \dfrac{Texg - Tmb - DTht}{Texg - Tair} & Tmb + DTht > 130 \end{cases}$	HSRG/Boiler Efficiency

Combined-cycle power plant (CC)

Model Description

$Ebpgg = 34.205 - 0.024 \cdot Tair - 0.0007 \cdot Tair^2$	Site specific gross efficiency of GT

$Ebl = \frac{Texg - 130}{Texg - Tair}$	Boiler/HRSG efficiency
$Qcr = Qtp \cdot (1 - (1 - Ebpgg) \cdot (1 - Ebl)) - Peg$	Condenser reject heat load
$Pegg = \frac{(134.44 - 0.786 \cdot Tair)}{123.4} \cdot Pen$	Output of gas turbines
$Pegs = Pen - Pegg$	Output of steam turbines

D.1.2. Desalination Model

The desalination plant model is formulated as follows: given a required plant capacity, water salinity and inlet temperature feed, estimate the thermal and electrical energy needs. The energy needs are used in the power plant model in order to estimate the lost electricity that is caused by the extraction of heat in a higher temperature.

Table 2

Desalination plant specifications		
Required desalination plant capacity	Wdrc	m3/d
Cooling Water Temperature	Tsd	°C
Total Dissolved Solids	TDS	ppm

Thermal Desalination (MED+MSF)

Model Description

This model describes the performance of a MED and MSF plant in terms of energy consumption. It is used to calculate the maximum water production capacity within a given temperature interval. It is based on an empirical calculation of GOR as a function of the effects.

Thermal desalination plants operate on a specific temperature range (*DTao*) that depends on the lower available water feed temperature (*Tsd*) and the selected maximum brine temperature (*Tmb*). Supposing a given minimum temperature interval (*DTae*) of operation for each effect the total effects (*Nemed*, *Ncmsf*) and the gain output ratio (*GOR*) can be calculated. The required heat (*Qdt*) and electricity (*Qdp*) can then be approached for given capacity (*Wdrc*). If thermal vapor compression is desired (TVC) then the user is asked also to enter the ratio of entrained vapor flow to motive steam flow (*Rtvc*). MED and MSF only differ in the calculation of GOR.

Table 3 : Process Model

$Tdc = DTdcr + Tsd$	Last stage temperature
$DTao = Tmb - Tdc$	

Multi Effect Distillation	Multi Stage Flash
$Nemed = \mathrm{TRUNC}\left(\frac{DTao}{DTae}\right)$	$Ncmsf = \mathrm{TRUNC}\left(\frac{DTao}{DTae}\right)$ $dTbh = DTao \frac{Njmsf}{Ncmsf + Njmsf}$ $dTbh(T,TDS) =$ $TDS \cdot (6.71 + 0.0634 \cdot T + 0.0000974 \cdot T^2) \cdot 10^{-6}$

$GOR = 0.8 \cdot Nemed \cdot (1 + Rtvc)$	$GOR = \frac{\Delta H(Tcm)}{Ch \cdot (dTbh + dTbe)} \cdot \left(1 - e^{\frac{cvm \cdot DTao}{\Delta H(\frac{Tmb+Tdc}{2})}}\right)$
$Qsdp = \begin{cases} 2 + 0.1 \cdot (GOR - 10) & \text{with TVC} \\ 2.5 + 0.1 \cdot (GOR - 10) & \text{without TVC} \end{cases}$	$Qsdp = 3.2 + 0.2(GOR - 8)$

$$Qdp = \frac{Wdrc}{24 \cdot 1000} \cdot Qsdp$$

$$Qdt = \frac{Wdrc}{GOR \cdot 24 \cdot 3600} \cdot \Delta H(Tcm)$$

$$Wbd = Wdrc \cdot (CF - 1)$$

$$Wfd = Wdrc \cdot CF$$

The parameters of the model along with their default values are presented in the following Table.

Table 4

Thermal Desalination Technical Data			*MED*	*MSF*
Max brine temperature	*Tmb*	°C	65	110
Difference between feed steam temp. and max brine temp.	*DT1s*	°C	5	5
Distillation plant condenser range	*DTdcr*	°C	10	10
Avg Temperature Drop between stages	*DTae*	°C	2.5	2.5
Concentration Factor	*CF*		2	2
Ratio for entrained vapour flow to motive steam flow (*TVC*)	*Rtvc*		1	-
Number of MSF reject stages (*MSF Only*)	*Njmsf*		-	3
Average brine specific heat capacity (*MSF Only*)	*cvm*	kJ/(kg K)	-	3.8
Specific Heat in Brine Heater (*MSF Only*)	*ch*	kJ/(kg K)	-	3.8
Interm. loop temperature drop	*DTft*	°C	10	10
Intermediate Loop Temperature Rise	*DTmcr*	°C	10	10
Intermediate Loop Pressure	*DPip*	bar	1	1
Intermediate Loop pump efficiency	*Eip*		0.85	

Reverse Osmosis (RO)

Model Description

DEEP Reverse osmosis model is used in order to estimate the total power use needed (*Qms*) for the desalination of a given capacity plant (*Wacs*). Power use depends on the power consumed on each high head, seawater pumping and booster pump minus the power recovered from the energy recovery device. Auxiliary flows depend on given efficiencies and given pressure drops or heads. High head pump pressure rise (DPhm) depends on the average osmotic pressure (Pavg) and the net driving pressure (NDP). The overall model is structured as follows:

$$Rr = 1 - \frac{0.00115}{P\max} \cdot TDS$$ Optimal Recovery Ratio

$$Wfm = \frac{Wacs}{Rr}$$ Feed Flow (m3/d)

$$Wbm = Wfm - Wacs$$ Brine Flow (m3/d)

$$Fsms = Wfm \cdot \frac{1000}{24 \cdot 3600}$$ Feed Flow (kg/s)

$$dso = \frac{TDS}{1-Rr}$$ Brine salinity (ppm)

$$dspms = 0.0025 \cdot TDS \cdot \frac{Nflux}{Dflux} \cdot 0.5 \cdot (1+\frac{1}{1\text{-}Rr}) \cdot (1+(Tim-25)\cdot 0.03)$$ Permeate Salinity (ppm)

$$\mathit{\Pi(C,T)} = 0.0000348 \cdot (Tim+273) \cdot C / 14.7$$ Osmotic pressure function (bar)

$$Pavg = \frac{\mathit{\Pi(TDS,Tim)} + \mathit{\Pi(dso,Tim)}}{2} \cdot kmAiiCF$$ Average osmotic pressure (bar)

$$kmTCF = \mathrm{EXP}\left(A \cdot (\frac{1}{Tim+273} - \frac{1}{25+273})\right)$$ Temperature correction factor

$$kmSCF = 1.5 - 0.000015 \cdot 0.5 \cdot (1+\frac{1}{1-Rr}) \cdot TDS$$ Salinity correction factor

$$NDP = \frac{Dflux}{Nflux \cdot kmSCF} \cdot NDPn \cdot \frac{kmTCF}{kmFF}$$ Design net driving pressure (bar)

$$Dphm = Pavg + NDP + \frac{DPspd}{2} + DPpp + DPps$$ High head pump pressure rise (bar)

$$Qhp = \frac{Fsms \cdot DPhm}{Ehm \cdot Ehhm \cdot 9866}$$ High head pump power (MW)

$$Qsp = \frac{Fsms \cdot DPsm}{Esm \cdot 9866}$$ Seawater pumping power (MW)

$$Qbp = \frac{Fsms \cdot DPbm}{Ebm \cdot 9866}$$ Booster pump power (MW)

$$Qom = \frac{Wacs \cdot Qsom}{24 \cdot 1000}$$ Other power (MW)

$$Qer = \begin{cases} -Fsms \cdot (1-Rr) \cdot Eer \cdot (DPhm - DPspd - DPcd) \cdot \dfrac{kmSGC}{10000} & PLT \\ -(1-Rr) \cdot Eer \cdot Qhp & Other \end{cases}$$ Energy Recovery(MW)

$$Qms = Qsp + Qbp + Qhp + Qer + Qom$$ Total power use (MW)

$$Qdp = \frac{Qms}{Wacs} \cdot 24 \cdot 1000$$ Specific power use (MW)

The parameters of the model along with their default values are presented in the following Table:

Table 5

Model Parameters			
Membrane Specifications			
Maximum design pressure of the membrane	*Pmax*	69	bar
Constant used for recovery ratio calculation	*Ccalc*	0.0012	-
Design average permeate flux	*Dflux*	13.6	l / (m2 h)
Nominal permeate flux	*Nflux*	27.8	l / (m2 h)
Polyamide membrane permeability constant	*A*	4200	-
Nominal net driving pressure	*NDPn*	28.2	bar
Fouling factor	*kmFF*	0.8	-
Aggregation of individual ions correction factor	*kmAiiCF*	1.05	-
Pump Data			
Pressure drop across the system	*DPspd*	2	bar
Permeate pressure losses	*DPpp*	1	bar
Pump suction pressure	*DPps*	1	bar
Concentrate discharge pressure	*DPcd*	0.5	bar
Seawater pump head	*DPsm*	1.7	bar
Booster pump head	*DPbm*	3.3	bar
Specific gravity of concentrate correction factor	*kmSGC*	1.04	-
High head pump efficiency	*Ehm*	85%	
Hydraulic pump hydraulic coupling efficiency	*Ehhm*	97%	
Seawater pump efficiency	*Esm*	85%	
Booster pump efficiency	*Ebm*	85%	
Energy recovery efficiency	*Eer*	95%	
Other specific power use	*Qsom*	0.4	kWh/m3

Discussion

The sensitivity of each parameter on the specific power requirements (*Qdp*) is shown on the following tornado plot (Figure 4 : Sensitivity Analysis of parameters for RO). By modifying each parameter by ± 10% from the default value of Table 5, we can see the impact on the energy consumption. The results are sorted from the most sensitive to the least sensitive parameter (for +10%).

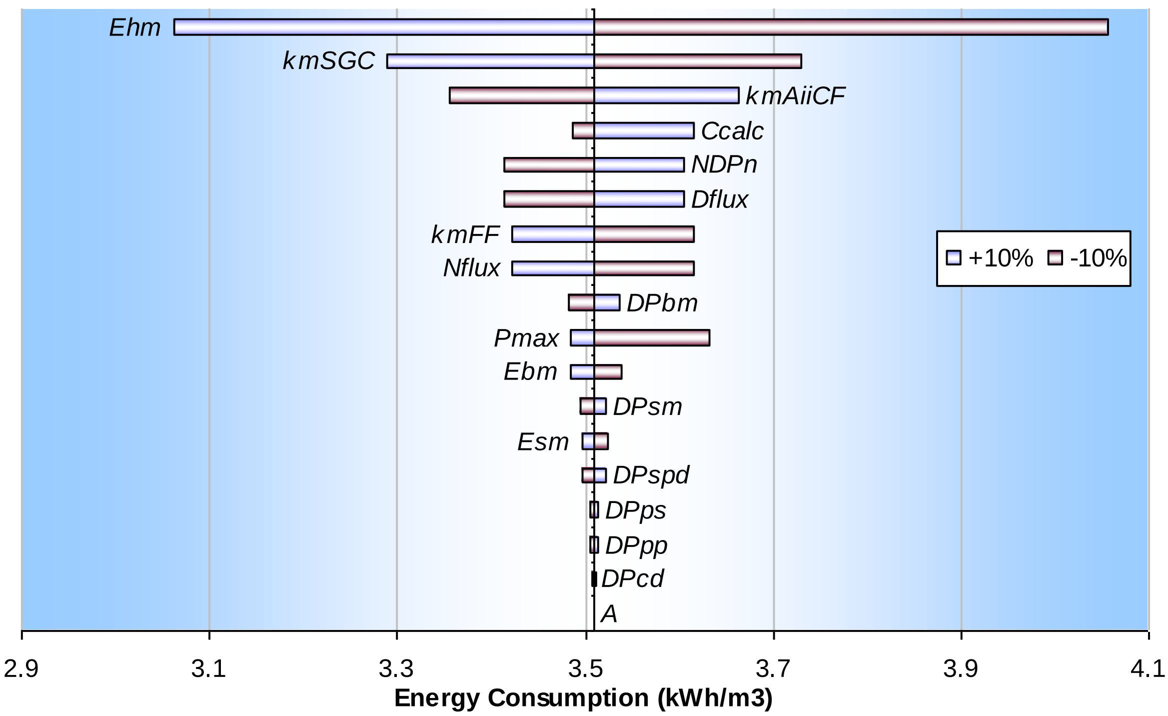


Figure 4 : Sensitivity Analysis of parameters for RO

The most important parameter is the high head pump efficiency, followed by correction or empirical factors for specific gravity, individual ions aggregation and optimal recovery ratio. This implies that the model is governed by empiricism that could lead to false estimations if the above parameters are modified arbitrarily without reflecting a realistic situation. The effect of pressure drops, pressure heads and pump efficiencies of auxiliary pumps is much smaller.

The effect of feed water temperature is also discussed. It has two contradicting effects:

- Rise of water temperature causes rise to its viscosity which facilitates its permeability through the membrane. This is expressed via an Arrhenius style equation of temperature correction factor (*kmTCF*), which 'corrects' the net driving pressure needed.
- Rise of water temperature causes rise of osmotic pressure which reduces the permeability of the water through the membrane. This is expressed via the theoretical osmotic pressure function and the assumption that the transmembrane osmotic pressure is the average of inlet and outlet osmotic pressure.

The high head pressure rise (*DPhm*) needed is the sum of the above effects: the average osmotic pressure, the 'corrected' net driving pressure and some fixed pressure drops and losses. The following figure shows the trade-offs as formulated in the model (default parameters are used).

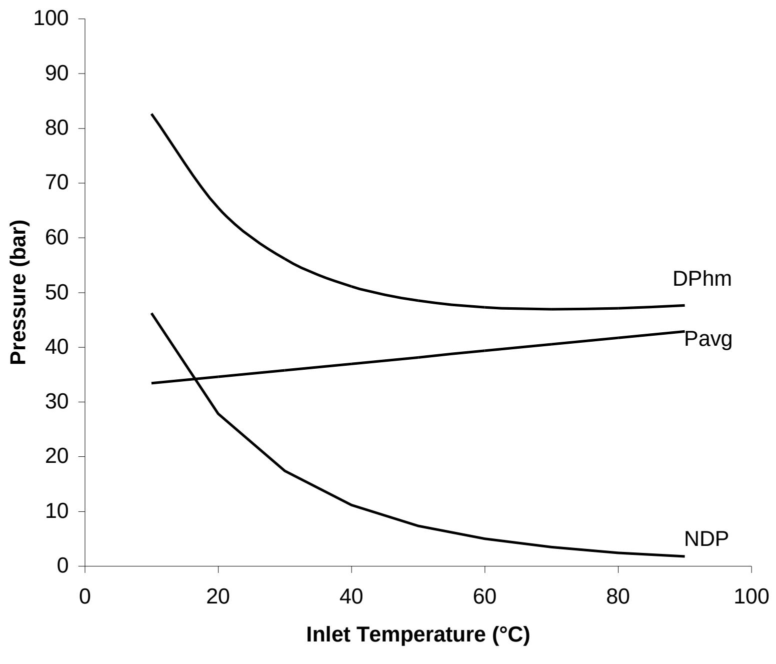


Figure 5: Effect of inlet temperature on pressure needed

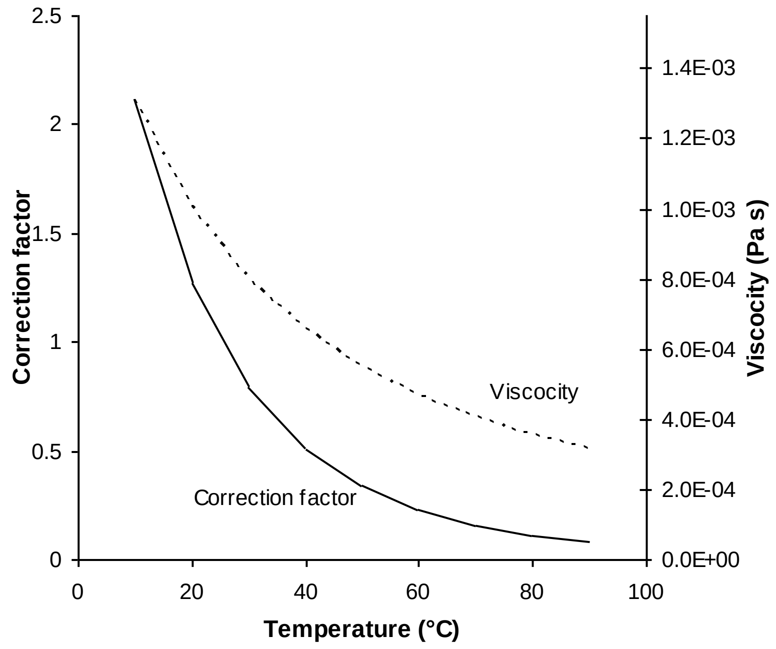
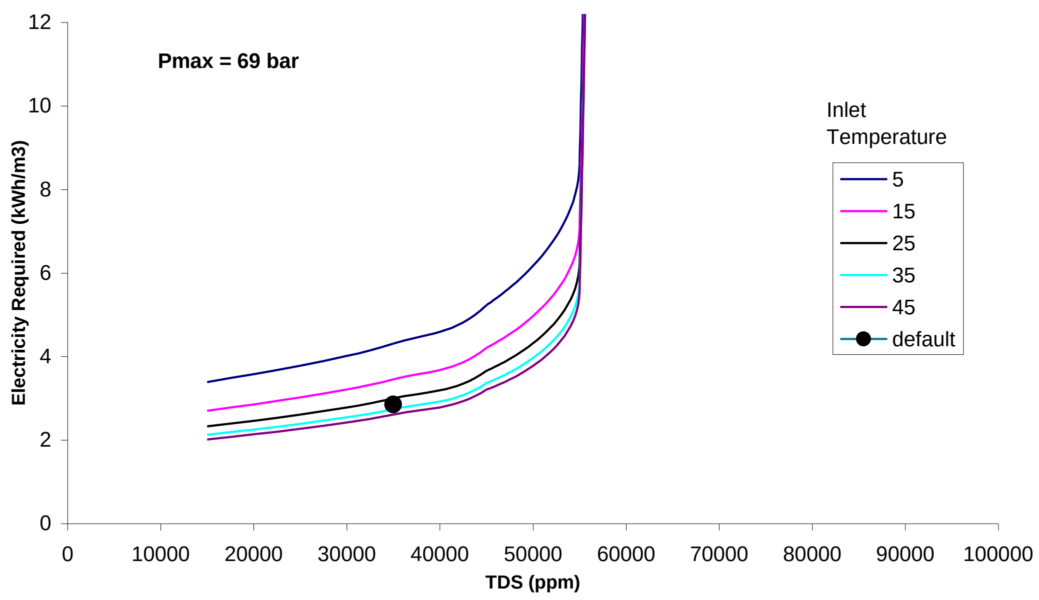


Figure 6 : Effect of temperature on the membrane permeability

Comparing the behaviour of the correction factor to the theoretical viscosity values, it is observed that indeed the correction factor and subsequently net design pressure is oversensitive to the temperature. The effect of feed water salinity is also discussed. The electricity consumption versus the feed water salinity is presented below for two membranes: One with *Pmax=69* bar (default) and one with *Pmax=85* bar.



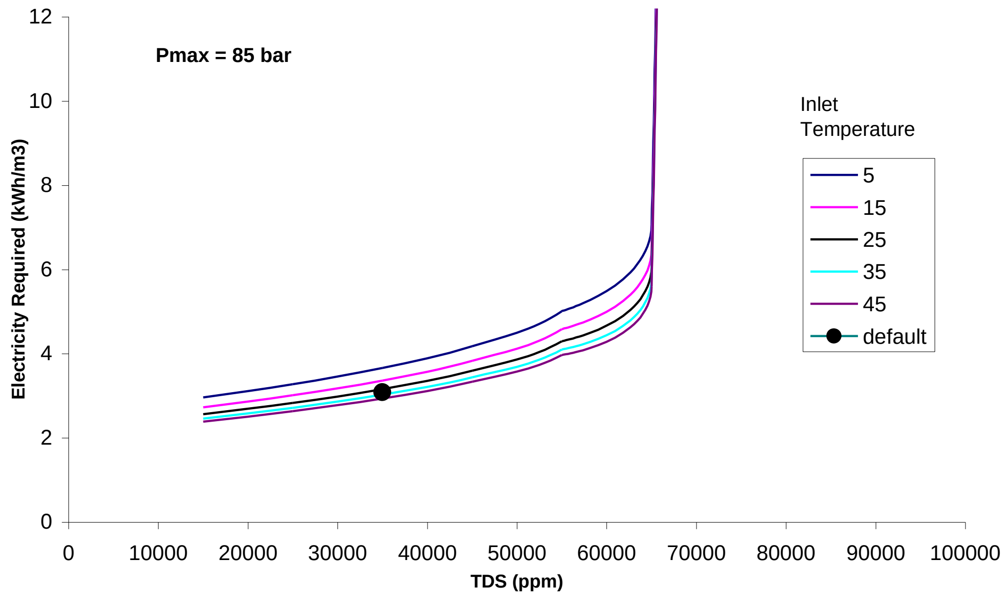


Figure 7 : Electricity requirement as a function of Total Dissolved Solids (TDS)

There seems to be an upper limit on feed water salinity that the system can desalinate which grows as a better membrane is used (larger maximum pressure allowable). This is expressed by an empirical relationship which correlates recovery ratio with feed water salinity for various maximum pressures and is illustrated below:

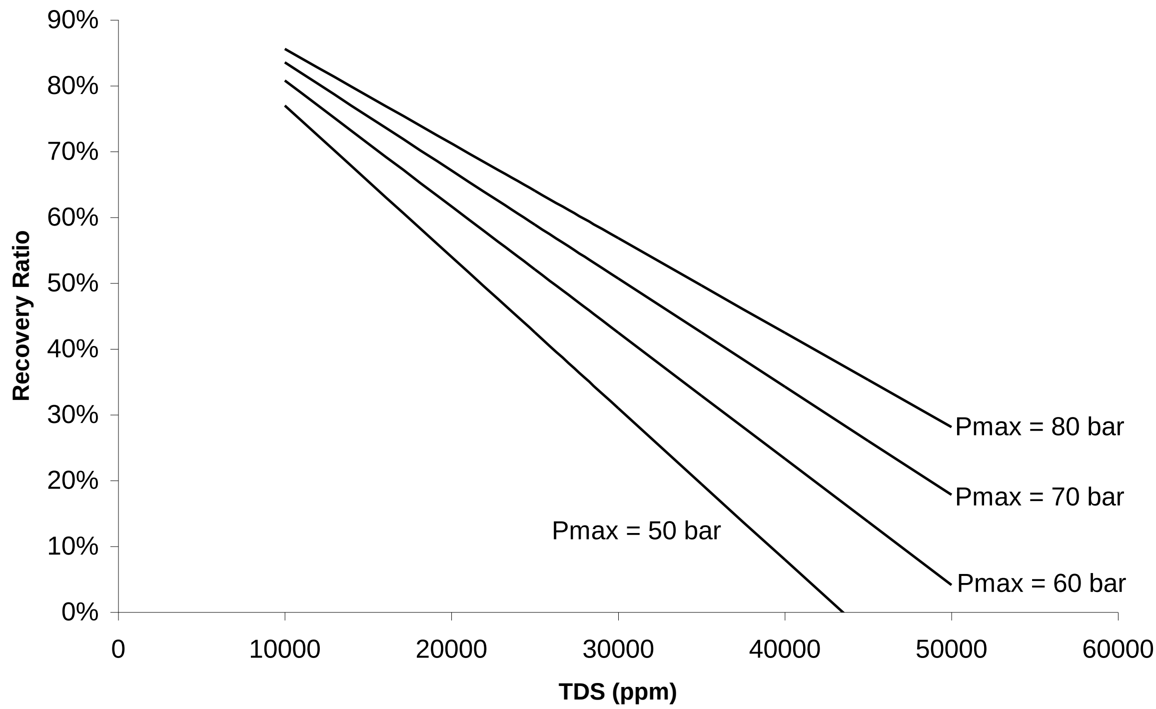


Figure 8 : Empirical approximation of recovery ratio versus feed salinity (TDS)

As recovery ratio tends to zero, energy needed tends to infinity. Thus, the theoretical feed salinity limit of each membrane described by its maximum pressure can be found by solving Eq (C.1) for $Rr=0$ and it is illustrated below.

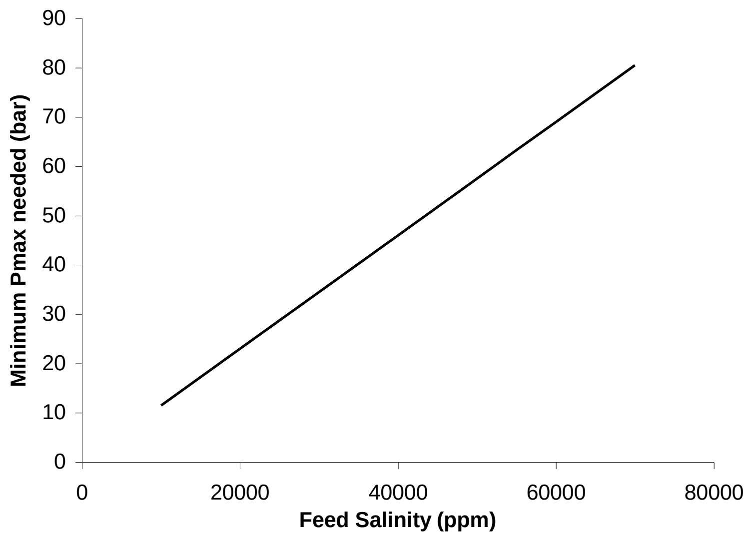


Figure 9 : Minimum pressure needed for RO as a function of feed salinity

The contours of energy cost as a function of TDS and pressure applied, having imposed the recovery ratio are presented below.

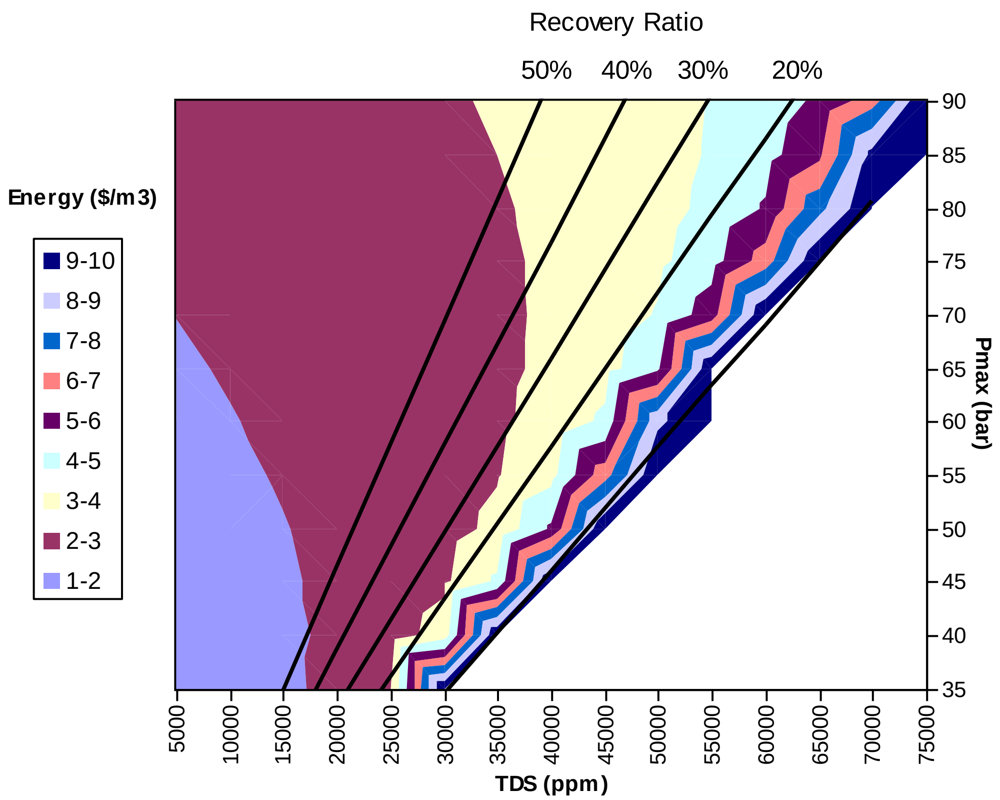


Figure 10 : Energy cost as a function of feed salinity and pressure applied

Hybrid Plants (MSF+RO, MED+RO)

The formulation of the hybrid plants i.e. one thermal and one electrical desalination plant, is actually the combination of the models having a separate feed. From a technical point of view the two plants operate completely independently and they do not interact (e.g. they do not use discharge of MED for RO, as documented)

D.2. Economic models

In this section the methodology for the economic evaluation of various desalination and energy source options is presented as modelled on DEEP software. The methodology includes simplified models of several types of nuclear/fossil power plants, and both distillation and membrane desalination plants.

A specific plant can be modelled by adjustment of input data including size, cost and performance data. Output includes the levelised cost of water and power and breakdowns of cost components of each selected component.

Sizing variables and other exogenous parameters, that characterize a specific case, are defined in the following table.

Case-specific Input		
Power Plant Capacity	*P*	MW
Water Plant Capacity	*Wacd*	m3/d
Interest	*ir*	%
Discount Ratio	*i*	%
Fossil fuel annual real escalation	*eff*	%
Currency reference year	*Ycr*	-
Initial year of operation	*Yi*	-

D.2.1. Economic Evaluation of Power Plant

All power plants have a similar way for the estimation of unit cost.

Costs involved in the economic evaluation of energy sources are summarized below:

- The plant construction cost: excluding site related cost, contingencies, escalation and interest during construction. This cost is also referred to as overnight construction cost. The specific cost is put in US $/kW(e) for power plants and US $/kW(th) for heating plants. For NPPs, this cost is the main contributor to the electricity generation cost.

- Additional site related construction cost: This may include additional estimated costs for site levelling, foundations, cooling water intake/outfall, special provisions for plant safety and environmental protection. This is usually a percentage of the above cost.

- Contingency factor: This factor reflects uncertainties of the construction cost estimate which are not known at the time of the estimate, including provisions for additional regulatory requirements and/or cost impacts from an extended construction period. The default contingency factor of 10% would apply to a proven power plant type and size to be constructed at a qualified site. It will have to be chosen considerably higher for innovative technologies and/or sites, which were not investigated in detail.

- Interest during construction: The time period between the first pouring of concrete and the start of commercial operation is the construction lead time. This time period depends strongly on the plant type, net output and site specific conditions. It could be about 12 months for a gas turbine plant and about 60 months for a medium or large size NPP. The construction lead-time is used to calculate the interest during construction (*IDCp*) and the real escalation of the fuel price.

- Decommissioning cost: This includes all costs for the dismantling of a nuclear plant and for management and disposal of the decommissioning waste.

- Fuel cost: For nuclear plants, this includes all nuclear fuel cycle costs, comprising uranium supply, enrichment, fuel fabrication and spent fuel management and disposal, in $/MW(e)・h (or $/MW(th)・h for heating plants).

- Specific O&M cost: This is the non-fuel operating and maintenance cost of the energy source, including staff cost, spare parts, external assistance, insurance cost, in \$/MW(e)・h (or \$/MW(th)・h for heating plants).

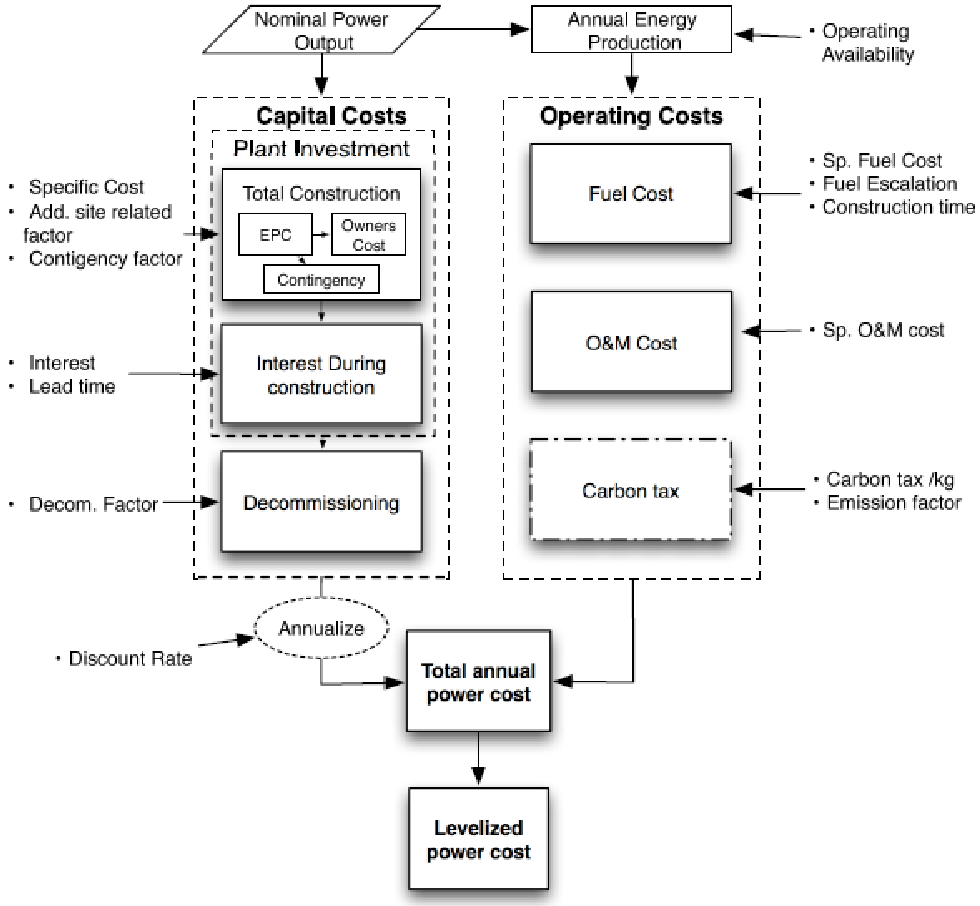


Figure 11: Cost Breakdown of power plant economic model

Capital Costs		**Operating Costs (Annual)**	
	Construction Costs	*afc*	Fuel Costs
Cecon	Add. Construction Costs	*aom*	Operation and Maintenance Costs
	Contingency Costs	*tct*	Carbon tax cost (*for fossil*)
IDCp	Interest during construction		
Cdec	Decommissioning Costs (*for nuclear*)		

All the technology-specific parameters needed for the economic model as well as their default values for each type of power plant type and fuel are in the following table[1]:

Table 6 Default parameters of all fuels and power plant types (SC = steam cycle, GC=gas cycle, CC=combined cycle, H=heat only)

			Nuclear				Oil/Gas				Coal	
POWER PLANT			**SC**	**GC**	**CC**	**H**	**SC**	**GC**	**CC**	**H**	**ST**	**H**
Operation and Performance Data												
Construction lead time	*Le*	m	60	24	24	40	36	24	24	18	48	18
Lifetime of energy plan	*Lep*	yr	60	40	40	60	35	25	25	35	35	35
Op Availability	*App*	%	90%	90%	90%	90%	85%	85%	85%	85%	85%	85%
Planned outage rate	opp	%	10%	10%	10%	10%	10%	10%	10%	5%	10%	5%
Unplanned outage rat	oup	%	11%	11%	11%	11%	11%	11%	11%	5%	11%	5%
Technology Efficiency	*Eb*	%	32%	42%	55%	90%	40%	34%	53%	90%	39%	90%
Specific CO2 Emmissio	*CO2e*	kg//kWh	0.029	0.029	0.029	0.01	0.8	0.65	0.4	0.5	1.1	0.6
Specific construction c	*Ce*	$/kW(e) or	4000	3500	4000	1300	2300	500	850	50	2500	50
Contruction cost scale	*Cen*	-	1	1	1	1	1	1	1	1	1	1
Specific fuel cost	*Csf*	$/MWh(e) c	5.9	6.0	4.5	3.3	121.4	80.3	51.3	54.0	25.44	11.0
Primary Fuel Price	*Cff*	$/(bbl or tn	1.9	2.5	2.5	3	80	8	8	80	75	75
Specific O&M cost	*Ceom*	$/MWh(e) c	8.8	12	12	2	3.3	6.6	5.5	1	3.5	1
Carbon tax	*ct*	$/t	0	0	0	0	0	0	0	0	0	0
Additional site related c	*DCr*	%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Energy plant contingen	*kec*	%	0	0	0	0	0	0	0	0	0	0
Nuclear plant decommi:	*kdcopp*	%	15%	15%	15%	15%						

Capital Cost

First, the construction cost *Cecon* (in M$) is calculated from the given specific construction cost (*Cets*) (in $/kW(e)), site related cost, unit net output and number of units. Then, the interest during construction (*IDCp*) is calculated with an approximative formula. For the approximation, it is assumed that the total construction costs are spent at mid-time of the construction period. Since the construction period *Le* is put in months, and the interest rate on an annual basis, *Le* is divided by 24 in the formula.

The *IDCp* is then added to the total construction cost for obtaining the total plant investment *Ceinv*. The fixed charge rate (capital recovery factor) *lfc* is calculated from the interest/discount rate *i* and the plant economic life *Lep*. This fixed charge rate is multiplied by the total plant investment to obtain the annual levelised capital cost *alcc*. In case of nuclear power plant decommissioning costs are added to the plant annualized capital cost.

Energy Source Capital Costs Calculations

$Cets = Ce \cdot (1 + DCr) \cdot (1 + kec)$	Specific construction cost	(B.1)
$Cecon = P \cdot Cets$	Construction cost	(B.2)
$IDCp = Cecon \cdot \left((1+ir)^{\frac{Le}{24}} - 1 \right)$	Interest during construction	(B.3)

[1] WNA (2010), The Economics of Nuclear Power
EIA (2010), Annual Energy Outlook 2011
Du and Parsons, (2009), Update on the cost of Nuclear Power, EIA, Annual Energy Outlook
MIT, (2009), Update of the MIT 2003 Future of Nuclear Power Study
Economic Modelling Working Group (EMWG) of the GIF (2007), Cost Estimating Guidelines for Generation IV nuclear energy systems Rev 4.2
Global Water Intelligence (2010), Desalination Markets 2010 : Global Forecasts and analysis
Global Water Intelligence (2011), IDA Desalination Plant Inventory

$Ceinv = Cecon + IDCp$	Total plant investment	(B.4)
$Cdec = kdcopp \cdot Ceinv$	Decommissioning Costs	(B.5)
$lfc(i,n) = \dfrac{i \cdot (1+i)^n}{(1+i)^n - 1}$	Capital recovery factor function	(B.6)
$alcc = Ceinv \cdot lfc(i, Lep)$	Annualized capital cost	(B.7)
$adec = kdcopp \cdot alcc$	Annualized decommissioning cost	(B.8)

Operating Costs

The fuel price per end-use energy produced is dependent on the efficiency of the power plant and the primary fuel price Eq. (B.9).

$$C_{sf} = \begin{cases} \dfrac{C_{ff}}{Eb \cdot 6500 \cdot 4.1868} \cdot 3600 & \text{COAL} \\ \dfrac{C_{ff}}{Eb \cdot 1.6471} & \text{OIL, GT, CC} \\ \dfrac{C_{ff}}{13 \cdot 1055} \cdot 3600 & \text{RH} \\ \dfrac{C_{ff}}{1.6471} & \text{FH} \\ C_{ff} \; * & \text{NSC, NBC} \end{cases} \qquad \text{Specific fuel cost} \qquad \text{(B.9)}$$

**For nuclear power plants Csf is an input; no calculations based on primary fuel are made.*

Availability of the plant (*App*) is calculated by planned (*opp*) and unplanned (*oud*) outage rate of the plant. The energy produced per year (*adpr*) can then be estimated.

The fuel cost levelisation factor (*lff*) is defined as the ratio of the present values of the lifetime fuel costs, including real escalation, and the unescalated lifetime fuel costs. It is calculated from the real escalation rate of the fuel price, the real interest rate *i*, the initial year of operation and the economic life of the power plant.

The levelised cost (either electricity or heat) is calculated on an annual basis by summing up the levelised capital cost, levelised decommissioning cost (if applicable), levelised fuel and O&M cost. The total of these costs, i.e. the (levelised) annual required revenue (in M$/a), is divided by the annual energy generation (*lpc*, in kWh(e) or kWh(t)) of the base power plant.

Power Plant Operating Costs calculations

$App = (1 - opp)(1 - oup)$	Operating Availability
$adpr = P \cdot 8760 \cdot App$	Annual electricity production
$lff(i,n) = (1+eff)^{Yi-Ycr} \cdot \dfrac{lfc(i,n)}{\dfrac{1+i}{1+eff} - 1} \cdot \left(1 - \left(\dfrac{1+eff}{1+i}\right)^n\right)$	Fuel levelisation factor

$afc = Csf \cdot adpr \cdot lff\,(i, Lep)$	Annual fuel cost
$aom = Ceom \cdot adpr$	Annual O&M cost
$tct = ct \cdot CO2e \cdot P \cdot 8760$	Total carbon tax

Power Plant Total annual costs

$arev = alcc + adec + afc + aom + tct$	Total annual cost ($)
$lpc = arev / adpr$	Levelised power cost ($)
$slcc = alcc / adpr$	Sp. levelised capital cost ($)
$sfc = afc / adpr$	Sp. fuel cost ($)
$som = aom / adpr$	Sp. O&M cost ($)
$sdec = adec / adpr$	Sp. levelised decommissioning cost ($)

D.2.2. Economic Evaluation of Water Plant

Costs involved in the economic evaluation of energy sources (along with their variables names) are summarized below:

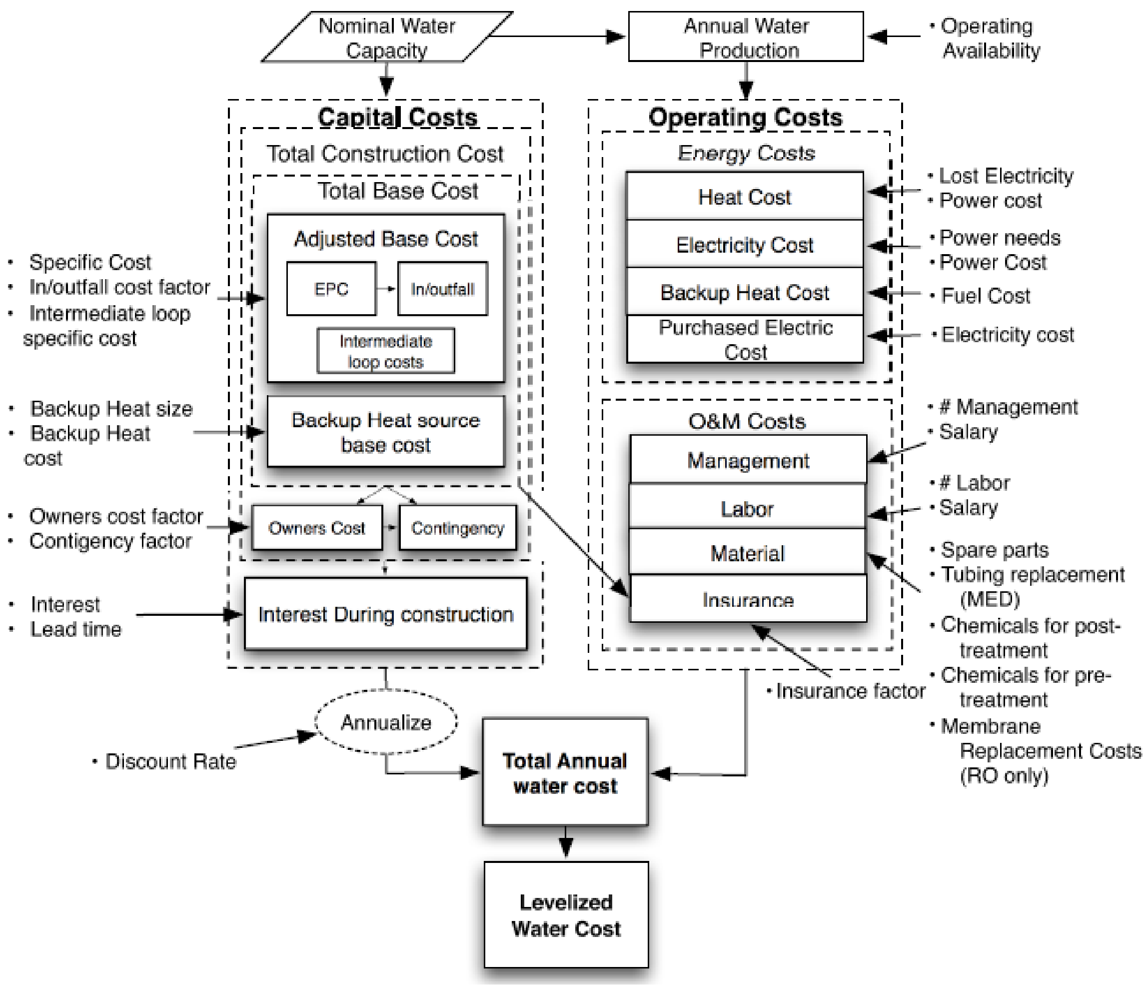


Figure 12 : Cost Breakdown of desalination plant economic model

Capital Costs			**Operating Costs (Annual)**	
Specific ($/capacity)	Total ($)		Energy Costs ($/yr)	
Cdu	*Cda*	Construction Costs	*adhc*	Heat Cost
Cdio		In/Outfall costs	*adpc*	Power Cost
Cinl		Intermediate loop costs (for nuclear source)	*adfbh*	Backup Heat Cost
Cbu	*Cbh*	Backup Heat (*for thermal plant*)	*adepu*	Purchased Power Cost
	DCdo	Water plant owners cost	O&M Costs	
	DCdc	Water plant contingency cost	*Cdm*	O&M Management
	IDCd	Interest during Construction	*Cdl*	O&M Labour
			Cdmt	O&M Material
			Cdins	O&M Insurance

Distillation plants

For dual purpose power plants, the levelised electricity cost (*lpc*, as calculated above) is used to calculate the energy cost *adhc* of the water plant by multiplying the sum of lost electricity generation *Qle* and the water plant electricity use by the electricity generation cost of the base power plant. This method is also referred to as power credit method by which full credit is given to the electricity generation cost, and the thermodynamic and cost benefit of combined production is given to the water production.

At heating plants, the energy cost of the water plant is the levelised heat cost as defined above.

If a backup heat source was specified, the backup heat cost is calculated from the levelised fuel cost (fuel price times levelisation factor, which accounts for real escalation), the backup heat source capacity and the backup heat source load factor.

The water production costs are then calculated by dividing the annual required revenue attributable to water production by the annual water production. The annual required revenue consists of the levelised annual capital cost and O&M cost of the water plant as well as the energy cost of the water plant including the backup heat cost, as defined above.

Economic calculations for both types of thermal desalination plants are similar.

All the technology-specific parameters needed for the economic model as well as their default values for each type of energy source are summarized below:

Table 7

Model Parameters				MED	MSF	RO
Operation and Performance Data	MSF,MED	RO	Units			
Water plant lead time	*Ld*	*Lm*	m	12	12	12
Lifetime of water plant	*Lwp*	*Lwp*	yr	20	20	20
Lifetime of Backup Heat	*LBK*	-	yr	20	20	-
Water plant operating availability	*Adp*	*Amp*	%	90%	90%	90%
WP Planned outage rate	*opd*	*opm*	%	3.0%	3.0%	3.2%
WP Unplanned outage rate	*oud*	*oum*	%	6.5%	6.5%	6.0%
Backup Heat unplanned outage rate	*oub*	-	%	0%	0%	-
Management Personnel *	*Ndm*	*Nmsm*	#	3	3	3
Labor Personnel *	*Ndl*	*Nmsl*	#	23	23	23
Cost Data						
Base Unit Cost	*Cdu*	*Cmu*	$/(m3/d)	900	1000	900
Backup heat source	*Cbu*	-	$/MW(t)	55000	55000	-
IL specific cost *	*Cinl*	-	$/(m3/d)	0	0	-
Fossil fuel price for BH	*Cffb*	-	$/bbl	20	20	-
Purchased Power Cost	*Cpe*	*Cpe*	$/kWh	0.06	0.06	0.06
Management Salary	*Sdm*	*Smm*	$	66 000	66 000	66 000
Labor Salary	*Sdl*	*Sml*	$	29 700	29 700	29 700
Specific O&M spare parts cost	*csds*	*cmsp*	$/m3	0.03	0.03	0.04
Tubing replacement cost (LT- MED)	*cdtr*	-	$/m3	0.01	-	-
Specific O&M chemicals cost for pre-treatment	*cdcpr*	*cmcpr*	$/m3	0.03	0.03	0.03
Specific O&M chemicals cost for post-treatment	*cdcpo*	*cmcpo*	$/m3	0.02	0.02	0.01
O&M membrane replacement cost (RO)	-	*cmm*	$/m3	-	-	0.07
Unit size correction factor	*kdus*	*kmsus*	%	1	1	1
In/outfall sp. Cost factor	*Csdo*	*Csmo*	%	7%	10%	7%
Water plant owners cost factor	*kdo*	*kmo*	%	5%	5%	5%
Water plant cost contingency factor	*kdc*	*kmc*	%	10%	10%	10%
Water plant O&M insurance cost	*kdi*	*kmi*	%	0.5%	0.5%	0.5%

Technical data, such as required equipment capacity derived from the thermodynamic calculation module of DEEP are as follows:

Technical Parameters		
Lost Electricity Production	*Qle*	MW
Power Use *	*qdi*	MW(e)
Intermediate loop pumping power	*qil*	MW(e)
Backup heat source size	*Bhs*	MW(t)

*All variables noted with a * can be also estimated by empirical relationships (see Annex).*

Capital Cost

Water Plant Capital Costs Calculations

$Cdio = Csdo \cdot Cdu$	In/Outfall specific cost
$Cdst = Cdu \cdot kdus + Cdio + Cinl$	Total specific base cost
$Cda = Wacd \cdot Cdst$	WP adjusted Base cost
$Cbh = Cbu \cdot Bhs$	Backup heat source base cost
$Cdt = Cda + Cbh$	Total WP base cost
$DCdo = Cdt \cdot kdo$	WP owners cost
$DCdc = (Cdt + DCdo) \cdot kdc$	WP contingency cost
$Cdcon = Cdt + DCdo + DCdc$	WP total construction cost
$IDCd = Cdcon \cdot \left((1+ir)^{\frac{Ld}{24}} - 1 \right)$	Interest during construction
$Csinv = Cdcon + IDCd$	Total investment
$adfc = Csinv \cdot lfc(i, Lwp)$	Annual WP fixed charge

Operating Cost

Water Plant Operating Costs calculations

Availability Calculations

$Adp = (1 - opd)(1 - oud)$	WP operating availability
$Ahs = \begin{cases} 1 - (1 - App) \cdot oub & \text{Backup heat} \\ App & \text{No backup heat} \end{cases}$	(Combined) Heat source availability
$Apd = Adp \cdot Ahs$	Total water production availability
$Wpd = Wacd \cdot Apd \cdot 365$	Total water production
$Acpd = \begin{cases} App \cdot (1 - oud) & \text{Backup heat} \\ Apd & \text{No backup heat} \end{cases}$	WP Load factor
$Abh = Apd - Acpd$	BH Load Factor

Energy Cost Calculations	
$efbh(i,n) = (1+effb)^{Yi-Ycr} \cdot \dfrac{lfc(i,Lep)}{\dfrac{1+i}{1+effb}-1} \cdot \left(1-\left(\dfrac{1+effb}{1+i}\right)^n\right)$	Fuel levelization factor
$adhc = \begin{cases} arev & \text{, Heat only power plant} \\ Qle \cdot Acpd \cdot 8760 \cdot lpc \end{cases}$	Heat Cost
$adfbh = Bhs \cdot 8760 \cdot Abh \cdot Cffb \cdot \dfrac{efbh(i,LBK)}{1.6471}$	Backup Heat Cost
$adpc = \begin{cases} 0 & \text{, Heat only power plant} \\ (qdi+qil) \cdot Acpd \cdot 8760 \cdot lpc \end{cases}$	Electric Cost
$adepu = (qdi+qil) \cdot Abh \cdot 8760 \cdot Cpe$	Purchased Electric Cost
O&M Cost Calculations	
$Cdm = Ndm \cdot Sdm$	Management cost
$Cdl = Ndl \cdot Sdl$	Labour cost
$Cdmt = (csds+cdtr+cdcpr+cdcpo) \cdot Wpd$	Material cost
$Cdins = kdi \cdot Cdt$	Insurance cost
$Cdom=Cdm+Cdl+Cdmt+Cdins$	Total O&M cost

Water Plant Total annual Cost	
$adrev=adfc+adhc+adfbh+adepc+adepu+Cdom$	Total annual cost
$sdfc=adfc/Wpd$	Sp. WP capital cost
$sddc=(adhc+adfbh)/Wpd$	Sp. WP heat cost
$sdepc=adepc/Wpd$	Sp. WP electricity cost
$sdepu=adepu/Wpd$	Sp. WP purchased electricity cost
$sdoamc=Cdom/Wpd$	Sp. WP O&M cost
$Wdt=adrev/Wpd$	Water production cost

RO plant

The economic evaluation of the RO plant is similar to the procedure for the distillation plant. It is less complex since there is no heat cost and there is no backup heat source, but the electricity consumption and cost are higher than those of distillation plants are.

The annual required revenue of the RO plant is calculated by summing up the levelised annual capital cost and O&M cost of the water plant as well as the electricity cost, which is calculated from the electricity use of the RO plant and the levelised electricity cost (lpc). The water production cost is then calculated by dividing the annual required revenue by the annual water production. The economic calculations are exactly the same as in distillation plants, but in DEEP different variables names are used.

Water production costs of both distillation plant and RO plant: these costs include all costs attributable to water production, but exclude costs of

- water storage,
- transportation,
- distribution.

Hybrid plant

The total cost of water produced by hybrid desalination plants, i.e. the combination of a distillation and a RO plant, is based mostly on the individual costs of each plant. However, capital Costs are reduced because of the the synergy of in/outfall and the need for less personnel. Personnel are calculated on total capacity basis and not for each individual plant.

$Wph = Wpd + Wpms$	Total water production	
$ahfc = adfc + amsfc$	WP capital cost (annualized)	(C.)
$ahhc = adhc + adfbh *$	WP heat cost	(C.)
$ahepc = adepc + amsepc$	WP electric cost	(C.)
$ahepu = adepu + amsepu$	WP purchased electricity cost	(C.)
$Chom = Cdom +$	WP O&M cost	(C.)
$ahrev = ahfc + ahhc + ahepc + ahepu + Chom$	Total annual specific cost	(C.)

E. Index of variables

A	Polyamide membrane permeability constant
Adp	Water plant operating availability (MSF,MED)
Amp	Water plant operating availability (RO)
App	Op Availability
Cbu	Backup heat source unit cost
Ccalc	Constant used for recovery ratio calculation
cdcpo	Specific O&M chemicals cost for post-treatment
cdcpr	Specific O&M chemicals cost for pre-treatment
cdtr	Tubing replacement cost (LT- MED)
Cdu	Base Unit Cost
Ce	Specific construction cost
Ceom	Specific O&M cost
CF	Concentration Factor
Cff	Primary Fuel Price
Cffb	Fossil fuel price for BH
ch	Specific Heat in Brine Heater (MSF Only)
Cinl	Intermediate loop specific cost *
CO2e	Specific CO2 Emmissions
Cpe	Purchased Power Cost
Csdo	In/outfall sp. Cost factor
csds	Specific O&M spare parts cost
Csf	Specific fuel cost
ct	Carbon tax
cvm	Average brine specific heat capacity (MSF Only)
DCr	Additional site related construction cost factor
Dflux	Design average permeate flux
DPbm	Booster pump head
DPcd	Concentrate discharge pressure
DPcp	Condenser cooling water pump head
DPip	Intermediate Loop Pressure
DPpp	Permeate pressure losses
DPps	Pump suction pressure
DPsm	Seawater pump head
DPspd	Pressure drop across the system
dsd	Product water TDS
DT1s	Difference between feed steam temp. and max brine temp.
DTae	Avg Temperature Drop between stages
Dtcr	Condenser range
DTdcr	Distillation plant condenser range
DTft	Interm. loop temperature drop
DTht	Approach in HRSG
DTmcr	Intermediate Loop Temperature Rise
Eb	Technology Efficiency
Ebm	Booster pump efficiency
Ecp	Condenser cooling water pump efficiency
Eem	Electric motor efficiency
Eer	Energy recovery efficiency
EerType	Energy Recovery Type
eff	Annual fuel real escalation
effb	Fossil fuel real escala. for backup heat source
Eg	Generator efficiency
Ehhm	Hydraulic pump hydraulic coupling efficiency
Ehm	High head pump efficiency
Eip	Intermediate Loop pump efficiency
Esm	Seawater pump efficiency
Etm	Turbine mechanical efficiency
Fal	Factor Auxiliary Loads
hlpt	Low Pressure turbine isentropic efficiency

i	Discount rate
ir	Interest rate
kdc	Water plant cost contingency factor
kdcopp	Nuclear plant decommissioning cost factor
kdi	Water plant O&M insurance cost
kdo	Water plant owners cost factor
kdus	Unit size correction factor (MSF,MED)
kec	Energy plant contingency factor
kmAiiCF	Aggregation of individual ions correction factor
kmFF	Fouling factor
kms	Pipeline system length
kmSGC	Specific gravity of concentrate correction factor
kmSGW	Specific gravity of seawater feed correction factor
kmsus	Unit size correction factor (RO)
LBK	Lifetime of Backup Heat
Ld	Water plant lead time (MSF,MED)
Le	Construction duration
Lep	Lifetime of energy plant
Lm	Water plant lead time (RO)
lmp	Pipeline construction lead time
Lwp	Lifetime of water plant
lwpp	Pipeline system operation lifetime
mwep	Pipeline system pumping requirements
NDPn	Nominal net driving pressure
Nflux	Nominal permeate flux
Njmsf	Number of MSF reject stages (MSF Only)
oicp	Other investment costs
omp	Pipeline system O&M cost
oomp	Annual material costs
opd	WP Planned outage rate (MSF,MED)
opm	WP Planned outage rate (RO)
opp	Planned outage rate
oub	Backup Heat unplanned outage rate
oud	WP Unplanned outage rate (MSF,MED)
oum	WP Unplanned outage rate (RO)
oup	Unplanned outage rate
Pmax	Maximum design pressure of the membrane
Qsom	Other specific power use
Qtp	Thermal power
Rtvc	Ratio for entrained vapour flow to motive steam flow (TVC)
sccp	Pipeline system construction cost
Sdl	Labor Salary (MSF, MED)
Sdm	Management Salary (MSF, MED)
Sml	Labor Salary (RO)
Smm	Management Salary (RO)
Tair	Air temperature
Tca	Condenser approach temperature
ThRo	Thermal/RO ratio
Tht	Exhaust gas temperature of HRSG
Tim	Feed water inlet temperature at RO element entry
Tmb	Max brine temperature
Tms	Main steam temperature
Tsd	Cooling Water Temperature
Tsw	Average annual cooling water temperature

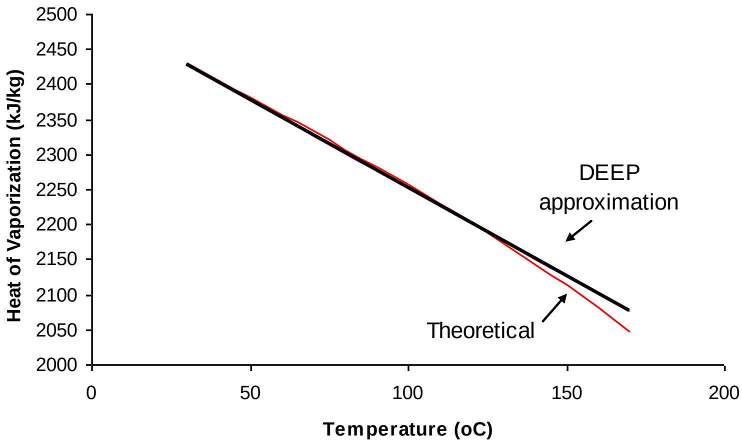
Appendix

Enthalpy/Entropy and Heat of vaporization estimations

The following linear approximation is used throughout DEEP:

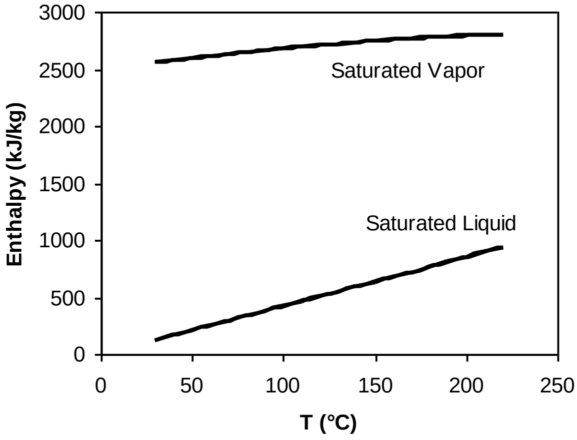
$$\Delta H(T) = (598 - 0.6 \cdot T) \cdot 4.1868$$

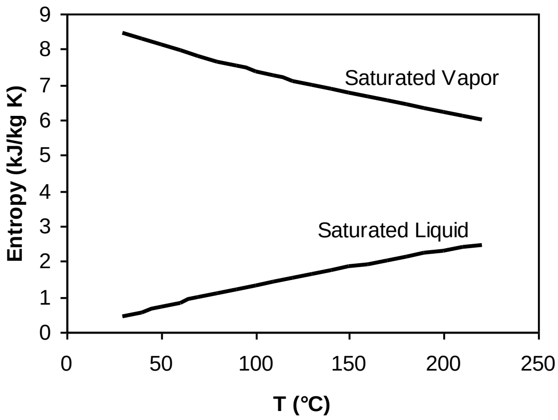
The above approximation along with real steam table data is presented below:



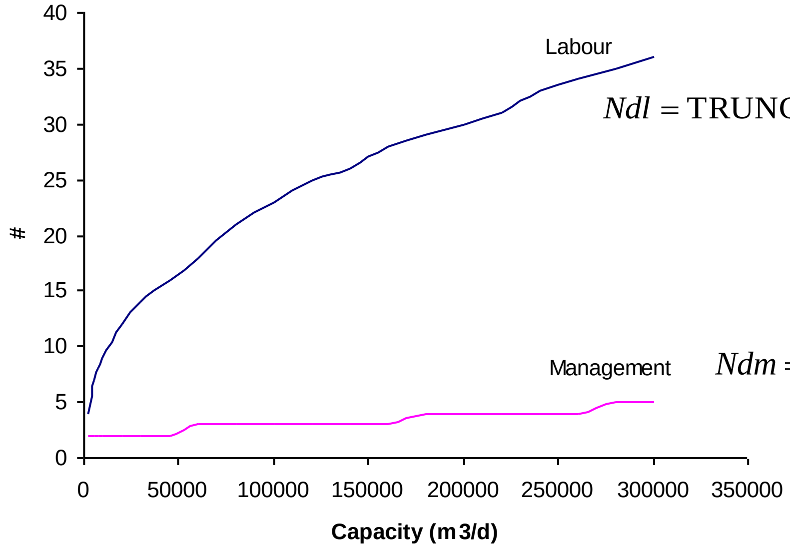
This approximation appears to be accurate for temperatures <150, which fall in the range of DEEP calculations.

The specific saturation enthalpies and entropies for the calculation of Rankine cycle are presented below:





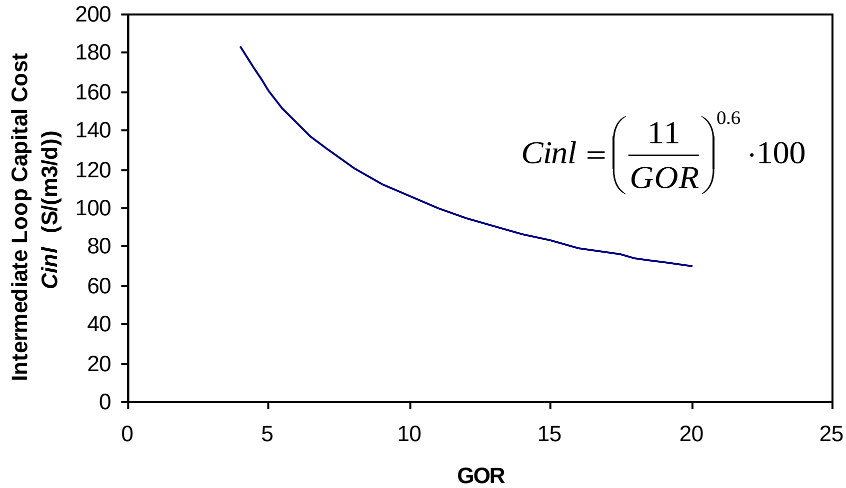
Other empirical formulas



$$Ndl = \mathrm{TRUNC}\left(\left(\frac{Wacd \cdot 264}{10^6 \cdot 6}\right)^{0.4} \cdot \frac{18}{1.4}\right)$$

$$Ndm = \mathrm{TRUNC}\left(\frac{5 + \dfrac{Wacd}{55000}}{2}\right)$$

Figure: Labour and Management versus desalination capacity



$$Cinl = \left(\frac{11}{GOR}\right)^{0.6} \cdot 100$$

Figure: Intermediate loop specific capital cost versus gain output ratio

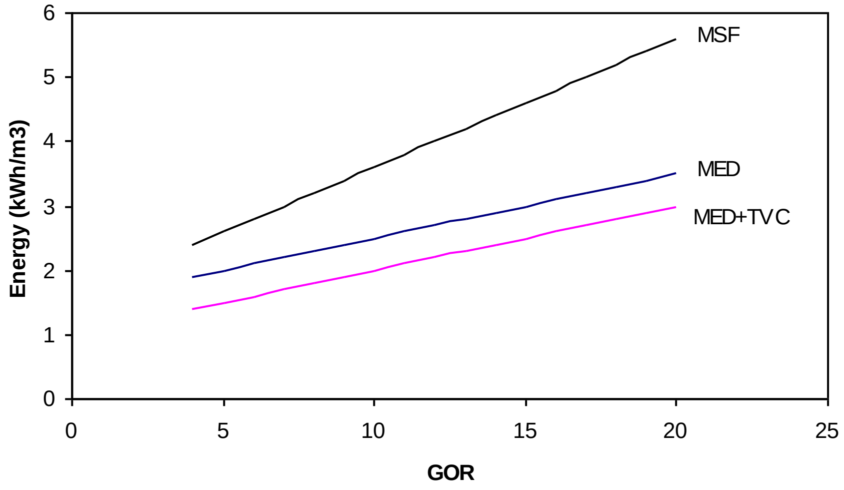


Figure: Electric power needed for thermal desalination plants vs Gain output ratio

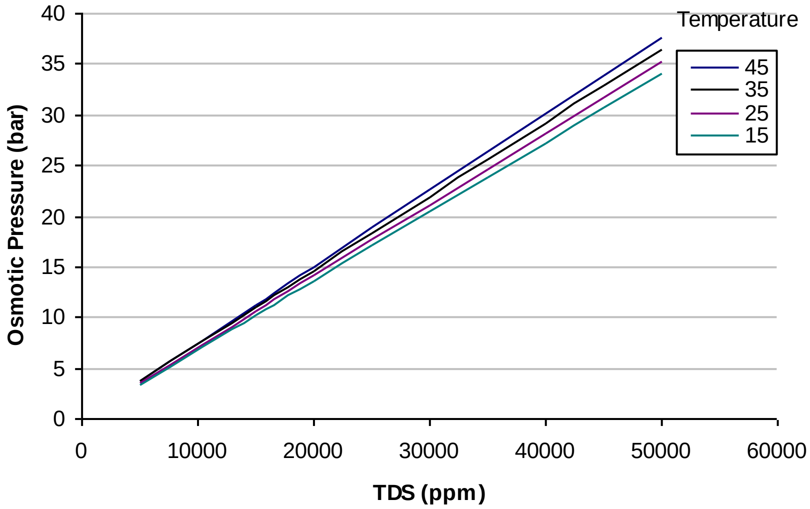


Figure: Osmotic Pressure vs Salinity