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Examining the economics of seawater desalination using the DEEP code

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FOREWORD

For human life, a sufficient amount of water of adequate quality is essential. Seawater desalination offers a promising option for the supply of potable water. In this context, since 1989, the IAEA has been carrying out an active programme in the investigation of nuclear desalination.

This programme has included technical assessments of the feasibility of nuclear desalination and comparative studies on the relative economics of both nuclear and fossil energy for the desalination of seawater. During 1991–1992, a generic investigation was conducted on the technical approach and the comparative costs for utilizing nuclear energy with various state of the art desalination technologies. Findings from this investigation were presented in IAEA-TECDOC-666 (1992). In addition, the evaluation methodology Co-generation and Desalination Economic Evaluation (CDEE) was developed.

A number of significant factors have changed since the publication of IAEA-TECDOC-666. The use of seawater desalination has become widespread, and experience has continued to grow. As the technology has improved and developed, capital costs for systems and components have been reduced and performance characteristics have improved. In addition to changes in desalination technology, new reactor design concepts have been introduced with specific emphasis on nuclear desalination. Existing reactor types have also been re-examined with desalination as a possible application.

In parallel, the IAEA has continued the development of its economic evaluation model. Work was initiated to incorporate all of the advances in economic modelling, technological changes in both desalination and reactor technologies and changes in economic conditions and parameters into a new, user-friendly version of the CDEE code that was released in 1998 under the name of Desalination Economic Evaluation Program (DEEP.

In view of the above and of market changes in competing energy sources, the IAEA initiated in 1998 a new comparative study of costs between nuclear and fossil energy sources coupled with selected desalination processes, based on both updated economic and technical data and on updated cost modelling using the DEEP code.

This Technical Document presents an analysis of the results obtained, together with results and data from five independent national studies. The report is addressed to decision makers, programme planners, engineers, and administrators of governmental and industrial organizations involved in assessing and developing nuclear desalination programmes.

The IAEA officer responsible for this publication was P.J. Gowin of the Division of Nuclear Power.

CONTENTS

1. OBJECTIVE OF THE STUDY

1.1. Introduction and background

For human life, a sufficient amount of water of adequate quality is essential. The scarcity of fresh water and especially potable water is jeopardizing life in many regions of the world [1]. By 2025, about two-thirds of the world population may suffer from high or moderate water shortages. Seawater desalination offers a promising option for the supply of potable water. Seawater desalination is an energy intensive process; nuclear energy is an attractive candidate as an energy source. Combining the use of nuclear energy with the industrial process of seawater desalination has been considered as far back as in the 1960s. Nevertheless, the primary interest within the nuclear industry at that time was in the development of nuclear technology for electrical power generation. With relatively few exceptions, the focus on electrical generation remained dominant through the early 1990s, when other applications for nuclear energy began to attract attention.

Increasingly severe worldwide water problems have now given a new momentum to nuclear desalination[1] studies. In this context, since 1989, the IAEA has been carrying out an active programme in the investigation of nuclear desalination.

This programme has included technical assessments of the feasibility of nuclear desalination and comparative studies on the relative economics of both nuclear and fossil energy for the desalination of seawater. In 1990 the IAEA published a report [3] that assessed the need for desalination based on analyses performed in the late eighties of the world's potable water resources and information published during the last decade on the most promising desalination processes and energy sources, including nuclear systems proposed by potential suppliers. During 1991/1992, a generic investigation was conducted on the technical approach and the comparative cost for utilising nuclear energy with various state-of-the-art desalination technologies. Findings from this investigation are presented in IAEA-TECDOC-666 [4]. In addition, the economic evaluation methodology developed for IAEA-TECDOC-666 was subsequently used as a tool to evaluate the potential for nuclear desalination as a possible source for the economical production of potable water for North Africa [5].

A significant outcome of the work leading to the publication of IAEA-TECDOC-666 was the development of a convenient methodology for preliminary economic evaluation and comparison of various energy source options to be coupled with different seawater desalination processes [6]. The Co-generation and Desalination Economic Evaluation (CDEE) model thus developed imbedded in the form of a spreadsheet routine contained simplified sizing and cost algorithms that were easy to implement, generally applicable to a variety of equipment and representative of state-of-the-art technologies.

A number of significant factors have changed since the publication of IAEA-TECDOC-666. There is widespread use of seawater desalination, and experience has continued to grow. By 1999 the total worldwide operating experience with nuclear seawater desalination reached about 100 reactor-years. In addition to that, experience with nuclear district heating, where a similar technology for heat extraction is used, yields another 600 reactor-years of worldwide operating experience. As the technology has improved and developed, capital costs for systems and components have reduced and performance characteristics have improved. In addition to changes in desalination technology, new reactor design concepts have been introduced with a specific emphasis on nuclear desalination. Existing reactor types have also been re-examined with desalination as a possible application.

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[1] As defined in IAEA-TECDOC-898 [2], "nuclear desalination" is taken to mean the production of potable water from seawater in an integrated facility in which both the nuclear reactor and the desalination system are located on a common site, there is some sharing of common systems and/or facilities, and the energy used for the desalination system is supplied by the nuclear reactor.

In parallel, the IAEA continued the development of its economic evaluation model. Work was initiated to incorporate all of the advances in economic modelling, technological changes in both desalination and reactor technologies and changes in economic conditions and parameters into a new, user-friendly version of the code. In 1998 the updated Desalination Economic Evaluation Program (DEEP) was released.

In view of the above and of market changes in competing energy sources, the IAEA contracted with the Institute of Nuclear Energy Technology (INET) in China in December 1998 to carry out a new comparative study of costs between nuclear and fossil energy sources coupled with selected desalination processes, based on both updated economic and technical data and on updated cost modelling using DEEP.

1.2. Objective

The study was carried out with the objective of making a comprehensive evaluation of cost comparisons between nuclear and fossil energy sources with selected desalination processes, including regional studies and sensitivity analyses.

1.3. Note on the use of the results of the study

Although much useful qualitative and quantitative information may be drawn from the results of the calculations carried out by INET, caution must be exercised in using these results.

It should be recalled that owing to the highly site-specific nature of many of the factors influencing the cost of water production, the most suitable application of the IAEA methodology and of the DEEP program is for relative comparisons of design alternatives for water production in a given area or region, not for obtaining absolute numbers.

Results should be interpreted as one, but not the only source of information and guidance for business leaders and decision makers in Member States facing severe water shortages and considering seawater desalination as one of the potential solutions.

2. TECHNOLOGIES

This section presents a short introduction to the technologies selected for the comparative evaluation used in the assessment of DEEP 1.1.

Both the electric energy production section and the desalination section of a typical large size desalination complex are discussed.

The processes and technologies described below are incorporated in the IAEA methodology and in the DEEP program as the basis for modelling the performance and cost characteristics of production plants.

2.1. Desalination processes

Seawater desalination is the processing of seawater to obtain “pure” water through the separation of the seawater feed stream into a product stream that is relatively free of dissolved substances and a concentrated brine discharge stream. There are many proven desalination technologies available. However, after more than 40 years of intensive research and development in seawater desalination technology, only the multi-stage flash (MSF) and multi-effect distillation (MED) processes and the reverse osmosis (RO) membrane process have achieved commercial large-scale application. In recent years, the hybrid process consisting of combinations of distillation and RO processes is gaining interest. Distillation and RO are expected to continue to be the leading desalination processes in the near future. The technologies considered in this study are indicated in Table 1.

TABLE 1. DESALINATION PROCESSES

Process	Abbreviation	Description
Distillation	MED	Multi-effect distillation
	MSF	Multi-stage flash
Membrane	SA-RO	Stand-alone reverse osmosis
	C-RO	Contiguous reverse osmosis
Hybrid	MED/RO	Multi-effect distillation with reverse osmosis
	MSF/RO	Multi-stage flash with reverse osmosis

2.1.1. Distillation processes

In distillation processes, seawater is heated to evaporate pure water that is subsequently condensed. With the exception of mechanical vapour compression, distillation processes are driven by low-temperature fluid (below 130°C). This fluid is generally steam, which may be taken from a power plant after partial utilization.

From the beginning, distillation processes have been implemented in heat recovery chambers placed in series as a result of the high specific heat required to evaporate water. The performance of distillation processes increases with increasing number of chambers. However, the overall temperature difference between the heat source and the cooling water sink as well as economic considerations limit the number of chambers. Typical temperature differences for commercial distillation plants are 2–6°C per heat recovery chamber.

2.1.1.1. Multi-stage flash (MSF) distillation

Figure 1 illustrates the schematic flow diagram of an MSF system [7].

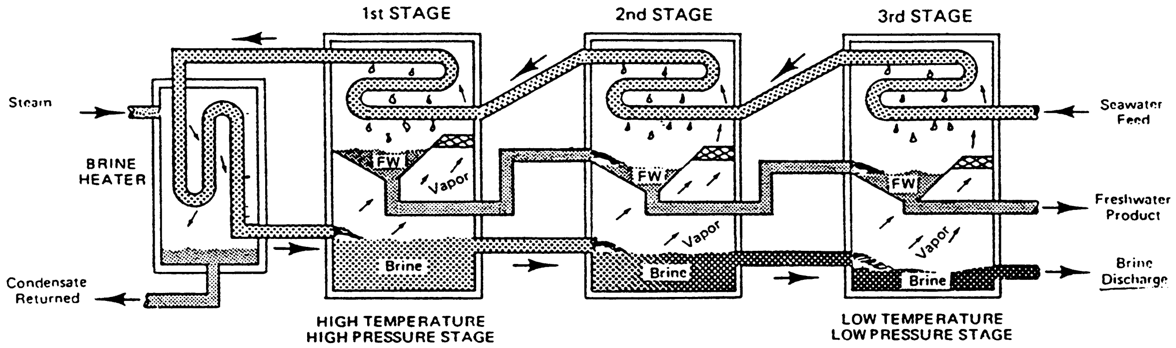

FIG. 1. Schematic flow diagram of a simplified MSF system.

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 demister 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 discharged to the atmosphere.

Today, corrosion resistant materials are available at reasonable costs as well as high temperature, cost effective antiscalants. MSF plants have reached a mature and reliable stage of development. Unit sizes up to 60 000 m^3/d have been built.

2.1.1.2. Multi-effect distillation (MED)

MED is a distillation process with the oldest large-scale applications. Figure 2 illustrates the schematic flow diagram of an MED process using horizontal tube evaporators [7]. 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 generally supplied by steam boilers or dual-purpose plants (co-generation of electricity and steam).

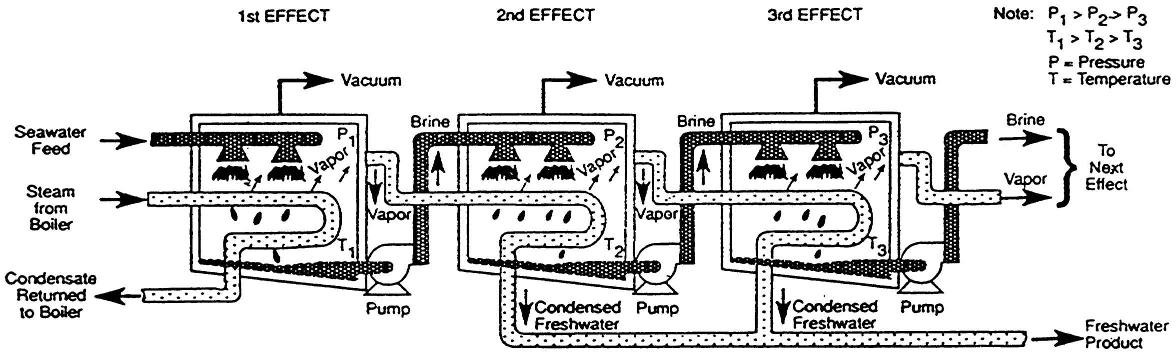

FIG. 2. Schematic flow diagram of a low-temperature horizontal-tube MED plant.

MED plants have a much more efficient evaporation heat transfer process than MSF plants. Due to the thin film evaporation of brine on one side of the tubes and the condensation of vapour on the other side, high heat transfer coefficients are achieved. Consequently, the number of effects for a given temperature difference between heat source and cooling water sink can be increased in comparison to MSF plants, thus decreasing the specific heat consumption.

The pre-treatment of seawater for MED plants is similar to that in MSF plants. In general, polyphosphate is introduced into the seawater feed to prevent calcium carbonate scale formation on the heat transfer tubes. A steam jet-ejector vacuum system is used to remove vent gases from the deaerator and non-condensable gases evolving during evaporation from the system. Some low temperature horizontal tube designs need a more stringent filtration of the seawater feed, as a result of the small nominal diameters of the brine distribution devices, which do not permit the presence of relatively large suspended particles in seawater.

2.1.2. Reverse osmosis (RO)

Reverse osmosis is a membrane separation process in which pure water passes from the high-pressure seawater side of a semi-permeable membrane to the low pressure permeate, or “pure” water, side of the membrane. In order to overcome the natural osmotic process (migration of pure water from a solution of low concentration into a solution of higher concentration in order to balance the osmotic pressures), the seawater side of the system has to be pressurized to create a sufficiently high net driving pressure[2] across the membrane. In practice, the seawater can be pressurized to pressures as high as 70–80 bar.

Within the framework of the nuclear desalination studies carried out by IAEA, two types of RO systems have been typically considered: “stand-alone” RO (SA-RO) and “contiguous” RO (C-RO). Stand-alone RO assumes that the RO plant is coupled to the power plant only through an electrical connection. In principle, the SA-RO plant does not have to be co-located with the power plant but for these studies is assumed to be. Contiguous RO assumes that the RO plant is not only co-located but also shares a common seawater intake and outfall with the power plant cooling system and may take advantage of other shared facilities and services. In addition, a C-RO plant may draw its feedwater from the outfall side of the plant (the condenser cooling water discharge stream), rather than directly from the seawater intake, in order to take advantage of the power plant reject heat for RO system feedwater preheating, a coupling concept that was first described in an IAEA Technical Committee Meeting on Coupling Aspects of Nuclear Reactors with Seawater Desalination Processes [8].

RO systems require a stringent feedwater pre-treatment in order to protect the membranes from effects such as scaling and fouling, including biological fouling. The extent of pre-treatment

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[2] Net driving pressure = feed pressure + osmotic pressure of permeate – permeate pressure – osmotic pressure of feed.

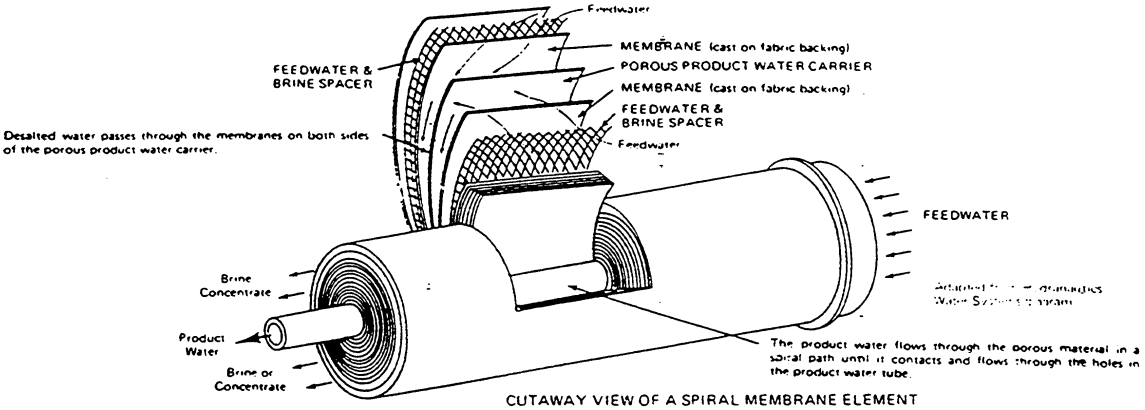
requirements depends on a variety of factors, such as seawater composition and temperature, seawater intake, membrane materials and recovery ratio. RO pre-treatment includes the following steps:

- Chlorine disinfection to prevent biological growth in feedwater,
- Coagulation followed by one of the mechanical separation methods (sedimentation, filtration, flotation) to remove colloidal and suspended matter from the feedwater,
- Conditioning with acids to adjust the pH index for carbonate scale suppression and with inhibitors (polyphosphates) to prevent sulphate scale formation,
- For chlorine sensitive membranes, in addition, feed de-chlorination through activated carbon filters and/or sodium bisulphate dosage is required.

RO membranes are made in a variety of modular configurations. Two of the commercially successful configurations are spiral-wound modules, or membrane elements, and hollow fibre modules. In both of these configurations, membrane elements are serially connected in pressure vessels (up to 7–8 with spiral wound modules and 2–3 with hollow fibre modules). High salt rejection and good high pressure operation qualities of current membranes permit the economical operation of seawater RO plants in single-stage systems, even on the high salt content waters found in the Middle East, while producing drinking water in accordance with World Health Organization (WHO) standards. In recent years, seawater RO has become a reliable commercial process applicable on a large scale.

2.1.2.1. Spiral wound membranes

A spiral wound membrane module is illustrated schematically in Figure 3.



CUTAWAY VIEW OF A SPIRAL MEMBRANE ELEMENT

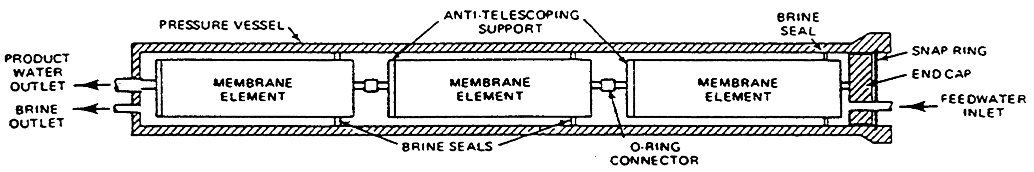


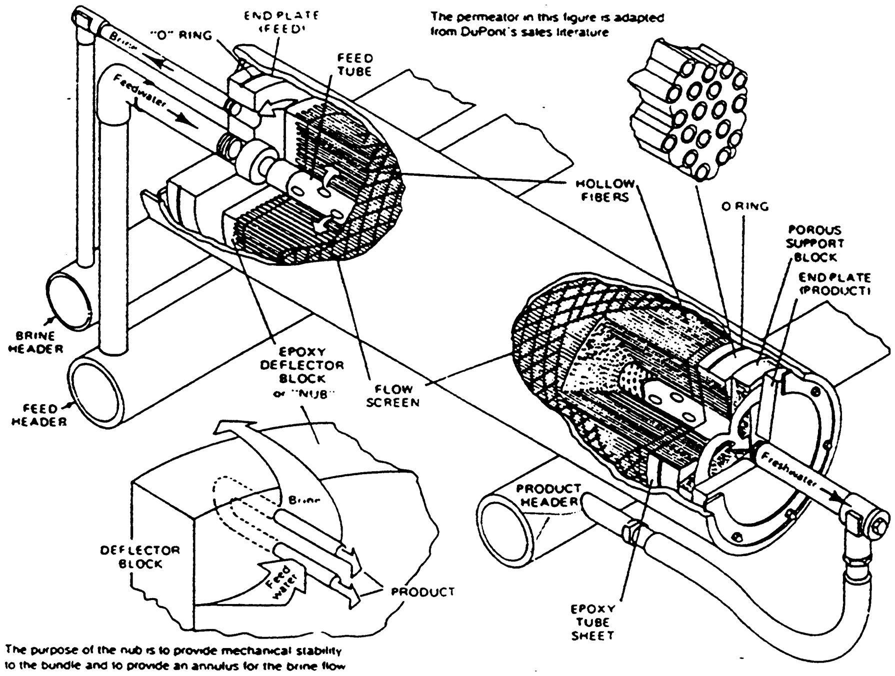
FIG. 3. Schematic diagram of a spiral wound RO membrane module.

A spiral wound module element consists of two membrane sheets supported by a grooved or porous support sheet. The support sheet provides the pressure support for the membrane sheets as well as providing the flow path for the product water. Each sheet is sealed along three of its edges, and the fourth edge is attached to a central product discharge tube. A plastic spacer sheet is located on each side of the membrane assembly sheets, and the spacer sheets provide the flow channels for the feed flow. The entire assembly is then spirally wrapped around the central discharge tube forming a compact RO module element.

The recovery ratio (permeate flow rate divided by the feed flow rate) of spiral wound membrane elements is rather low, so that as many as 7–8 elements are arranged in series in one module to get a higher overall recovery ratio. Spiral wound membranes have a simple design (reasonable production costs) with a relatively high resistance to fouling. Spiral wound membranes are typically operated at pressures as high as 69 bar and recovery ratios up to 45–50%. Spiral wound membranes, which can operate at pressures as high as 82.7 bar, are available commercially.

2.1.2.2. Hollow fibre membranes

A hollow fibre membrane module is illustrated schematically in Figure 4.



The permeator in this figure is adapted from DuPont's sales literature

The purpose of the nub is to provide mechanical stability to the bundle and to provide an annulus for the brine flow

FIG. 4. Schematic diagram of a hollow fibre RO membrane module.

Hollow fibre membranes are made of hair-like fibres, which are united in bundles and arranged in pressure vessels. Typical configurations of hollow fibre modules are U-tube bundles, similar to shell and tube heat exchangers. The feed is introduced along a central tube and flows radially outward on the outside of the fibres. The pure water permeates the fibre membranes and flows axially along the inside of the fibres to a "header" at the end of the bundle. Typical outside diameters of hollow fibres are somewhere in the order of 85 μm to 200 μm. Hollow fibres can withstand pressures as high as 82.7 bar and typically have recovery ratios up to 55%.

2.1.3. Hybrid desalination plant

A hybrid desalination plant is composed of a distillation plant (MSF or MED) and an RO plant operating in conjunction. In the hybrid concept, the distillation and the membrane plants together provide the desired desalinated water demand. Feed to the RO portion of the plant is typically taken from the condenser reject water of the distillation plant. A hybrid plant results in production of water with salinity lower than RO permeate but higher than distillation product water.

Such a combination can be appropriate in a number of situations, and user requirements, e.g.:

- To enhance the water production capacity at a given power plant site.
- When more than one water quality is required.

Analysis of hybrid plants is carried out by DEEP in parallel with its calculations for distillation and RO plants, but an evaluation of the hybrid plant results has not been included in this study.

2.2. Energy sources

Desalination is an energy intensive process. Although the technologies described above are very different, they all have a common feature — they require a significant consumption of energy. There are many proven energy sources available. Nine combinations of energy source and power level were chosen for this assessment, with the intent that they represent a range of nuclear and fossil power plant sizes and that they include existing power generation options as well as promising power supply concepts currently being developed. (BWRs were not considered for the sole reason that they are not modelled in the DEEP software, and in order to limit the overall number of options for the assessment. No technical or economic features or aspects were considered in this context.)

Table 2 summarizes the power plants and power levels assessed in this study.

TABLE 2. ENERGY SOURCES CONSIDERED

Energy source	Abbreviation	Description	Power level	Technology status
Nuclear	PWR-600	Pressurized light water reactor	600 MW(e)	Being developed
	PWR-900	Pressurized light water reactor	900 MW(e)	Existing
	PHWR-600	Pressurized heavy water reactor	600 MW(e)	Existing
	PHWR-900	Pressurized heavy water reactor	900 MW(e)	Being developed
	HTR-100	High temperature reactor	100 MW(e)	Being developed
	HR-200	Heating reactor (steam or hot water)	200 MW(th)	Being developed
Fossil	PC-600	Superheated steam boiler, pulverized coal	600 MW(e)	Existing
	PC-900	Superheated steam boiler, pulverized coal	900 MW(e)	Existing
	CC-600	Combined cycle gas turbine	600 MW(e)	Existing

2.2.1. Nuclear energy sources (1): Medium and large sized reactors

2.2.1.1. The pressurized (light) water reactor (PWR-600, PWR-900)

The pressurized water reactor (PWR) is the most common reactor type in operation today. Many different design configurations exits, but all have in common the use of light water as both coolant and moderator for the reactor core. The vertically oriented core consists of a large number of close-packed fuel channels housed in a large, heavy walled pressure vessel containing the primary coolant. Heat is typically removed from the PWR core by circulation of the primary coolant through steam generators producing saturated steam on their secondary side. The steam is circulated through high pressure and low-pressure turbine stages and is then condensed back into liquid and returned as feedwater to the steam generators. At a seawater site, the condenser cooling system circulates seawater through the condensers to remove waste heat from the energy generation process. (PWRs typically have an overall efficiency of about 32–34%, so that only about a third of the energy released in the reactor core is converted to electricity — the rest is discharged as waste heat.)

Power levels for operating PWRs range up to as much as 1400 MW(e), although it was judged that plants in excess of 900 MW(e) would be too large to be considered in this study: too small a portion of their energy output would be dedicated to the desalination plant, thus almost entirely reducing the competitiveness of nuclear desalination to the competitiveness of nuclear energy production, whereas the DEEP code is essentially a tool to evaluate co-production plants producing water and electricity. Notwithstanding these considerations, almost all nuclear plants, including larger sizes, would be technically suitable for desalination. For power levels at or below 900 MW(e) the plants become more truly dual-purpose plants, producing significant quantities of both water and electricity.

A variety of PWR designs have been described in more detail, including schematic diagrams, in IAEA-TECDOC-881 [9] and IAEA-TECDOC-968 [10]. The PWR-600 design considered for this study is an innovative PWR, derived from the 900 MW(e) French reactor, whose feasibility is currently being studied.

2.2.1.2. The pressurized heavy water reactor (PHWR-600, PHWR-900)

The pressurized heavy water reactor (PHWR) is characterized by a horizontally oriented core, with the fuel channels housed in individual small diameter pressure tubes through which heavy water (D_2O) circulates as the primary coolant. The pressure tubes are housed in a large diameter horizontal tank (calandria) containing low temperature, low pressure heavy water as the moderator. Heat produced by the fission process in the reactor core is removed by circulation of primary coolant through a steam generator, which produces steam on its secondary (light water) side. As with the PWR, the secondary system circulates steam through a turbine and then a condenser, where it is condensed back into water and returned to the steam generator. Conversion efficiencies are very similar to those for the PWR, and so about two thirds of the energy released by fission is discharged as waste heat via the condenser cooling system. With the PHWR there is also a small amount of heat produced in the moderator, and this is removed via a separate moderator heat removal system.

Although PHWRs in excess of 800 MW(e) are currently in operation, the 900 MW(e) considered for this study was the CANDU 9 currently under development. None are currently in operation or under construction. This design is an evolutionary advance from the existing 600 MW(e) CANDU 6, incorporating typical features of innovative reactors: a number of technological advances intended to further enhance safety, reliability and economics. A number of the plant characteristics assumed for this study were based on these technological advances.

The PHWR has been described in more detail in a number of publications, including IAEA-TECDOC-881 [9].

2.2.2. Nuclear energy sources (2): Small sized innovative reactors

2.2.2.1. The high temperature reactor (HTR-100)

The high temperature reactor (HTR) evaluated in this study is a modular gas cooled pebble bed reactor using helium as its primary coolant. The reactor core consists of several hundred thousand spherical fuel pebbles in a loose pebble bed cooled by helium. The process cycle used is a standard Brayton cycle with a closed circuit water cooled inter-cooler and pre-cooler. A closed cycle gas turbine is used for electricity generation. The system has a thermal power rating of 265 MW(th) with expected electrical conversion efficiencies on the order of 40–45%.

For this study a power level of 100 MW(e) was considered. Although the reactor is currently being developed and none is under construction, it was included in this study as an indication of future developments and how they might influence the economics of nuclear desalination.

2.2.2.2. The heating reactor (HR-200)

The 200 MW(th) heating reactor, HR-200, differs from the previously described energy sources in that it is a heat-only reactor rather than a dual-purpose reactor — it is intended only for the production of heat for process applications such as nuclear desalination or district heating. The HR-200 can be coupled with either the MED or MSF desalination process.

The nuclear heating reactor is a pressurized water reactor with integral arrangement, natural circulation, self-pressurized performance and a dual vessel structure. The core is located at the bottom of the reactor vessel. The primary heat exchangers are arranged on the periphery in the upper part of the reactor pressure vessel. The system pressure is maintained by inert gas and steam. A containment fits tightly around the reactor pressure vessel so that the core will not become uncovered under any postulated coolant leakage within it. Reactor coolant is circulated by density differences between the hot and cold regions inside the reactor pressure vessel. There is a long riser on the core outlet to enhance the natural circulation capacity.

The nuclear heat supply system contains triple loops. Primary coolant absorbs heat from the reactor core, then passes the riser and enters the primary heat exchangers, where its heat content is transferred to the intermediate circuits. Finally, heat is delivered to the heating grid via the intermediate heat exchangers. An intermediate circuit is needed in the nuclear heating to keep the heating grid free of radioactivity.

2.2.3. Fossil fuelled energy sources

Heat or electricity to be used for desalination purposes may be produced by burning fossil fuels. Several power plant options are applicable and some of them are presently used to produce the majority of desalted water in the world.

In this study, two fossil power production plants were taken into consideration. They were selected for their industrial maturity and for their suitability for economic production of large amounts of electricity and heat. The two options considered include: fossil fuelled steam boiler electric power plants (superheated steam boiler with pulverized coal, PC) and combined cycle (gas turbine + steam turbine) electric production plants (combined cycle gas turbine, CC).

2.2.3.1. Fossil fuelled steam boiler electric power plants (PC)

These plants produce electricity through a steam cycle, with superheated steam produced in a boiler. Any type of fossil fuel may be burnt, i.e. pulverised coal, sprayed oils or gas. The efficiency in electric energy conversion in modern plants reaches 42% without utilization of heat for other purposes. Plant sizes cover a wide range, up to some 600 MW(e) per production unit. In dual-purpose power plants, the steam expansion is interrupted to provide low pressure steam to a heat user such as a desalination plant, either in a counter-pressure scheme, or spilling steam streams from the turbines. Reject heat is delivered into a heat sink (cooling water body, atmosphere). The plant cost is strongly affected by the type of fuel (large fuel storage and handling equipment is needed for coal fired plants) as well as by exhaust gas treatment selected to match local standards on environmental emissions.

2.2.3.2. Combined cycle electric power plants (CC)

These plants include two conversion cycles for producing electricity: the exhaust heat of a gas turbine (first cycle) is utilized to produce steam to drive a steam turbine (second cycle). Only clean liquid or gaseous fuels are suitable for this application. The efficiency in electric energy conversion exceeds 50% without utilization of heat for other purposes. Plant sizes cover a wide range, with the possibility of several combinations of gas turbine and heat recovery boiler units. As in the preceding case, in dual-purpose power plants, the steam expansion is interrupted to provide low-pressure steam to a heat user (e.g., desalination plant), either in a counter-pressure scheme, or spilling steam streams from the turbines. Reject heat is delivered into a heat sink (cooling water body, atmosphere). This solution is characterized by a high complexity and by a rather high fuel cost (solid or dirty fuels being incompatible), but it has the advantages of high efficiency and low environmental impact.

3. SOFTWARE DESCRIPTION AND ASSUMPTIONS

3.1. DEEP description

3.1.1. Purpose and goals of DEEP

DEEP is not intended to provide a precise calculation of the cost of producing either electricity or potable water, nor is it intended to be used as an ‘engineering’ or ‘design’ tool by those involved in the detailed development of fossil fuelled or nuclear electric generation and desalination facilities. Rather, it is intended to be used as a tool to provide guidance and insight to those involved in developing and planning national programmes aimed at dealing with strategic water and energy issues. DEEP serves three very important and specific goals:

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

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

3.1.2. The DEEP program structure

The DEEP package consists of essentially three parts, implemented as Excel spreadsheet files. These include the “Case” files, the “Comparative Presentation” files, and the “Control” file.

The “Case” files are EXCEL files that are based on previous versions of CDEE [6]. It is within an individual case file that the desalination technology performance and economic evaluation calculations are carried out for a single, specific nuclear or fossil power plant option. For that specific power plant, DEEP carries out the performance and economic evaluation automatically for four desalination technology combinations, as applicable. These include:

— Distillation plant	(MSF or MED)
— Stand-alone RO plant	(Hollow fibre or spiral wound)
— Contiguous RO plant	(Hollow fibre or spiral wound)
— Hybrid plant *(Combination of distillation and membrane plant)*	(MSF or MED, hollow fibre or spiral wound)

The “Comparative Presentation” file is a summary of the selected cases from which a comparison table is made automatically. This table is then stored as a usual EXCEL file within one worksheet.

The “Control” file is the DEEP user-friendly interface, which helps the user with selection of input data for the calculation files, helps create and maintain Comparative Presentation files, provides for a consolidated presentation of results including a set of predefined graphs which are updated according to values from the selected cases, and includes a variety of menu items to simplify the printing of output sheets.

The DEEP package includes a knowledge base of Reference Cases from which new cases can be generated. Using the “New Case” and “New Case By Modification” commands, the user can readily generate many cases based on the reference cases that differ only in input data values.

One of the main design principle used for developing DEEP is to keep all EXCEL functions available for the user and to leave the basic calculation spreadsheet open for user changes. The intent is to provide a user-friendly interface for most users, while retaining the flexibility for the more advanced user to modify not only input and default data but also the underlying correlations and calculations.

3.1.3. User considerations with regard to input data and output

Preparation of meaningful and consistent input is essential for obtaining meaningful results with DEEP. The variables that are used in DEEP are either 'expected input' by the user or 'default data' not foreseen for user input via the INPUT SHEET (even though these may be changed by an experienced user) or 'part of the model' data that should not normally be changed. DEEP includes both generally applicable default data (e.g. for economic parameters and electric motor efficiency) and default data that are specific for certain energy sources and desalination technologies. These categories of data parameter are colour coded, and the user can change the category of each input parameter by changing its colour, and can then change 'default' or 'part of the model' data if there is a specific need to do so.

DEEP can be used both for generic studies, in order to analyse the performance and costs of a range of combinations of power and/or heat plants and coupled desalination plants, and for site-specific studies. For generic studies, it is assumed that the user will often refer to default data contained in DEEP and provide only some other input data from other sources.

For site-specific studies, it is assumed that the user has **indicative data** for specific projects. (DEEP is not intended for the detailed design or technical and economic evaluation of specific projects.) He would then base the input data on construction and operating experience as well as on statistics and on studies performed in the context of national, regional or site-specific energy and water demand and supply planning. He will thus have information on the existing regional energy and water supply system, on energy and water demand projections, available energy and water resources, and on possible sites for future desalination plants close to existing or foreseeable areas with insufficient water supply.

An experienced user will also usually have information on performance and cost experience with existing plants and on the performance and costs of energy sources and/or desalination technologies which are considered for future projects. He may have an idea which energy sources and which desalination technologies would be suitable for a specific site. This information will be used to prepare site-specific input.

The user should keep in mind that the DEEP empirical performance and cost models are valid for certain ranges of input parameters (in particular unit sizes of power and desalination plants, RO feedwater temperature and salinity), usually over a range of plus or minus 10–20%. Analyses with input data outside these ranges are of questionable value.

3.2. Assumptions/characteristics inherent in the DEEP methodology

3.2.1. Power plant calculations

The energy sources included in DEEP are steam power plants, gas turbines, combined cycle, diesel and heating plants. DEEP includes simplified models of the nuclear and fossil fired steam power plants to estimate performance and economic characteristics. While this approach is necessary to provide a model that is possible within the framework of the spreadsheet approach taken to the DEEP calculations, it has the disadvantages of introducing some inherent "assumptions" into the analysis and of imposing some inherent limitations on the results obtained. These inherent characteristics of the tool must be kept in mind when evaluating and interpreting the results obtained. Some of the key characteristics/limitations inherent in the power plant calculations include the following:

- Total construction costs of the power plant are calculated on the basis of specific construction costs, expressed in US \$[3]/kW of plant capacity. The specific construction cost is a user input value that has a direct consequence on the cost of energy produced, hence the quality of the energy cost calculation can be only as good as the input specific construction cost.
- Power plant operating availability is calculated from a combination of the "planned outage rate" and the "unplanned outage rate". Inherent in this approach is the assumption that the plant is either out of service or is operating continuously at full power over the rest of the year. Default

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[3] Throughout this report all costs are expressed in US dollars.

values of these two parameters are provided by DEEP, but can be changed by the user. The default values provide result in an estimate of overall availability that tends to be on the low side for modern power plants. However, care must be taken in changing these values so that unrealistically high values of availability do not result.

- The calculation of net saleable power in DEEP for a power plant coupled to an MED system is based on a power level that is artificially adjusted to account for the steam conditions associated with the MED system. In some cases this can lead to a calculated power that is higher than the rated plant power.

3.2.2. Desalination plant calculations

The desalination processes treated in DEEP include both distillation and membrane technologies, as well as hybrid combinations of the two. As with the power plant calculations, performance and economic calculations are based on simplified models and correlations. As before, this approach is necessary to provide a model that is possible within the framework of the spreadsheet approach taken to the DEEP calculations, but it has the disadvantages of introducing some inherent "assumptions" into the analysis and of imposing some inherent limitations on the results obtained. These inherent characteristics of the tool must be kept in mind when evaluating and interpreting the results obtained. Some of the key characteristics/limitations inherent in the desalination plant calculations include the following:

- A desalination plant of a given capacity is made up of a number of smaller "units". The default unit size is calculated by DEEP as multiples of 12 000 m^3/d up to a maximum of 48 000 m^3/d for distillation plants and either 12 000 or 24 000 m^3/d for RO plants. The selection logic by which DEEP calculates the size and number of units required results in an installed capacity that exceeds the capacity specification. The extent by which specified capacity and installed capacity differ is not directly related to capacity, and hence some caution must be exercised in comparing water costs from plants of different capacities.
- Water plant costs are calculated on the basis of a "base unit cost", expressed in \$/(m^3/d), times the number of units. An "economy of scale" is assumed by applying correction factors for the both the unit size and the number of units. However, since the correction factor for number of units does not depend on unit size, the combination of these factors may give results that are "counter-intuitive" and hence again some caution must be exercised in comparing water costs from plants of different capacities.
- For RO plants, DEEP calculates costs for both stand-alone and contiguous configurations. For the contiguous plant the feedwater temperature to the RO system can be increased to reflect the use of power plant condenser cooling water discharge as feedwater to the RO system. This increased feedwater temperature is reflected in some of the correlations for membrane performance but does not result in changes in water production rate or water cost for the contiguous plant. As currently configured, DEEP cannot be used to calculate the beneficial effect of spiral wound membrane performance characteristics or of the lower water costs from using preheated feedwater.
- The discount rate assumed in DEEP for economic assessment of the desalination plant is the same as that assumed for the power plant. This may be a totally inappropriate assumption in some cases, particularly where there the cost of the power plant is significantly higher than that of the desalination plant and given the shorter construction times taken for the desalination plant. If capital investment were easier to obtain for the desalination plant, it would have the effect of reducing the cost of water production, and this factor should be taken into account in considering the results from DEEP calculations.
- The water cost calculated by DEEP is based on the constant money levelized cost method.
- In all MED and MSF cases, the DEEP "Maximum Brine Temperature" was set to be at least 70°C or higher, if the required water production made that necessary, in accordance with instructions for the use of DEEP as contained in the DEEP Manual [6].
- Some simplifications in the plant process schemes are adopted in the program: an example is the absence of recirculation stages in the MSF process. These simplifications should be taken into account in the analysis of results, for their possible impact on the validity of conclusions.

4. RESULTS OF THE INET DEEP 1.1 CALCULATIONS

4.1. Input data and assumptions for DEEP calculations

4.1.1. Calculation scheme

As noted in the introduction, the IAEA contracted with the Institute of Nuclear Energy Technology (INET) in China in December 1998 to carry out a new comparative study of costs between nuclear and fossil energy sources coupled with selected desalination processes, based on both updated economic and technical data and on updated cost modelling, to be used as the basis of an assessment of the DEEP 1.1 computer program.

The studies carried out for this economic evaluation consisted of a set of detailed DEEP calculations carried out for three broad geographical regions. Within each region, the studies considered four nuclear power plant options and two fossil-fuelled power plant options, operating at a variety of power levels and coupled as appropriate with three desalination processes. For each of these combinations, two different economic scenarios were considered.

In addition to the region-by-region studies, a sensitivity analysis was also carried out to permit evaluation of the impact of variations in a number of important input parameters. Calculations were carried out for three power plants (all at the same power level) in combination with the various desalination processes.

4.1.2. Regional studies

The three regions studied were chosen on the basis of (but not entirely corresponding to) the DuPont World map for desalination, dividing the world into regions with similar seawater and economical conditions with respect to seawater desalination. The approximate geographic area and regional characteristics for each of these three regions are given in Table 3.

TABLE 3. INPUT DATA ASSUMPTIONS FOR REGIONAL CALCULATIONS

Region	Approximate geographic area	Seawater conditions		Personnel costs	
		Temp. °C	TDS ppm	Management $/year	Labour $/year
Region 1	Southern Europe (south of France, south of Italy, Greece, Spain)	20	38 000	160 000	80 000
Region 2	North Africa, Red Sea, South East Asia	25	41 000	60 000	30 000
Region 3	Arabian Sea	30	45 000	60 000	30 000

A subset of the Region 1 study, “Region 1 Outlook”, was also carried out. These calculations assumed as the power plant option two small reactors. The first one is a high temperature nuclear reactor (HTR-100) currently being developed [10] with very low predicted construction cost. The second one is a dedicated heat-only reactor, HR-200. Data were used as presented by the designers, without verification by the IAEA, to give an indication of possible future developments.

4.1.3. Power plant options

The nuclear reactors and fossil fuelled power plants considered in this assessment were chosen to represent a range of existing power plant types, as well as promising future generation power supply concepts. The energy sources considered in the DEEP calculations, and the various power levels for which calculations were carried out, are listed in Table 4.

TABLE 4. ENERGY SOURCES AND POWER LEVELS ASSUMED FOR DEEP CALCULATIONS

Energy Source	Abbreviation	Description	Power level
Nuclear	PWR-600	Pressurized light water reactor	600 MW(e)
Nuclear	PWR-900	Pressurized light water reactor	900 MW(e)
Nuclear	PHWR-600	Pressurized heavy water reactor	600 MW(e)
Nuclear	PHWR-900	Pressurized heavy water reactor	900 MW(e)
Fossil	PC-600	Superheated steam boiler with pulverized coal	600 MW(e)
Fossil	PC-900	Superheated steam boiler with pulverized coal	900 MW(e)
Fossil	CC-600	Combined cycle gas turbine	600 MW(e)
Nuclear	HTR-100	High temperature reactor	100 MW(e)
Nuclear	HR-200	Heating reactor (steam or hot water)	200 MW(th)

4.1.4. Desalination options

The RO and MED desalination processes were considered in all regions. In addition, MSF was included in Regions 2 and 3 as it is a technology that is already in common use in the countries making up these two regions. For the purposes of the Region 1 Outlook calculations with the HTR, only RO was considered.

Hybrid desalination plant options were not considered in the study. While the competitiveness of nuclear vs. fossil certainly depends, among other things, on the desalination option chosen (distillation or RO), it can be assumed as a first approximation that the competitiveness of nuclear vs. fossil for a hybrid plant will lie within the range defined by the single desalination technology options. In other words, it is assumed for this study that both nuclear and fossil options benefit to approximately the same extent from combining distillation and RO technologies into a hybrid plant.

Experts in the desalination field assessed the projected needs for desalted water based on historical records of installed seawater desalination capacity, known orders for new capacity to be installed over the next several years, population projections and expert judgement [12]. As a result of this assessment of demand for desalinated water, it was concluded that several countries would be candidates for nuclear desalination facilities and that the production capacities of interest would fall into two broad ranges. The first of these was for medium sized plant producing between 80 000 and 100 000 m^3/d of potable water. The second capacity range was between 200 000 and 500 000 m^3/d.

Based on recent desalination plant construction costs, the base unit cost for MED was assumed to be US $900 per m^3/d of installed capacity, for MSF US $1800 per m^3/d and for RO US $800 per m^3/d for all calculations.

The TDS content of the product water from distillation and from RO plants is vastly different. MED and MSF plants product water that has only a few ppm of total dissolved solids in the distillate, whereas the TDS of RO permeate will vary widely (on the order of a few hundred ppm) depending on the performance of the membranes (which in turn is determined by their age and condition) as well as on the design of the plant, which is usually configured to meet specified water quality standards. Two of the more common standards that are often specified are those of the World Health Organization (WHO) and the European Union (EU). Where water quality is an important factor, this must be considered in evaluating the cost of water produced by the two different types of technology.

One of the assumptions of DEEP calculations as for the desalination options is the economic equivalence of the product (water) for all desalination processes analyzed. This is only a first approximation, because the water quality of distillation processes (MED and MSF) is quite different (a few ppm TDS) from that from typical large scale RO plants (several hundred ppm). If the end user water standard specifications are compatible with some 500 ppm of salinity, the economic calculations of DEEP are meaningful in a comparison with MSF or MED. By contrast, a credit could be attributed to water produced through MSF or MED, or the default data regarding RO plants in DEEP could be modified to take into account a more stringent specification on allowable product salinity.

The desalination processes considered and their main characteristics are summarized in Table 5.

TABLE 5. DESALINATION PROCESSES AND ASSUMPTIONS FOR DEEP CALCULATIONS

Desalination process	**Base unit cost US \$/(m^3/d)**	**Regions**	**Desalination plant capacities considered m^3/d**
RO	800	1, 2, 3	60 000, 120 000, 240 000, 480 000
MED	900	1, 2, 3	60 000, 120 000, 240 000, 480 000
MSF	1 800	2, 3	60 000, 120 000, 240 000, 480 000

4.1.5. Economic comparisons of nuclear and fossil fuelled energy sources

One of the common difficulties in carrying out economic evaluations in which comparisons are to be made between the economics of nuclear power and fossil power is the selection of a set of economic parameters that provide a “fair” comparison. Nuclear power plants typically have a high capital cost with relatively long construction times, whereas fossil fuelled power plants typically have low capital cost and shorter construction times. On the other hand, nuclear plants have relatively low fuel cycle costs, whereas fossil plants have higher fuel cycle costs. The specific values of these competing factors for any given set of site-specific conditions may lead to more favourable conditions for nuclear power plants or to more favourable conditions for fossil fuelled power plants. Accordingly, for each power/desalination plant combination the detailed studies also included two economic scenarios evaluating the competing influence of factors such as interest /discount rate, overnight cost, and uncertainties in oil, gas and coal prices.

One scenario (in the following, identified as S_F) assumed values for these factors that tend to increase capital cost and decrease fuel cycle costs (higher overnight cost and discount rate, and cheaper fossil price) and are therefore favourable to the economics of fossil fuels.

The second scenario (in the following, identified as S_N) assumed values for these factors that tend to decrease capital cost and increase fuel cycle costs (lower overnight cost and discount rate, and more expensive fossil price), and are hence favourable to the economics of nuclear energy. The input data assumptions for the DEEP analyses for these two scenarios are identified in Table 6.

In addition to the input data assumptions identified above, a number of other parameters need to be specified for DEEP calculations. These are presented in Table 7. All costs given in that table are assumed costs, that is, all figures were chosen solely for this study, and their inclusion does not entail their endorsement or validation by the Agency. Similar considerations apply to related items of construction lead time, lifetime, and decommissioning cost. All figures are to some extent based on specifications obtained from reactor designers or suppliers, but were harmonized to allow better interpretation of the results obtained from DEEP.

The analysis scheme and the input data were tabulated and supplied to INET for their work following a Consultancy on Strategy for Calculations on the Competitiveness of Nuclear Seawater Desalination held at the IAEA in Vienna from 9 to 11 December 1998.

TABLE 6. INPUT DATA ASSUMPTIONS FOR ECONOMIC SCENARIOS S_N AND S_F

Power option	**Discount/interest rate %**				**Oil–gas and coal prices**		**Specific assumed construction cost in DEEP***	
	Region 1		**Regions 2 & 3**		**\$/boe (\$/T)**		**\$/kW(e) (\$/kW(th)**	
	S_N	S_F	S_N	S_F	S_N	S_F	S_N	S_F
PWR-600	5	8	8	10	30	20	1646.45	2227.55
PWR-900	5	8	8	10	30	20	1360	1840
PHWR-600	5	8	8	10	30	20	1425.45	1928.55
PHWR-900	5	8	8	10	30	20	1319.2	1784.8
HTR 100	5	8	8	10	30	20	935	1265
HT 200	5	8	8	10	30	20	413.44	559.36
PC-600	5	8	8	10	70	50	2118.3	1565.7
PC-900	5	8	8	10	30	20	1790.55	1323.45
CC-600	5	8	8	10	30	20	913.1	674.9

* These values are variations of ±15% from the assumed overnight cost in Table 7.

4.1.6. Sensitivity analyses

In addition to the region-by-region studies, sensitivity analyses were also carried out with variations in several important parameters that could potentially have a significant influence on the final water cost. The parameters that were varied for these sensitivity analyses are listed in Table 8. These calculations were carried out to permit an evaluation and understanding of possible trends in the cost of water production as potentially significant factors changed, and to help understand which of the many input parameters required for a nuclear desalination economic evaluation are in fact important to the cost of water production.

The sensitivity analyses were carried out for three power plant options (PWR-600, PHWR-600 and CC-600) and two desalination processes (MED and RO). In order to provide a consistent set of power options for comparison, only 600 MW(e) power plants were included in the sensitivity analyses.

4.1.7. Other considerations and limitations of the analysis

Of the various power plant options considered, four (PWR-600, PHWR-900, HR-200 and HTR-100) are plants that are in the design and development stage. Input data for these plants is based on "design expectations" for performance and economic characteristics, and not on actual operating experience. Accordingly, some care must be taken when comparing the analysis results for these plants with those from the other power plant options. While absolute comparisons in the cost of water production may not be appropriate, the changes in these costs under the varying conditions considered should be indicative of the trends to be expected.

Desalination plant availability is typically much higher than that of power plants. All DEEP calculations carried out for this analysis assume the presence of a backup heat source for nuclear power plants, so that distillation processes can continue to operate when the power plant is not available. The impact of this assumption has been studied as one of the sensitivity analyses, and is described in Section 5.4.9.

In the comparative economic assessment that is performed using DEEP, the cost of water storage, transport and distribution are not considered. These cost components are fundamentally site dependent and can only be analysed on a case-by-case basis. These costs are intentionally not included in DEEP as they are not factors in the cost of water production.

TABLE 7. INPUT PARAMETERS AND ASSUMED PLANT COST FOR ECONOMIC COMPARISON USING DEEP

DEEP Item	**Unit**	**PWR 600**	**PWR 900**	**PHWR 600**	**PHWR 900**	**HTR 100**	**PC 600**	**PC 900**	**CC 600**	**HT 200**
Reference Power Plant Unit Net Output	MW(e)	600	900	676	875	226 MW(th)	600	900	600	200 MW(th)
Reference Condensing Temperature	°C	42	42	DEEP default	DEEP default	DEEP default	DEEP default	DEEP default	15	DEEP default
Main Steam Temperature	°C	DEEP default	DEEP default	DEEP default	DEEP default	DEEP default	560	580	DEEP default	DEEP default
Reference Net Thermal Efficiency	%	31.5	33	32.8	32.2	47.7	42	42	53.3	N/A
Assumed Overnight Cost	\$/kW$_e$ (\$/kW$_t$)	1937	1600	1677	1552	1100	1842	1557	794	486
Availability	%	DEEP* default	DEEP default	95	95	DEEP default	DEEP default	DEEP default	DEEP default	94
Construction Lead Time	Months	60	72	52	50	24	36	48	36	40
Specific O&M Cost	\$/MW·h	11	9	6.8	6.3	1.5	6.2	5.2	5	2.2
Fuel (Cycle) Cost	\$/MW·h	5	8.5	2.4	2.3	4.1				2.6
Specific Decommissioning Cost	\$/kW$_e$	200	200	253	236	200	N/A	N/A	N/A	67
Economic and Technical Life Time	Year	40	40	40	60	40	30	30	25	40

* DEEP default availability value is 0.80.

TABLE 8. PARAMETERS VARIATION IN SENSITIVITY ANALYSIS

Parameter	Reference value	Sensitivity value
Average Management Salary, \$/y	110 000	66 000, 160 000
Average Labour Salary, \$/y	55 000	30 000, 80 000
Desalination Size, m^3/d	240 000	60 000, 120 000, 480 000
Seawater TDS, ppm	41 000	38 000, 45 000
Seawater Temperature, ºC	25	20, 30
Discount/Interest Rate, %/y	8	5, 10
Fossil Fuel Cost, \$/boe	25	10, 20, 30
Power Plant Overnight Cost	Values from Table 7	±15%

4.2. Results of the DEEP calculations

4.2.1. Regional study results

The "raw" results from DEEP calculations carried out by INET for each of the individual combinations of parameters on a regional basis are presented in the following tables and graphs. The results for Region 1 are presented in Table 9 and Figure 5, for Region 2 in Table 10 and Figure 6, and for Region 3 in Table 11 and Figure 7, respectively. An additional set of results for the Region 1 Outlook study is presented in Table 12.

TABLE 9. RESULTS OF DEEP CALCULATIONS FOR REGION 1

Power option	Levelized electricity cost \$/kW·h		Desalination plant size m^3/d	Net saleable electricity (with MED) MW(e)	Net saleable Water m^3/d	Levelized water cost \$/m^3			
	S_N	S_F				MED S_N	MED S_F	RO S_N	RO S_F
PWR-600	0.032	0.050	120 000	595.40	107 751	0.73	0.88	0.53	0.67
			240 000	570.00	215 502	0.66	0.79	0.51	0.64
			480 000	514.00	431 004	0.65	0.79	0.48	0.62
PWR-900	0.032	0.047	120 000	904.20	107 751	0.73	0.87	0.53	0.66
			240 000	878.90	215 502	0.66	0.78	0.50	0.63
			480 000	825.40	431 004	0.64	0.77	0.48	0.61
PHWR-600	0.022	0.035	120 000	657.90	108 542	0.56	0.73	0.47	0.60
			240 000	632.60	217 083	0.49	0.65	0.44	0.57
			480 000	577.10	434 166	0.48	0.65	0.42	0.55
PHWR-900	0.019	0.031	120 000	859.80	108 552	0.52	0.70	0.45	0.58
			240 000	834.50	217 104	0.46	0.62	0.42	0.55
			480 000	781.10	434 208	0.44	0.62	0.40	0.53
PC-600	0.050	0.045	120 000	588.00	107 751	0.82	0.85	0.62	0.67
			240 000	560.00	215 502	0.76	0.78	0.59	0.64
			480 000	494.70	431 004	0.72	0.75	0.56	0.61
PC-900	0.046	0.041	120 000	896.00	107 751	0.81	0.84	0.60	0.66
			240 000	869.50	215 502	0.73	0.75	0.57	0.63
			480 000	809.20	431 004	0.73	0.75	0.55	0.60
CC-600	0.059	0.045	120 000	478.60	107 751	0.89	0.88	0.66	0.68
			240 000	449.10	215 502	0.79	0.77	0.63	0.65
			480 000	338.10	431 004	0.78	0.77	0.61	0.62

TABLE 10. RESULTS OF DEEP CALCULATIONS FOR REGION 2

Power option	**Levelized Electricity cost $/kW·h**		**Desal. plant size m^3/d**	**Net saleable electricity (with MED) MW(e)**	**Net saleable water m^3/d**	**Levelized water cost $/$m^3$**					
	S_N	**S_F**				**MED S_N**	**MED S_F**	**MSF S_N**	**MSF S_F**	**RO S_N**	**RO S_F**
PWR-600	0.042	0.061	60 000	597.90	53 876	0.90	1.03	1.67	1.92	0.69	0.83
			120 000	585.30	107 751	0.84	0.95	1.61	1.86	0.64	0.77
			240 000	561.80	215 502	0.76	0.87	1.50	1.73	0.62	0.75
			480 000	509.40	431 004	0.77	0.88	1.35	1.62	0.60	0.73
PWR-900	0.040	0.057	60 000	902.10	53 876	0.90	1.02	1.66	1.88	0.68	0.82
			120 000	889.50	107 751	0.83	0.94	1.60	1.82	0.63	0.75
			240 000	865.90	215 502	0.76	0.86	1.47	1.67	0.61	0.73
			480 000	816.10	431 004	0.76	0.86	1.41	1.64	0.59	0.71
PHWR-600	0.029	0.042	60 000	659.70	54 272	0.71	0.86	1.25	1.55	0.62	0.75
			120 000	647.10	108 543	0.66	0.80	1.20	1.51	0.56	0.68
			240 000	623.60	217 087	0.59	0.73	1.10	1.38	0.54	0.66
			480 000	571.70	434 174	0.60	0.74	1.06	1.36	0.52	0.64
PHWR-900	0.026	0.038	60 000	857.40	54 277	0.68	0.83	1.18	1.49	0.59	0.72
			120 000	844.80	108 554	0.63	0.77	1.14	1.44	0.54	0.66
			240 000	821.30	217 108	0.56	0.70	1.04	1.32	0.52	0.64
			480 000	771.50	434 216	0.57	0.70	1.02	1.31	0.50	0.62
HR-200			60 000		57 105	1.76	2.15	2.15	2.60		
			120 000		116 143	1.08	1.31	1.76	2.12		
PC-600	0.061	0.051	60 000	594.90	53 876	0.97	0.96	1.79	1.74	0.78	0.81
			120 000	582.20	107 751	0.90	0.89	1.75	1.70	0.72	0.74
			240 000	557.00	215 502	0.84	0.82	1.51	1.48	0.70	0.72
			480 000	492.30	431 004	0.83	0.82	1.50	1.49	0.68	0.70
PC-900	0.056	0.047	60 000	898.70	53 876	0.95	0.95	1.75	1.71	0.76	0.79
			120 000	886.00	107 751	0.88	0.87	1.70	1.65	0.70	0.73
			240 000	862.20	215 502	0.81	0.80	1.55	1.48	0.68	0.70
			480 000	807.50	431 004	0.82	0.81	1.44	1.45	0.66	0.68
CC-600	0.063	0.048	60 000	490.10	53 876	1.00	0.97	1.77	1.74	0.81	0.81
			120 000	476.90	107 751	0.94	0.90	1.73	1.62	0.75	0.74
			240 000	449.00	215 502	0.85	0.81	1.55	1.50	0.72	0.72
			480 000	392.30	431 004	0.86	0.82	1.56	1.52	0.70	0.70

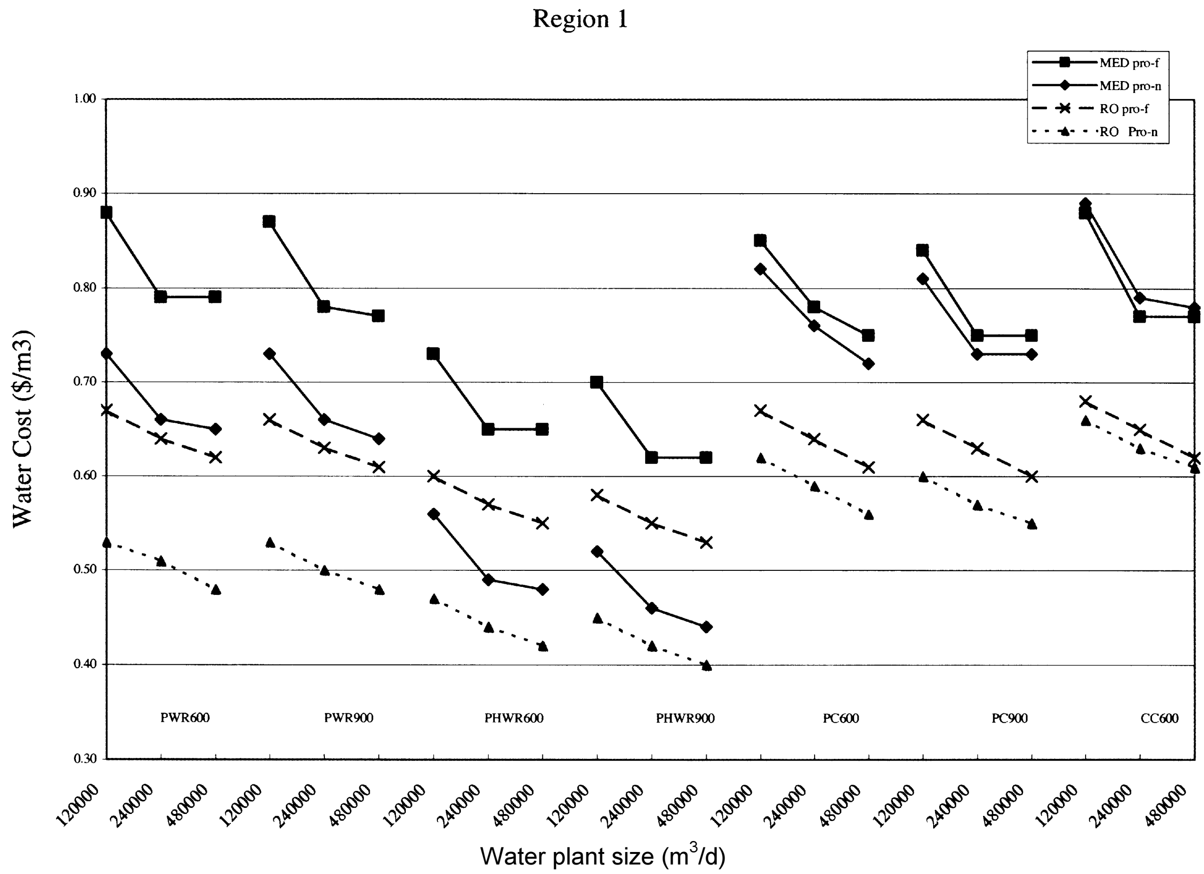

FIG. 5. Results of DEEP calculations for Region 1.

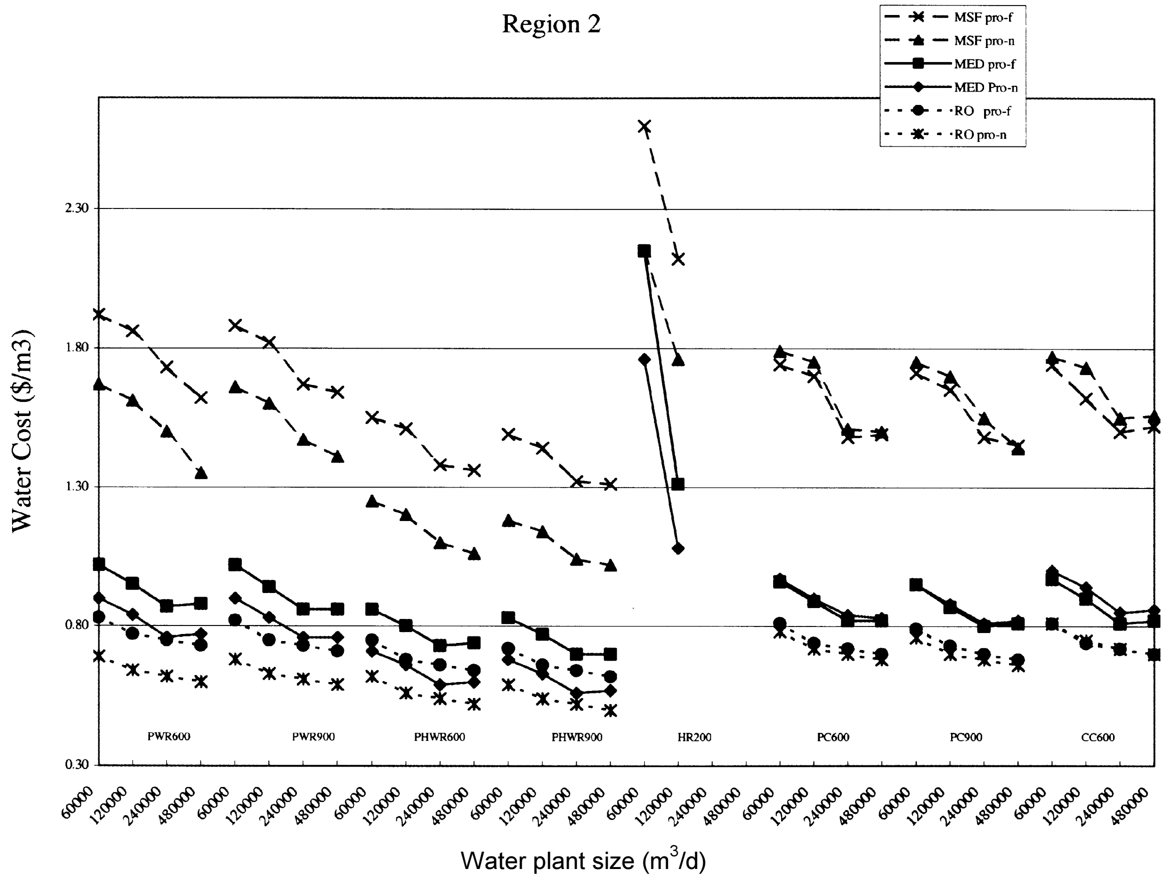

FIG. 6. Results of DEEP calculations for Region 2.

TABLE 11. RESULTS OF DEEP CALCULATIONS FOR REGION 3

Power option	Levelized electricity cost $/kW·h		Desal. plant size m^3/d	Net saleable electricity (with MED) MW(e)	Net saleable water m^3/d	Levelized water cost $/m^3					
	S_N	S_F				MED S_N	MED S_F	MSF S_N	MSF S_F	RO S_N	RO S_F
PWR-600	0.043	0.062	60 000	587.10	53 876	0.89	1.02	1.65	1.89	0.75	0.90
			120 000	575.40	107 751	0.83	0.94	1.59	1.83	0.69	0.83
			240 000	553.70	215 502	0.76	0.86	1.48	1.69	0.67	0.81
			480 000	504.90	431 004	0.76	0.87	1.35	1.62	0.65	0.79
PWR-900	0.041	0.058	60 000	886.70	53 876	0.89	1.01	1.63	1.85	0.74	0.88
			120 000	875.00	107 751	0.82	0.93	1.58	1.79	0.68	0.81
			240 000	853.20	215 502	0.75	0.84	1.45	1.64	0.66	0.79
			480 000	806.90	431 004	0.75	0.85	1.39	1.62	0.64	0.77
PHWR-600	0.029	0.043	60 000	648.10	54 272	0.70	0.85	1.23	1.53	0.66	0.81
			120 000	636.40	108 543	0.65	0.79	1.19	1.48	0.60	0.74
			240 000	614.70	217 087	0.58	0.72	1.08	1.36	0.58	0.71
			480 000	566.50	434 174	0.59	0.73	1.05	1.35	0.56	0.69
PHWR-900	0.027	0.039	60 000	841.80	54 277	0.67	0.82	1.17	1.47	0.63	0.78
			120 000	830.10	108 554	0.62	0.76	1.13	1.42	0.58	0.71
			240 000	808.30	217 108	0.56	0.69	1.02	1.29	0.56	0.69
			480 000	762.10	434 216	0.56	0.69	1.00	1.28	0.54	0.67
HR-200			60 000		57 105	1.76	2.15	2.15	2.60		
			120 000		116 143	1.08	1.31	1.76	2.12		
PC-600	0.061	0.052	60 000	587.80	53 876	0.94	0.94	1.74	1.70	0.85	0.87
			120 000	576.40	107 751	0.88	0.87	1.70	1.65	0.79	0.80
			240 000	554.00	215 502	0.82	0.80	1.48	1.46	0.76	0.78
			480 000	490.90	431 004	0.81	0.81	1.48	1.48	0.74	0.76
PC-900	0.056	0.048	60 000	887.40	53 876	0.93	0.93	1.70	1.66	0.82	0.85
			120 000	876.00	107 751	0.86	0.85	1.65	1.61	0.76	0.78
			240 000	855.00	215 502	0.79	0.78	1.51	1.47	0.74	0.76
			480 000	805.80	431 004	0.80	0.79	1.43	1.43	0.72	0.74
CC-600	0.063	0.048	60 000	487.10	53 876	0.97	0.95	1.73	1.69	0.87	0.87
			120 000	475.40	107 751	0.91	0.88	1.69	1.60	0.81	0.80
			240 000	448.80	215 502	0.83	0.80	1.54	1.49	0.79	0.77
			480 000	396.10	431 004	0.84	0.81	1.54	1.50	0.77	0.75

TABLE 12. RESULTS OF DEEP CALCULATIONS FOR REGION 1 OUTLOOK

Power option	Levelized electricity cost $/kW·h		Desalination plant size m^3/d	Net saleable electricity (with MED) MW(e)	Net saleable water m^3/d	Levelized water cost $/ m^3	
	S_N	S_F				RO S_N	RO S_F
HTR-100	0.015	0.024	120 000	200.50	131 028	0.47	0.58
			240 000	179.20	240 219	0.44	0.55
			480 000	136.70	458 600	0.42	0.53

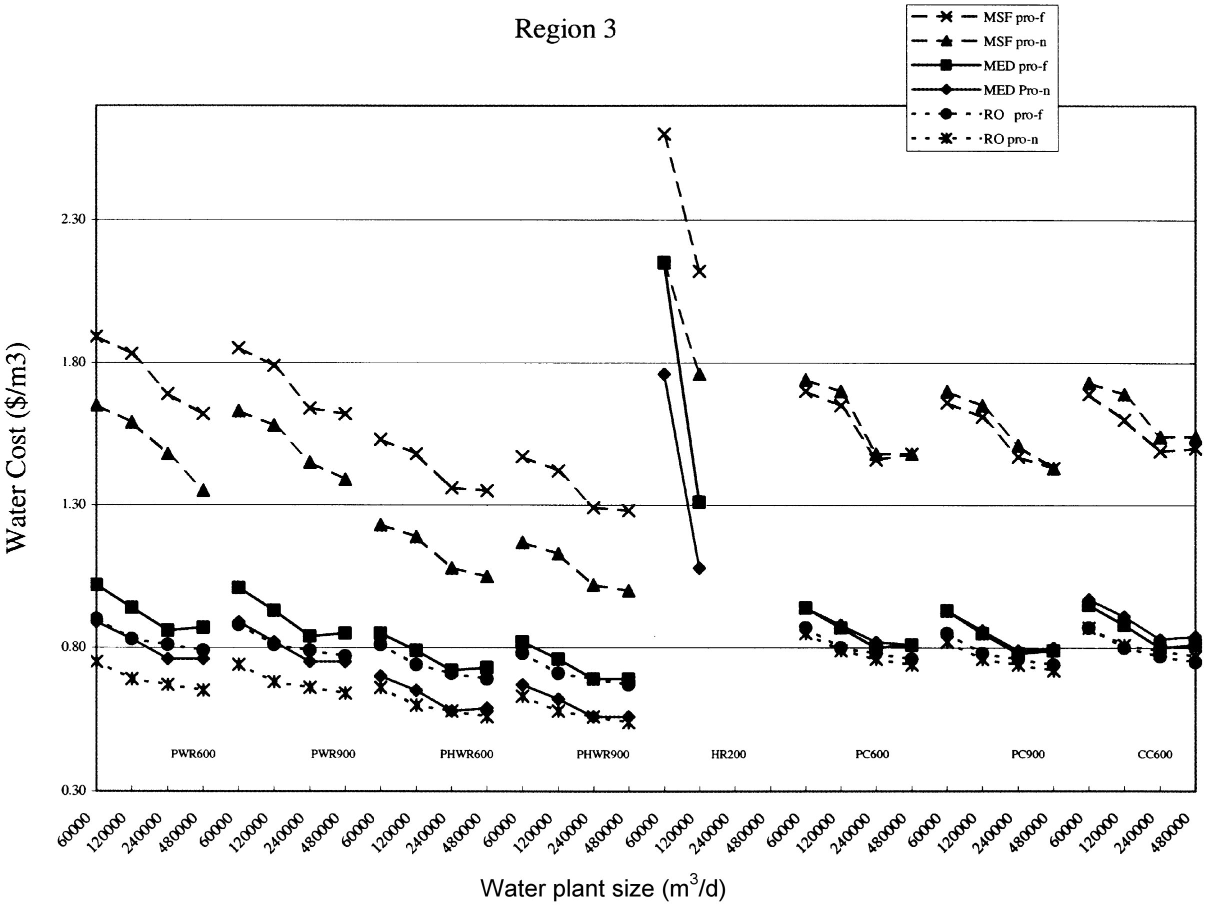

FIG. 7. Results of DEEP calculations for Region 3.

4.2.2. Sensitivity study results

The main purpose of the sensitivity analysis was to identify and quantify factors that have an important effect on the results obtained from the reference cases undertaken as a part of the regional study. In order to provide a consistent basis for comparison, the sensitivity calculations were carried out for three power plants of the same power level (PWR-600, PHWR-600 and CC-600). It was not the intent of this analysis to compare desalination processes, but rather a comparison was made within MED and within RO with respect to major parameters such as discount rate, desalination capacity, fossil fuel cost and overnight cost. To the maximum extent possible, all parameters other than those specifically being changed for the sensitivity analysis were held constant.

An overall summary of results is presented in Table 13. and Figure 8 for the PWR-600, Table 14 and Figure 9 for the PHWR-600, and Table 15 and Figure 10 for the CC-600.

Data from these tables, as well as additional DEEP calculations carried out by INET, has been presented in subsequent sections for each of the parameters having a significant impact on water costs.

TABLE 13. RESULTS OF DEEP SENSITIVITY CALCULATIONS FOR PWR-600

			Levelized water cost $\$/m^3$	
		%	**MED**	**RO**
Average management (labour) salary	160 000 (80 000)		0.79	0.66
	110 000 (55 000)	**100**	**0.77**	**0.65**
	66 000 (30 000)		0.76	0.63
Desalination size (m^3/d)	60 000	25	0.93	0.74
	120 000	50	0.85	0.67
	240 000	**100**	**0.77**	**0.65**
	480 000	200	0.78	0.62
Seawater TDS (ppm) and temperature (°C)	38 000 and 20		0.78	0.62
	41 000 and 25	**100**	**0.77**	**0.65**
	45 000 and 30		0.76	0.70
Discount/interest rate (%)	5	62.5	0.63	0.53
	8	**100**	**0.77**	**0.65**
	10	125	0.88	0.74
Fossil fuel cost ($/boe)	10	40	0.71	0.65
	20	80	0.75	0.65
	25	**100**	**0.77**	**0.65**
	30	120	0.80	0.65
Power plant cost	Table 7 + 15%	85	0.81	0.68
	Table 7	**100**	**0.77**	**0.65**
	Table 7 – 15%	115	0.74	0.62

* The bold values define the base case.

TABLE 14. RESULTS OF DEEP SENSITIVITY CALCULATIONS FOR PHWR-600

			Levelized water cost $/m^3	
		%	**MED**	**RO**
Average management (labour) salary	160 000 (80 000)		0.63	0.58
	110 000 (55 000)	**100**	**0.62**	**0.57**
	66 000 (30 000)		0.60	0.56
Desalination size (m^3/d)	60 000	25	0.76	0.66
	120 000	50	0.69	0.60
	240 000	**100**	**0.62**	**0.57**
	480 000	200	0.62	0.55
Seawater TDS and temperature (ppm and °C)	38 000 and 20		0.63	0.55
	41 000 and 25	**100**	**0.62**	**0.57**
	45 000 and 30		0.61	0.61
Discount/interest rate (%)	5	62.5	0.48	0.46
	8	**100**	**0.62**	**0.57**
	10	125	0.72	0.65
Fossil fuel cost ($/boe)	10	40	0.609	0.569
	20	80	0.615	0.569
	25	**100**	**0.618**	**0.569**
	30	120	0.621	0.569
Power plant cost	Table 7 + 15%	85	0.64	0.59
	Table 7	**100**	**0.62**	**0.57**
	Table 7 – 15%	115	0.59	0.54

* The bold values define the base case.

TABLE 15. RESULTS OF DEEP SENSITIVITY CALCULATIONS FOR CC-600

			Levelized water cost $\$/m^3$	
		%	**MED**	**RO**
Average management (labour) salary	160 000 (80 000)		0.82	0.71
	110 000 (55 000)	**100**	**0.81**	**0.70**
	66 000 (30 000)		0.79	0.69
Desalination size (m^3/d)	60 000	25	0.97	0.80
	120 000	50	0.90	0.73
	240 000	**100**	**0.81**	**0.70**
	480 000	200	0.81	0.68
Seawater TDS and temperature (ppm and °C)	38 000 and 20		0.82	0.67
	41 000 and 25	**100**	**0.81**	**0.70**
	45 000 and 30		0.79	0.76
Discount/interest rate (%)	5	62.5	0.70	0.62
	8	**100**	**0.81**	**0.70**
	10	125	0.89	0.77
Fossil fuel cost ($/boe)	10	40	0.66	0.62
	20	80	0.76	0.68
	25	**100**	**0.81**	**0.70**
	30	120	0.85	0.73
Power plant cost	Table 7 + 15%	85	0.82	0.72
	Table 7	**100**	**0.81**	**0.70**
	7 – 15%	115	0.79	0.69

* The bold values define the base case.

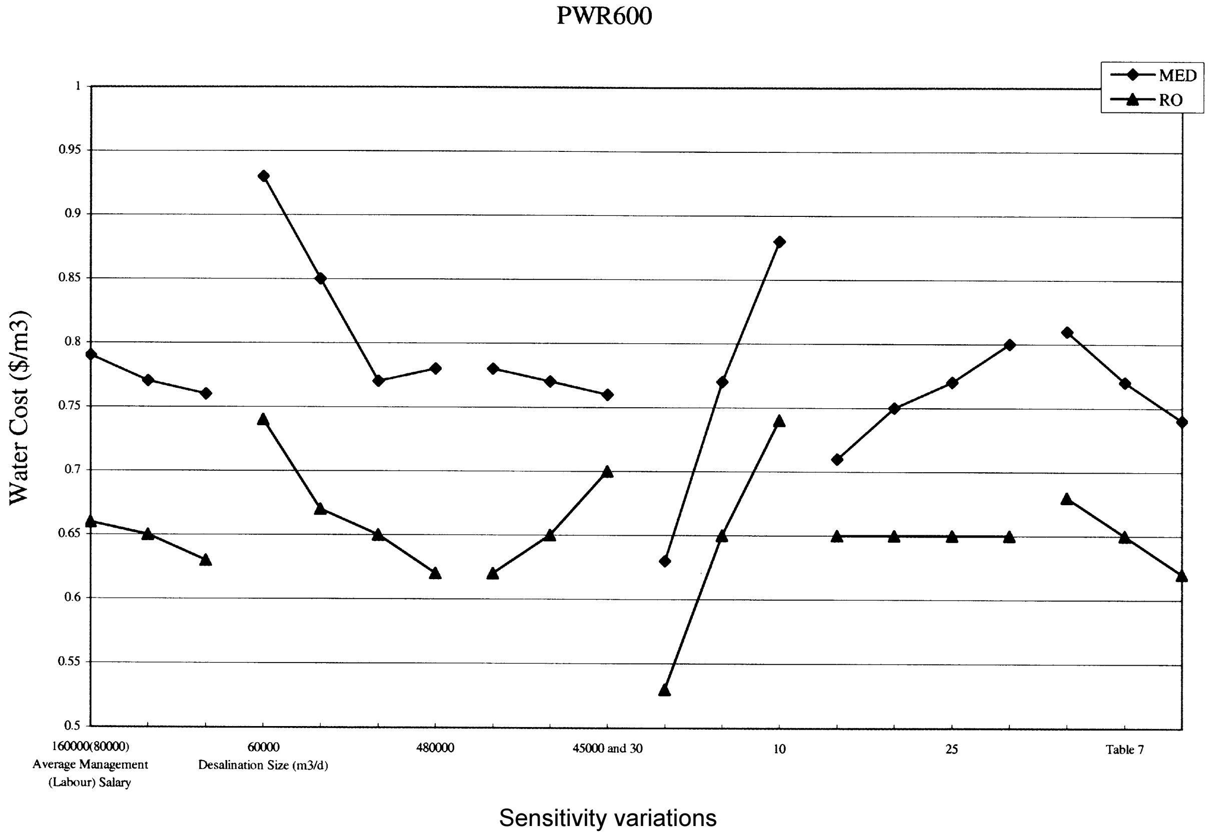

FIG. 8. Results of DEEP sensitivity calculations for PWR-600.

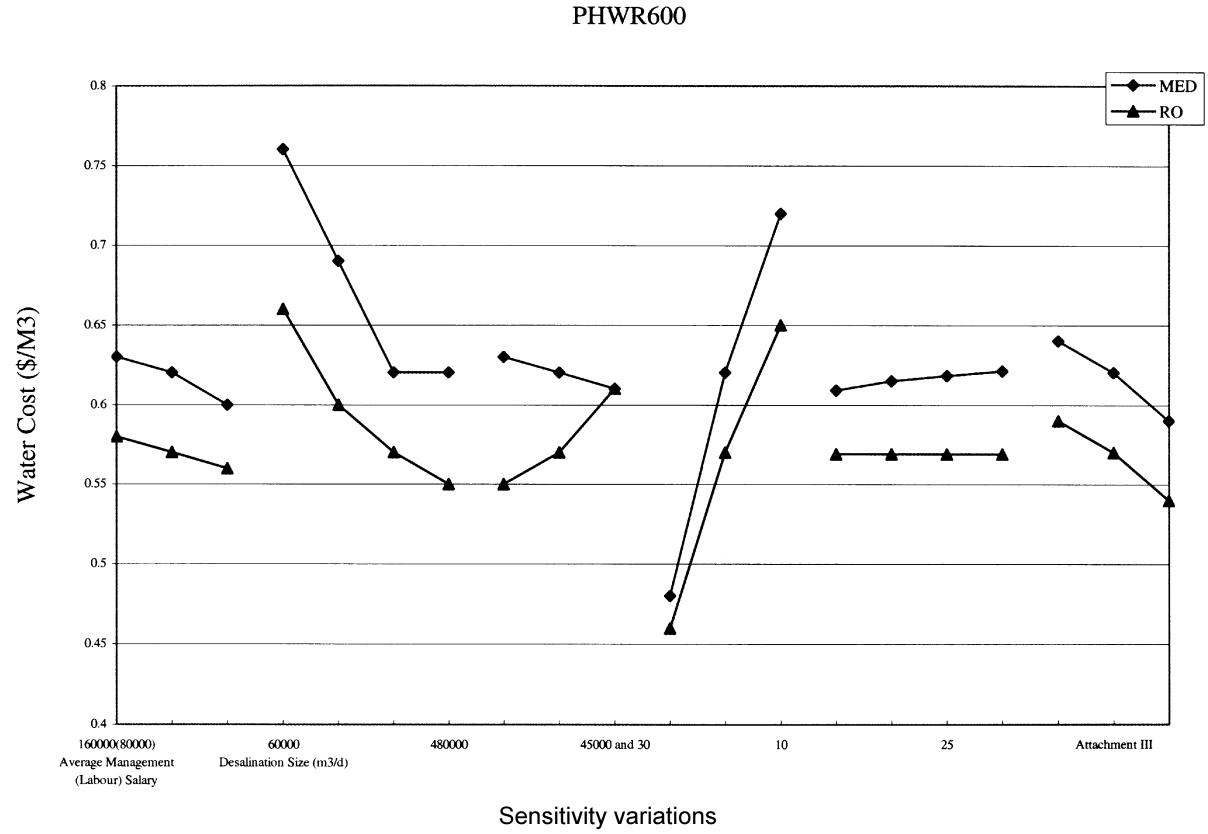

FIG. 9. Results of DEEP sensitivity calculations for PHWR-600.

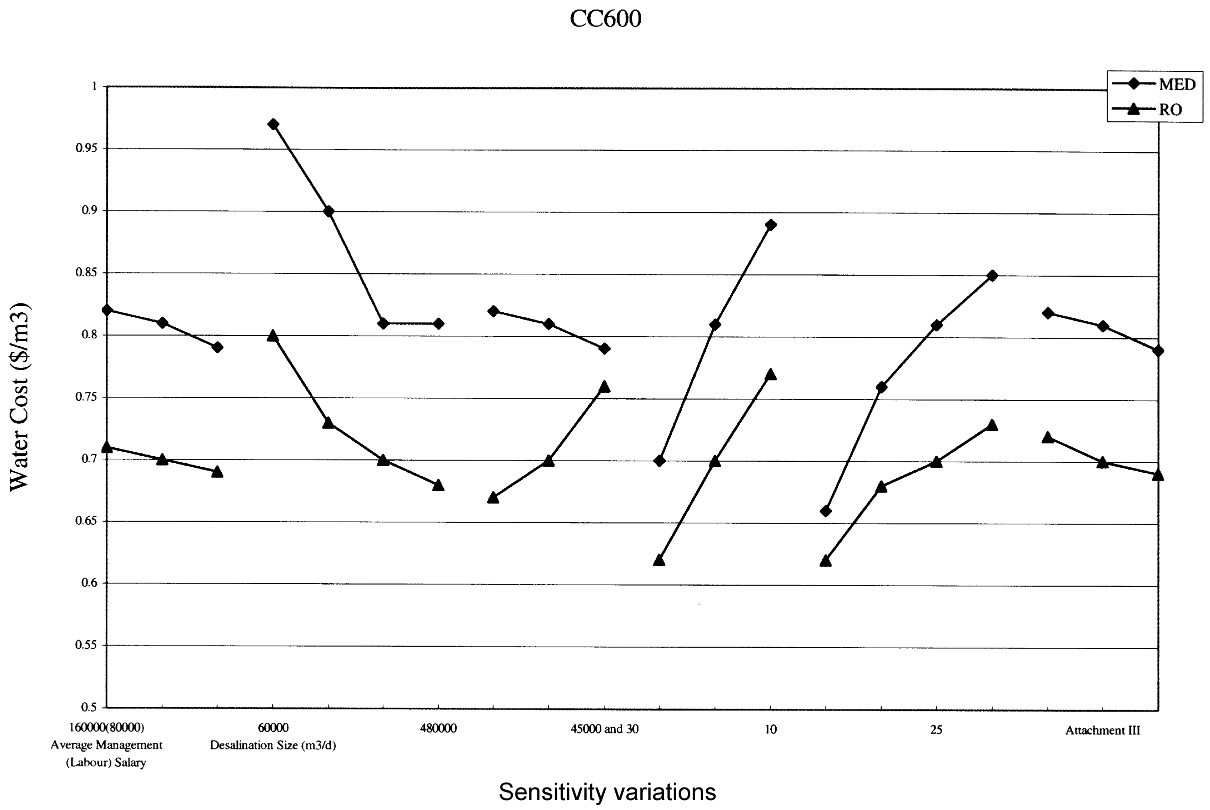

FIG. 10. Results of DEEP sensitivity calculations for CC-600.

5. ANALYSIS OF RESULTS FOR LARGE AND MEDIUM SIZED POWER PLANTS

5.1. General findings

5.1.1. Overall observations

The purpose of this section is to summarize the key observations and findings that derive from the "raw" results obtained from the INET DEEP calculations. In doing so, it is emphasized that the findings are valid and meaningful primarily from the perspective of the DEEP assessment. Some of the indications emerging from the analysis of results may also have a more general validity, provided that they are not affected adversely by specific characteristics of the DEEP code. It should also be noted that the results must be interpreted as generic results; that is, they are affected by the adoption of certain technical and economic input data and assumptions that do not necessarily reflect the conditions of a specific project in any particular Member State.

Within the framework of these conditions and of the calculation assumptions, it can be noted that in general the relative competitiveness of desalination between the nuclear energy options and fossil energy options is strongly dependent on the power plant costs and the cost of fossil fuel. An economically stable economy with low interest and discount rates would favour nuclear desalination, particularly if combined with high fossil fuel costs. Considering the high potential for increasing fossil fuel prices, the nuclear options are relatively attractive and should be studied very carefully on a case-by-case basis when considering seawater desalination as a source of potable water supply.

Detailed analysis results are provided in the following sections. In summary, though, among the more salient findings it can be noted that:

— Desalination costs range from 0.40 $/m^3$ to about 1.90 $/m^3$ depending upon the water plant type and size, energy source, specific region and economic scenarios.

— Over a wide range of power sources and regional conditions, the differences between the water production costs by RO and MED tend to be small as compared to the large differences introduced by changes in discount rate.

— Independent of the energy sources and regions considered, in all investigated cases water production costs from MSF appear to be systematically higher than those from RO or MED.

— If a relatively less stringent drinking water standard, such as WHO rather than EU, is adopted then whatever the energy source, the required desalination capacity or the region, water costs from RO are systematically lower than from other desalination processes.

— Water production costs with small reactors dedicated to heat production only are systematically higher compared to larger dual-purpose nuclear reactors. Thus for example, for the MED process the water production costs from the heat-only reactor are about 30–40% higher than those from the dual-purpose reactor with the highest water costs, mainly because energy costs are higher roughly by a factor of 2.

5.1.2. Power costs

In dual-purpose plants, designed for the production of both water and electricity, the cost of electrical power production is an important parameter both because of its contribution to the cost of water production and its potential for revenue generation as a separate commodity. The following general findings regarding the levelized cost of electrical power generation can be noted:

— The PHWR yields the lowest electricity costs (with the exception of the HTR-100, which has been treated as a separate case in this study). Under the high availability assumptions made in this study, generation cost ranges from about 0.02 $/kW·h (Region 1, 900 MW(e)) to 0.04 $/kW·h (Regions 2 & 3, 600 MW(e)).

- Electricity costs from PWR and PC plants are comparable, although under certain extreme conditions power costs from a PWR can be as much as 35% lower or 22% higher that those from a PC plant.
- For each technology, economy of scale plays a fair role; the power costs are reduced by as much as 0.05 \$/kW·h as the capacity increases from 600 to 900 MW(e). In some cases, technological advances, including advanced construction techniques leading to shorter construction times, have tended to minimize the impact of economy of scale.
- Mainly due to lower discount rates, the power costs in Region 1 are lower by 10-30% than in Regions 2 and 3. There are almost no differences between the power costs in Regions 2 and 3 since the effect of the higher discount rate assumed for these regions is the overriding effect (the discount rate assumed for Regions 2 and 3 are the same, and are higher than for Region 1).

5.1.3. Water costs

Water production costs are highly dependent on site-specific input data and assumptions, particularly electricity costs and economic assumptions. Nevertheless, some general observations can be made, as summarized below:

- For the S_N scenario (economic conditions favouring nuclear power), the nuclear option appears to be particularly advantageous with both RO and MED.
- For the S_F scenario (economic conditions favouring fossil power), costs from nuclear and fossil options are comparable.
- Water costs from RO systems are typically lower than those from MED systems (varying mostly from 10 to 30% in favour of RO). This gives RO an economic advantage even though its product water has a higher TDS content than that from MED.
- The water costs from RO are underestimated, due to the assumption of equivalence between the price of grid electricity used during unavailability periods of power production plants and the production cost calculated by DEEP for the specific power plant.
- Water costs from MSF systems are significantly higher than those from MED systems (by as much as 0.45–0.90 \$/m^3). The difference between MSF and RO is even greater.
- There appears to be a relatively significant economy of scale as plant capacities increase. This effect is more pronounced for lower sized plants. For higher capacities, the economics of scale are only a few percent of the water production costs.
- Water production costs in Regions 2 and 3 are higher than in Region 1, mainly because of the predominant effect of higher discount rates in Regions 2 and 3.

5.2. Regional analysis

5.2.1. Scenarios favouring the economics of nuclear energy (S_N)

As noted in Section 4.1.5, economic scenarios in which interest/discount rates are low and fossil fuel costs are high tend to favour the economics of nuclear as an energy source for desalination. The results from DEEP calculations using such an economic scenario, labelled S_N, have been extracted from the tables in Section 4.2 and presented here to illustrate water costs under such a scenario, by region, for each of the 3 desalination processes studied. To facilitate a comparison, energy sources of similar size have been grouped together in the following tables.

5.2.1.1. MED

Water costs for MED systems coupled to 600 MW(e) power plants are given in Table 16 and for MED systems coupled to 900 MW(e) power plants in Table 17.

It can be seem from these tables that under the economic conditions of scenario S_N the cost of water produced from MED systems coupled to nuclear power plants is always lower than that from fossil power plants, for all regions and at all water production capacities.

TABLE 16. SCENARIO S_N LEVELIZED WATER COSTS FOR THE MED PROCESS BY REGION COUPLED WITH 600 MW(e) POWER PLANTS

Water production costs for 600 MW(e) power plants coupled to an MED system
\$/m^3

Region	60 000 m^3/d water production capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	—	—	—	—
Region 2	0.90	0.71	0.97	1.00
Region 3	0.89	0.70	0.94	0.97

Region	120 000 m^3/d water production capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	0.73	0.56	0.82	0.89
Region 2	0.84	0.66	0.90	0.94
Region 3	0.83	0.65	0.88	0.91

Region	240 000 m^3/d water production capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	0.66	0.49	0.76	0.79
Region 2	0.76	0.59	0.84	0.85
Region 3	0.76	0.58	0.82	0.83

Region	480 000 m^3/d water production capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	0.65	0.48	0.72	0.78
Region 2	0.77	0.60	0.83	0.86
Region 3	0.76	0.59	0.81	0.84

TABLE 17. SCENARIO S_N LEVELIZED WATER COSTS FOR THE MED PROCESS BY REGION COUPLED WITH 900 MW(e) POWER PLANTS

Water production costs for 900 MW(e) energy sources coupled to an MED system
$/$m^3$

Region	60 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	0.90	0.68	0.95
Region 3	0.89	0.67	0.93

Region	120 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.73	0.52	0.81
Region 2	0.83	0.63	0.88
Region 3	0.82	0.62	0.86

Region	240 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.66	0.46	0.73
Region 2	0.76	0.56	0.81
Region 3	0.75	0.56	0.79

Region	480 000 m^3/d Water Production Capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.64	0.44	0.73
Region 2	0.76	0.57	0.82
Region 3	0.75	0.56	0.80

5.2.1.2. MSF

Water costs for MSF systems coupled to 600 MW(e) power plants are given in Table 18 and for MSF systems coupled to 900 MW(e) power plants in Table 19.

It can be seen from these tables that under the economic conditions of scenario S_N the cost of water produced from MSF systems coupled to nuclear power plants is always lower than that from MSF coupled to either the PC or CC fossil power plants, for all regions and at all water production capacities. The PHWR, because of its low energy cost, produced the lowest cost water under all conditions.

TABLE 18. SCENARIO S_N LEVELIZED WATER COST FOR THE MSF PROCESS BY REGION COUPLED WITH 600 MW(e) POWER PLANTS

Water production costs for 600 MW(e) energy sources coupled to MSF systems
$/m^3

Region	60 000 m^3/d water production capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	—	—	—	—
Region 2	1.67	1.25	1.79	1.77
Region 3	1.65	1.23	1.74	1.73

Region	120 000 m^3/d water production capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	—	—	—	—
Region 2	1.61	1.20	1.75	1.73
Region 3	1.59	1.19	1.70	1.69

Region	240 000 m^3/d water production capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	—	—	—	—
Region 2	1.50	1.10	1.51	1.55
Region 3	1.48	1.08	1.48	1.54

Region	480 000 m^3/d Water Production Capacity			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	—	—	—	—
Region 2	1.35	1.06	1.50	1.56
Region 3	1.35	1.05	1.48	1.54

TABLE 19. SCENARIO S_N LEVELIZED WATER COST FOR THE MSF PROCESS BY REGION COUPLED WITH 900 MW(e) POWER PLANTS

Water production costs for 900 MW(e) energy sources coupled to MSF systems
$/m^3

Region	60 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	1.66	1.18	1.75
Region 3	1.63	1.17	1.70

Region	120 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	1.60	1.14	1.70
Region 3	1.58	1.13	1.65

Region	240 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	1.47	1.04	1.55
Region 3	1.45	1.02	1.51

Region	480 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	1.41	1.02	1.44
Region 3	1.39	1.00	1.43

5.2.1.3. RO

Water costs for RO systems coupled to 600 MW(e) power plants are given in Table 20 and for RO systems coupled to 900 MW(e) power plants in Table 21.

It can be seem from these tables that under the economic conditions of scenario S_N the cost of water produced from RO systems coupled to nuclear power plants is always lower than that from fossil power plants, for all regions and at all water production capacities.

TABLE 20. SCENARIO S_N LEVELIZED WATER COST FOR THE RO PROCESS BY REGION COUPLED WITH 600 MW(e) POWER PLANTS

Water production costs for 600 MW(e) energy sources coupled to RO systems
$/m^3

Region	60 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	—	—	—	—
Region 2	0.69	0.62	0.78	0.81
Region 3	0.75	0.66	0.85	0.87

Region	120 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	0.53	0.47	0.62	0.66
Region 2	0.64	0.56	0.72	0.75
Region 3	0.69	0.60	0.79	0.81

Region	240 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	0.51	0.44	0.59	0.63
Region 2	0.62	0.54	0.70	0.72
Region 3	0.67	0.58	0.76	0.79

Region	480 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	0.48	0.42	0.56	0.61
Region 2	0.60	0.52	0.68	0.70
Region 3	0.65	0.56	0.74	0.77

TABLE 21. SCENARIO S_N LEVELIZED WATER COST FOR THE RO PROCESS BY REGION COUPLED WITH 900 MW(e) POWER PLANTS

Water production costs for 900 MW(e) energy sources coupled to RO systems, $/m³

Region	60 000 m³/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	0.68	0.59	0.76
Region 3	0.74	0.63	0.82

Region	120 000 m³/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.53	0.45	0.60
Region 2	0.63	0.54	0.70
Region 3	0.68	0.58	0.76

Region	240 000 m³/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.50	0.42	0.57
Region 2	0.61	0.52	0.68
Region 3	0.66	0.56	0.74

Region	480 000 m³/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.48	0.40	0.55
Region 2	0.59	0.50	0.66
Region 3	0.64	0.54	0.72

5.2.2. Scenarios favouring the economics of fossil energy (S_F)

Economic scenarios in which interest/discount rates are high and fossil fuel costs are low tend to favour the economics of fossil fuel as an energy source for desalination. The results from DEEP calculations using such an economic scenario, labelled S_F, have been extracted from the tables in Section 4.2 and presented here to illustrate water costs under such a scenario, by region, for each of the three desalination processes studied. To facilitate a comparison, energy sources of similar size have been grouped together in the following tables. Water costs for MED and MSF systems coupled to the HR-200 heat-only reactor and for an RO system coupled to the HTR-100 reactor are presented separately.

5.2.2.1. MED

Water costs for MED systems coupled to 600 MW(e) power plants are given in Table 22 and for MED systems coupled to 900 MW(e) power plants in Table 23.

It can be seem from these tables that under the economic conditions of scenario S_F the cost of water produced from MED systems coupled to nuclear power plants is lower than that from fossil power plants for PHWR but higher for PWR, for all regions and at all water production capacities. The latter yields the highest costs, 20 to 25% higher than that from the PHWR. The fossil fuel MED costs fall in the middle of this range.

TABLE 22. SCENARIO S_F LEVELIZED WATER COST FOR THE MED PROCESS BY REGION COUPLED WITH 600 MW(e) POWER PLANTS

Water PRODUCTION COSTS FOR 600 MW(e) energy sources coupled to MED systems $/m^3

Region	60 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	—	—	—	—
Region 2	1.03	0.86	0.96	0.97
Region 3	1.02	0.85	0.94	0.95

Region	120 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	0.88	0.73	0.85	0.88
Region 2	0.95	0.80	0.89	0.90
Region 3	0.94	0.79	0.87	0.88

Region	240 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	0.79	0.65	0.78	0.77
Region 2	0.87	0.73	0.82	0.81
Region 3	0.86	0.72	0.80	0.80

Region	480 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	0.79	0.65	0.75	0.77
Region 2	0.88	0.74	0.82	0.82
Region 3	0.87	0.73	0.81	0.81

TABLE 23. SCENARIO S_F LEVELIZED WATER COST FOR THE MED PROCESS BY REGION COUPLED WITH 900 MW(e) POWER PLANTS

Water production costs for 900 MW(e) energy sources coupled to MED systems
$/m^3

Region	60 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	1.02	0.83	0.95
Region 3	1.01	0.82	0.93

Region	120 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.87	0.70	0.84
Region 2	0.94	0.77	0.87
Region 3	0.93	0.76	0.85

Region	240 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.78	0.62	0.75
Region 2	0.86	0.70	0.80
Region 3	0.84	0.69	0.78

Region	480 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.77	0.62	0.75
Region 2	0.86	0.70	0.81
Region 3	0.85	0.69	0.79

5.2.2.2. MSF

Water costs for MSF systems coupled to 600 MW(e) power plants are given in Table 24 and for MSF systems coupled to 900 MW(e) power plants in Table 25.

It can be seem from these tables that under the economic conditions of scenario S_F the cost of water produced from MSF systems coupled to nuclear power plants follow the same pattern as MED with regards to PWR, fossil units and PHWR.

Quantitatively, the ratio between PWR and PWHR costs is closer to 1.25 while for MED it is about 1.2.

The costs of MSF versus MED are higher by 90 to 100%.

TABLE 24. SCENARIO S_F LEVELIZED WATER COST FOR THE MSF PROCESS BY REGION COUPLED WITH 600 MW(e) POWER PLANTS

Water production costs for 600 MW(e) energy sources coupled to MSF systems
$\$/m^3$

Region	60 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	—	—	—	—
Region 2	1.92	1.55	1.74	1.74
Region 3	1.89	1.53	1.70	1.69

Region	120 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	—	—	—	—
Region 2	1.86	1.51	1.70	1.62
Region 3	1.83	1.48	1.65	1.60

Region	240 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	—	—	—	—
Region 2	1.73	1.38	1.48	1.50
Region 3	1.69	1.36	1.46	1.49

Region	480 000 m^3/d water production capacity			
	PWR-600	PHWR-600	PC-600	CC-600
Region 1	—	—	—	—
Region 2	1.62	1.36	1.49	1.52
Region 3	1.62	1.35	1.48	1.50

TABLE 25. SCENARIO S_F LEVELIZED WATER COST FOR THE MSF PROCESS BY REGION COUPLED WITH 900 MW(e) POWER PLANTS

Water production costs for 900 MW(e) energy sources coupled to MSF systems
$/m³

Region	60 000 m³/d water production capacity		
	PWR-900	**PHWR-900**	**PC-900**
Region 1	—	—	—
Region 2	1.88	1.49	1.71
Region 3	1.85	1.47	1.66

Region	120 000 m³/d water production capacity		
	PWR-900	**PHWR-900**	**PC-900**
Region 1	—	—	—
Region 2	1.82	1.44	1.65
Region 3	1.79	1.42	1.61

Region	240 000 m³/d water production capacity		
	PWR-900	**PHWR-900**	**PC-900**
Region 1	—	—	—
Region 2	1.67	1.32	1.48
Region 3	1.64	1.29	1.47

Region	480 000 m³/d water production capacity		
	PWR-900	**PHWR-900**	**PC-900**
Region 1	—	—	—
Region 2	1.64	1.31	1.45
Region 3	1.62	1.28	1.43

5.2.2.3. RO

Water costs for RO systems coupled to 600 MW(e) power plants are given in Table 26 and for RO systems coupled to 900 MW(e) power plants in Table 27.

It can be seem from these tables that under the economic conditions of scenario S_F the cost of water produced from RO systems coupled to PHWR are lowest, due to its very low electricity cost. Fossil units and PWR yield a higher water cost, following qualitatively but not quantitatively, their power production cost.

Thus, for example, fossil PC-600 has a 0.01 \$/kW·h advantage over PWR and with 5 kW·h/m³ the expected difference in water costs is 0.05 \$/m³, while the table shows only 0.02 \$/m³ (Region 2, 60 000 m³/d).

TABLE 26. SCENARIO S_F LEVELIZED WATER COST FOR THE RO PROCESS BY REGION COUPLED WITH 600 MW(e) POWER PLANTS

Water production costs for 600 MW(e) energy sources coupled to RO systems
$/m^3

Region	**60 000 m^3/d water production capacity**			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	—	—	—	—
Region 2	0.83	0.75	0.81	0.81
Region 3	0.90	0.81	0.87	0.87

Region	**120 000 m^3/d water production capacity**			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	0.67	0.60	0.67	0.68
Region 2	0.77	0.68	0.74	0.74
Region 3	0.83	0.74	0.80	0.80

Region	**240 000 m^3/d water production capacity**			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	0.64	0.57	0.64	0.65
Region 2	0.75	0.66	0.72	0.72
Region 3	0.81	0.71	0.78	0.77

Region	**480 000 m^3/d water production capacity**			
	PWR-600	**PHWR-600**	**PC-600**	**CC-600**
Region 1	0.62	0.55	0.61	0.62
Region 2	0.73	0.64	0.70	0.70
Region 3	0.79	0.69	0.76	0.75

TABLE 27. SCENARIO S_F LEVELIZED WATER COST FOR THE RO PROCESS BY REGION COUPLED WITH 900 MW(e) POWER PLANTS

Water production costs for 900 MW(e) energy sources coupled to RO systems
$/m^3

Region	60 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	—	—	—
Region 2	0.82	0.72	0.79
Region 3	0.88	0.78	0.85

Region	120 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.66	0.58	0.66
Region 2	0.75	0.66	0.73
Region 3	0.81	0.71	0.78

Region	240 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.63	0.55	0.63
Region 2	0.73	0.64	0.70
Region 3	0.79	0.69	0.76

Region	480 000 m^3/d water production capacity		
	PWR-900	PHWR-900	PC-900
Region 1	0.61	0.53	0.60
Region 2	0.71	0.62	0.68
Region 3	0.77	0.67	0.74

5.3. Comparative analysis of nuclear vs fossil energy sources for desalination

5.3.1. Qualitative considerations

In general, the economics of nuclear desalination is driven by the same factors as the economics of nuclear electricity generation. Lower power generation costs and increased importance of environmental considerations would lead to a better competitive position for nuclear energy in comparison with power plants using fossil fuels. Therefore, the same factors that are known to improve economics of nuclear power plants would also have a positive effect on the economics of nuclear desalination. These factors include, for example, lower specific overnight costs, shorter construction period, higher capital availability (i.e., lower discount rates) and the expectation of increasing fossil fuel prices.

At the same time, there are some additional factors that are specific for desalination and that may make nuclear desalination better or, alternatively, worse than desalination schemes using fossil fuels. These factors, some of which are also discussed in Reference [7], are discussed below.

5.3.1.1. Effect of a higher load factor (+)

Normally, Nuclear plants operate in the base-load mode due to their low operating costs. If a desalination plant is coupled with such a nuclear plant, steady and predictable operation of the power plant would have a positive effect on the availability of the desalination plant and, consequently, on the costs of water.

5.3.1.2. Availability of larger amounts of heat (+)

Due to a number of factors, nuclear plants generally have a lower thermal efficiency than fossil fuel plants. Thus, nuclear plants produce larger amounts of energy potentially available for desalination. Moreover, even higher availability can be also expected in terms of steam, because almost all of the rejected heat of a nuclear plant goes to the steam condensers, while for fossil fuel plants some 15-20% of the rejected heat is useless, being directed to the atmosphere with the flue gases. Thus, for MED or MSF, the maximum amount of water that can be desalted (per unit of electricity generated) is considerably higher. Also, due to the economy of scale, if the higher production potential is realized, the cost of desalted water decreases.

5.3.1.3. Effect of reducing the final vapour moisture (+)

Usually, nuclear power plants provide saturated steam to the turbine. Consequently, nuclear plant turbines operate with an average moisture value higher than in the case of fossil fuelled plants, where the use of super-heated steam is usual. Therefore, energy and economic losses due to steam moisture are higher for nuclear plants than for fossil fuelled plants. Consequently, using steam extracted from the last turbine stages for desalination by MED or MSF would have a more positive effect for nuclear plants.

5.3.1.4. Effect of an additional loop (–)

In addition to the listed factors with anticipated positive impact on the competitiveness of nuclear desalination, one should note that a possible need to introduce an additional loop separating the nuclear and the desalination side, thus isolating the secondary circuit of the power plant from the desalination circuit could have a potentially negative effect on the economics of nuclear desalination using the MED (or MSF) process. This loop should have a higher pressure than the secondary circuit of the power plant. If the additional loop is required to achieve the desired level of safety, either as a result of safety analyses or as a requirement imposed by the regulatory authority, then it must be included as a part of the plant. This would be a factor tending to increase the water costs from distillation processes. For RO plants this additional circuit is not as likely to be required, and hence may be an additional economic advantage for RO.

5.3.1.5. Effect of reliability requirements (–)

Another factor that could have a negative impact on the cost of water produced using nuclear energy sources is the high requirement for reliability of water supply. Nuclear reactors typically have a lower availability than do desalination plants. In order to ensure a reliable water supply, a backup source of energy may be required. In the case of distillation processes this would most likely be a backup boiler, adding to the capital cost of the system and hence to the cost of water. For RO systems the desalination plant can draw its electrical supply from the grid in the event of a reactor shutdown, and hence an on-site source of backup power is not required. This would be a competitive advantage for RO systems.

5.3.2. Quantitative considerations

The results of the DEEP calculations carried out by INET were used to derive indices that could give a more quantitative evaluation of the relative competitiveness of the nuclear and fossil options as energy sources for seawater desalination. The derivation and conclusions arising from these indices are presented in the following sections. As a reminder, it should be noted that all conclusions regarding competitiveness of various options are limited by the input data and assumptions of the study and so are valid only within its scope.

5.3.2.1. Analysis approach

Cost ratios C_W and C_E have been defined by INET as:

$$C_W = \frac{\text{Cost of water with nuclear option}}{\text{Cost of water with fossil option}}$$

$$C_E = \frac{\text{Cost of electricity with nuclear option}}{\text{Cost of electricity with fossil option}}$$

Three competitiveness indicators are then defined as follows:

$$I_1 = C_W \text{ where the ratio is based on } \frac{\text{(Nuclear worst variant)}}{\text{(Fossil best variant)}}$$

$$I_2 = C_W \text{ where the ratio is based on } \frac{\text{(Nuclear best variant)}}{\text{(Fossil worst variant)}}$$

$$I_3 = C_W \text{ where the ratio is based on } \frac{\text{(Nuclear best variant)}}{\text{(Fossil best variant)}}$$

Based on these indicators, it can be seen that:

- If $I_1 < 1$ then the nuclear option is clearly the most competitive (i.e., most economical).
- If $I_2 > 1$ then the fossil option is clearly the most competitive (i.e., most economical).
- If $I_1 > 1$ or $I_2 < 1$ then further assessment is required and the result may favour either the nuclear or fossil option.
- If $I_3 < 1$ N then the nuclear option is the most competitive under the most favourable conditions (typically the most technologically advanced options) and either the nuclear or fossil options could be favourable where less advanced options are acceptable.

Using electricity and water cost data from Table 9, Table 10 and Table 11 as input, six new tables were generated to display the bounding values for each of these indicators for each region. The following abbreviations are used in these tables, which are presented in the sections below.

- N_B — nuclear best variant
- N_W — nuclear worst variant
- F_B — fossil best variant
- F_W — fossil worst variant.

5.3.2.2. Analysis of competitiveness

For Region 1

Table 28 summarizes the bounding results of the INET calculations for Region 1 and Table 29 provides a comparison of these results using the indices defined above.

From the results presented in these tables, it can be seen that:

- For the S_N scenario, having economic conditions that favour nuclear, the nuclear option is clearly the best both with MED and RO.
- Even for the S_F scenario, having economic conditions that favour fossil, no cases were identified where the fossil option is obviously preferable. Nuclear power should be considered as an energy source for any seawater desalination project in this region.
- The best variant within the nuclear option is always better than best variant within the fossil option.

TABLE 28. BOUNDING RESULTS FOR REGION 1

	Levelized electricity cost		**Desalination plant size**	**Levelized water cost US \$/m^3**			
	US \$/kW·h		**m^3/d**	**MED**		**RO**	
	S_N	**S_F**		**S_N**	**S_F**	**S_N**	**S_F**
N_B	0.019	0.031	120 000	0.52	0.70	0.45	0.58
			240 000	0.46	0.62	0.42	0.55
			480 000	0.44	0.62	0.40	0.53
N_W	0.032	0.050	120 000	0.73	0.88	0.53	0.67
			240 000	0.66	0.79	0.51	0.64
			480 000	0.65	0.79	0.48	0.62
F_B	0.046	0.041	120 000	0.81	0.84	0.60	0.66
			240 000	0.73	0.75	0.57	0.63
			480 000	0.72	0.75	0.55	0.60
F_W	0.059	0.045	120 000	0.89	0.88	0.66	0.68
			240 000	0.79	0.78	0.63	0.65
			480 000	0.78	0.77	0.61	0.62

TABLE 29. COMPARISON OF BOUNDING RESULTS FOR REGION 1

	C_E		**Desalination plant size**	**C_W**			
				MED		**RO**	
	S_N	**S_F**	**m^3/d**	**S_N**	**S_F**	**S_N**	**S_F**
I_1 (N_W/F_B)	0.70	1.22	120 000	0.90	1.05	0.88	1.02
			240 000	0.90	1.05	0.89	1.02
			480 000	0.90	1.05	0.87	1.03
I_2 (N_B/F_W)	0.32	0.69	120 000	0.58	0.79	0.68	0.85
			240 000	0.58	0.79	0.67	0.85
			480 000	0.56	0.80	0.66	0.85
I_3 (N_B/F_B)	0.41	0.76	120 000	0.64	0.83	0.75	0.88
			240 000	0.63	0.83	0.74	0.87
			480 000	0.61	0.83	0.73	0.88

For Regions 2 and 3

Table 30 and Table 32 summarize the bounding results of the INET calculations for Regions 2 and 3, respectively. Table 31 and Table 33 provide a comparison of these results using the indices defined above.

From the results presented in these tables, it can be seen that:

- For the S_N scenario, having economic conditions that favour nuclear, the nuclear option is better that the fossil option with MED and RO, as well as with MSF for capacities up to 120 000 m^3/d.
- Even for the S_F scenario, having economic conditions that favour fossil, no cases were identified where the fossil option is obviously preferable.
- Best variant within N option is always better than best variant within F option for MED and RO.
- The best variant within the nuclear option is always better than best variant within the fossil option for MED and RO. For MSF there is a variant where the best fossil options are better than the nuclear option.
- There is a general trend for higher competitiveness of nuclear options vs. fossil options in Region 1 than in Regions 2 and 3.

TABLE 30. BOUNDING RESULTS FOR REGION 2

	Levelized electricity cost US $/kW·h		**Desalination plant size m^3/d**	**Levelized water cost US $/m^3$**					
				MED		**MSF**		**RO**	
	S_N	**S_F**		**S_N**	**S_F**	**S_N**	**S_F**	**S_N**	**S_F**
N_B	0.026	0.038	60 000	0.68	0.83	1.18	1.49	0.59	0.72
			120 000	0.63	0.77	1.14	1.44	0.54	0.66
			240 000	0.56	0.70	1.04	1.32	0.52	0.64
			480 000	0.57	0.70	1.02	1.31	0.50	0.62
N_W	0.042	0.061	60 000	0.90	1.03	1.67	1.92	0.69	0.83
			120 000	0.84	0.95	1.61	1.86	0.64	0.77
			240 000	0.76	0.87	1.50	1.73	0.62	0.75
			480 000	0.77	0.88	1.41	1.64	0.60	0.73
F_B	0.056	0.047	60 000	0.95	0.95	1.75	1.71	0.76	0.79
			120 000	0.88	0.87	1.70	1.62	0.70	0.73
			240 000	0.81	0.80	1.51	1.48	0.68	0.70
			480 000	0.82	0.81	1.44	1.45	0.66	0.68
F_W	0.063	0.051	60 000	1.00	0.97	1.79	1.74	0.81	0.81
			120 000	0.94	0.90	1.75	1.70	0.75	0.74
			240 000	0.85	0.82	1.55	1.50	0.72	0.72
			480 000	0.86	0.82	1.56	1.52	0.70	0.70

TABLE 31. COMPARISON OF BOUNDING RESULTS FOR REGION 2

	C_E		**Desalination Plant Size**	**C_W**					
				MED		**MSF**		**RO**	
	S_N	**S_F**	**m^3/d**	**S_N**	**S_F**	**S_N**	**S_F**	**S_N**	**S_F**
I_1 (N_W/F_B)	0.75	1.30	60 000	0.95	1.08	0.95	1.12	0.91	1.05
			120 000	0.95	1.09	0.95	1.15	0.91	1.05
			240 000	0.94	1.09	1.00	1.17	0.91	1.07
			480 000	0.94	1.09	0.98	1.13	0.91	1.07
I_2 (N_B/F_W)	0.41	0.74	60 000	0.68	0.85	0.66	0.86	0.73	0.89
			120 000	0.67	0.86	0.65	0.85	0.72	0.89
			240 000	0.66	0.85	0.67	0.88	0.72	0.89
			480 000	0.66	0.85	0.65	0.86	0.71	0.88
I_3 (N_B/F_B)	0.46	0.81	60 000	0.72	0.87	0.67	0.87	0.78	0.91
			120 000	0.72	0.89	0.67	0.89	0.77	0.90
			240 000	0.69	0.87	0.69	0.89	0.76	0.91
			480 000	0.70	0.86	0.71	0.90	0.76	0.91

TABLE 32. BOUNDING RESULTS FOR REGION 3

	Levelized electricity cost US $/kW·h		**Desalination plant size m^3/d**	**Levelized water cost US $/m^3$**					
				MED		**MSF**		**RO**	
	S_N	**S_F**		**S_N**	**S_F**	**S_N**	**S_F**	**S_N**	**S_F**
N_B	0.027	0.039	60 000	0.67	0.82	1.17	1.47	0.63	0.78
			120 000	0.62	0.76	1.13	1.42	0.58	0.71
			240 000	0.56	0.69	1.02	1.29	0.56	0.69
			480 000	0.56	0.69	1.00	1.28	0.54	0.67
N_W	0.043	0.062	60 000	0.89	1.02	1.65	1.89	0.75	0.90
			120 000	0.83	0.94	1.59	1.83	0.69	0.83
			240 000	0.76	0.86	1.48	1.69	0.67	0.81
			480 000	0.76	0.87	1.39	1.62	0.65	0.79
F_B	0.056	0.048	60 000	0.93	0.93	1.70	1.66	0.82	0.85
			120 000	0.86	0.85	1.65	1.60	0.76	0.78
			240 000	0.79	0.78	1.48	1.46	0.74	0.76
			480 000	0.80	0.79	1.43	1.48	0.72	0.74
F_W	0.063	0.052	60 000	0.97	0.95	1.74	1.70	0.87	0.87
			120 000	0.91	0.88	1.70	1.65	0.81	0.80
			240 000	0.83	0.80	1.54	1.49	0.79	0.78
			480 000	0.84	0.81	1.54	1.50	0.77	0.76

TABLE 33. COMPARISON OF BOUNDING RESULTS FOR REGION 3

	C_E		Desalination Plant Size	C_W					
				MED		MSF		RO	
	S_N	S_F	m^3/d	S_N	S_F	S_N	S_F	S_N	S_F
I_1 (N_W/F_B)	0.77	1.29	60 000	0.96	1.10	0.97	1.14	0.91	1.06
			120 000	0.97	1.11	0.96	1.14	0.91	1.06
			240 000	0.96	1.10	1.00	1.16	0.91	1.07
			480 000	0.95	1.10	0.91	1.09	0.90	1.07
I_2 (N_B/F_W)	0.42	0.75	60 000	0.69	0.86	0.67	0.86	0.72	0.90
			120 000	0.68	0.86	0.66	0.86	0.72	0.89
			240 000	0.67	0.86	0.66	0.87	0.71	0.88
			480 000	0.67	0.85	0.65	0.85	0.70	0.88
I_3 (N_B/F_B)	0.48	0.81	60 000	0.72	0.88	0.69	0.89	0.77	0.92
			120 000	0.72	0.89	0.68	0.89	0.76	0.91
			240 000	0.71	0.88	0.69	0.88	0.76	0.91
			480 000	0.70	0.87	0.70	0.86	0.75	0.91

It should be kept in mind that the results presented above depend on the assumed set of parameters for the two competing options - nuclear and fossil energy sources. With variations in the two key parameters, the capital costs for nuclear plants and the cost of fuel for fossil plants, these results and general trends may well change. In this respect, the results of the sensitivity analyses below can give additional insights into the impact of the key economic factors that determine when and why nuclear desalination becomes competitive.

5.4. Sensitivity analysis

5.4.1. Purpose and methodology

As noted previously, the main purpose of sensitivity analysis is to identify and quantify factors that have an important effect on the results obtained from the reference cases undertaken as a part of the regional study. However, because of the wide range of parameters covered, these sensitivity studies also permit a certain degree of verification of the DEEP code through an inspection of the "reasonableness" of the results obtained over the sensitivity range for the various parameters investigated.

In order to provide a consistent basis for comparison, the sensitivity calculations were carried out for three power plants of the same power level (PWR-600, PHWR-600 and CC-600). It was not the intent of this analysis to compare desalination processes, but rather a comparison was made within MED and within RO with respect to major parameters such as discount rate, desalination capacity, fossil fuel cost and assumed overnight cost. To the maximum extent possible, all parameters other than those specifically being changed for the sensitivity analysis were held constant.

5.4.2. Analysis results

An overall summary of the "raw" results from the INET calculations was presented in Table 13. for the PWR-600, Table 14 for the PHWR-600, and Table 15 for the CC-600.

An assessment of the data from these tables, as well as additional DEEP calculations carried out by INET, has been presented in the following sections for each of the parameters having a significant impact on water costs.

TABLE 34. SENSITIVITY OF LEVELIZED WATER COST TO DISCOUNT RATE

Sensitivity parameter	Power plant and desalination plant options					
	PWR-600		PHWR-600		CC-600	
	MED	RO	MED	RO	MED	RO
Discount rate, %	**Levelized water cost, \$/m^3**					
5	0.63	0.53	0.48	0.46	0.70	0.62
8	**0.77**	**0.65**	**0.62**	**0.57**	**0.81**	**0.70**
10	0.88	0.74	0.72	0.65	0.89	0.77
Discount rate, %	**Variation from base case, %**					
5	-18.2	-18.5	-22.6	-19.3	-13.6	-11.4
8	—	—	—	—	—	—
10	14.3	13.8	16.1	14.0	9.9	10.0

5.4.3. Discount rate

As expected, discount rate is one of the factors that have the greatest effect on water cost. This effect is more pronounced for nuclear than for fossil-based desalination because of the high capital cost of nuclear power plants and their relatively long construction periods. As can be seen from Table 34, the effect of reducing discount rate from 8% to 5% for either of the nuclear plants is to reduce the water costs by about 18-20%, whereas for the fossil plant the cost reduction is only about 11–13%. This is the case whether an MED or an RO plant is coupled to the power plant.

Increasing the discount rate from 8% to 10% has the effect of increasing water costs, with the amount of increase roughly proportional to the relative increase in discount rate.

5.4.4. Water production capacity

Table 35 shows the dependency of levelized water cost on the water production capacity.

As one might expect, the economy of scale from the DEEP calculation is quite significant in going from 60 000 m^3/d to 2400 000 m^3/d (about 20% for MED plants and about 15% for RO plants). However, while the cost of water does continue to decrease for RO when increasing the production rate to 480 000 m^3/d, reflecting continued economy of scale, the calculations show no additional benefit for the MED plant.

TABLE 35. SENSITIVITY OF CALCULATED WATER COST TO PRODUCTION CAPACITY

Sensitivity parameter	**Power plant and desalination plant options**					
	PWR-600		**PHWR-600**		**CC-600**	
	MED	**RO**	**MED**	**RO**	**MED**	**RO**
Desalination plant size, m^3/d	**Levelized water cost, \$/m^3**					
60 000	0.93	0.74	0.76	0.66	0.97	0.80
120 000	0.85	0.67	0.69	0.60	0.90	0.73
240 000	**0.77**	**0.65**	**0.62**	**0.57**	**0.81**	**0.70**
480 000	0.78	0.62	0.62	0.55	0.81	0.68
Desalination plant size, m^3/d	**Variation from base case, %**					
60 000	20.8	13.8	22.6	15.8	19.8	14.3
120 000	10.4	3.1	11.3	5.3	11.1	4.3
240 000	—	—	—	—	—	—
480 000	1.3	-4.6	0.0	-3.5	0.0	-2.9

One of the reasons for this apparent anomaly lies in the methodology for selection of base unit size and number of units within DEEP. The unit size selected for any given production rate is calculated on the basis of the available unit sizes (up to a maximum of 24 000 m^3/d for RO and 48 000 m^3/d for MED and MSF) and the specified production rate. The number of units is selected so that the number of units times the production rate per unit equals or exceeds the required production rate. However, the algorithm is such that for the special case where the specified production rate is an integer multiple of the unit size, the number of units selected is one more than required. This is illustrated in Table 36, which presents results for a PWR-600 operating in Region 1. The table includes calculations for each of the four capacities used throughout this study, as well as a corresponding case for each that is just 1 m^3/d less than that value. While these are essential the same specified capacities, it can be seen from the table that the slightly higher value in each case results in an additional desalination unit being selected, with the result that the installed capacity exceeds that actually specified by one full unit of production capacity.

An examination of the results for RO shows that the excess installed capacity results in a corresponding increased in potable water production, and the corresponding water costs show a slight decrease reflecting the economy of scale. However, on investigation it was found that DEEP handles the calculation of average daily water production in a different fashion for distillation plants, such that under some circumstances it calculates an artificially high water cost. This effect is most pronounced for low water production rates and for specified production rates that are exact multiples of unit size. At higher production rates and for cases that are not multiples of unit size the effect is less pronounced.

TABLE 36. ILLUSTRATION OF UNIT SIZE EFFECT ON WATER PRODUCTION AND COST

Desal. plant	**Specified production m^3/d**	**Unit size m^3/d**	**No. of units**	**Installed capacity m^3/d**	**Production rate m^3/d**	**Cost of water \$/m^3**	**Correction for**	
							Unit size	**No. of units**
MED	59 999	12 000	5	60 000	53 825	0.90	1.12	0.851
	60 000	12 000	6	72 000	53 876	0.97	1.12	0.836
	119 999	24 000	5	120 000	107 750	0.82	1.00	0.851
	120 000	24 000	6	144 000	107 751	0.88	1.00	0.836
	239 999	24 000*	10	240 000	215 501	0.78	1.00	0.794
	240 000	24 000*	11	264 000	215 502	0.81	1.00	0.787
	479 999	48 000	10	480 000	431 004	0.77	1.11	0.794
	480 000	48 000	11	528 000	431 004	0.79	0.91	0.787
RO	59 999	12 000	5	60 000	54 595	0.77	1.11	0.851
	60 000	12 000	6	72 000	65 514	0.75	1.11	0.836
	119 999	24 000	5	120 000	109 190	0.69	1.00	0.851
	120 000	24 000	6	144 000	131 028	0.67	1.00	0.836
	239 999	24 000	10	240 000	218 381	0.65	1.00	0.794
	240 000	24 000	11	264 000	240 219	0.64	1.00	0.787
	479 999	24 000	20	480 000	395 086	0.62	1.00	0.741
	480 000	24 000	21	504 000	458 600	0.62	1.00	0.738

* This case defaulted to 36 000 m^3/d unit size; manually set to 24 000 to illustrate unit size effect.

5.4.5. Fossil fuel price

The levelized cost of water produced from fossil fuel power plants is strongly influenced by the price of fuel, as shown in Table 37. For the CC-600, for example, there is a nearly 28% increase in water cost going from 10 \$/boe to 30 \$/boe for MED and about 17% for RO.

For nuclear options, the cost of water produced by RO systems is not impacted by fossil fuel costs. Depending on the availability assumed in the calculations, there is some impact for MED systems since a backup boiler is assumed as a source of heat during periods of reactor shutdown. For the PHWR, where a high availability was assumed, there is no impact even for MED, whereas there is about a 12% impact for the PWR, for which an availability of about 80% was assumed. To provide a more consistent comparison for the PHWR, an additional calculation was done with an assumed availability of 80% for values of 20 and 30 \$/boe. For this fuel cost differential, the effect on water cost for MED was about 6%, similar to that for the PWR over the same fuel cost spread.

5.4.6. Assumed power plant cost

The influence of assumed power plant cost on the levelized water cost is shown in Table 38. Due to the high investment required for nuclear plants, the cost of water is more sensitive to the variation in the power plant cost than is the case for fossil. In any of the options, however, the impact is not large compared to the effect of discount rate or production capacity, which have a much larger effect on water costs.

TABLE 37. SENSITIVITY OF LEVELIZED WATER COST TO THE FOSSIL FUEL PRICE

Sensitivity parameter	Power plant and desalination plant options					
	PWR-600		PHWR-600		CC-600	
	MED	RO	MED	RO	MED	RO
Fossil fuel cost, $\$/\mathrm{boe}$	**Levelized water cost, $\$/\mathrm{m}^3$**					
10	0.71	0.65	0.609	0.57	0.66	0.62
20	0.75	0.65	0.615	0.57	0.76	0.68
25	**0.77**	**0.65**	**0.618**	**0.57**	**0.81**	**0.70**
30	0.80	0.65	0.621	0.57	0.85	0.73
	Variation from base case, %					
10	-7.8	0.0	0.0	0.0	-18.5	-11.4
20	-2.6	0.0	0.0	0.0	-6.2	-2.9
25	—	—	—	—	—	—
30	3.9	0.0	0.0	0.0	4.9	4.3
Fossil fuel cost, $\$/\mathrm{boe}$	**Levelized water cost, $\$/\mathrm{m}^3$, For PHWR with availability set to 80% for consistency with other options**					
20			0.71	0.60		
30			0.75	0.60		

TABLE 38. SENSITIVITY OF LEVELIZED WATER COST TO POWER PLANT COST

Sensitivity parameter	Power plant and desalination plant options					
	PWR-600		PHWR-600		CC-600	
	MED	RO	MED	RO	MED	RO
Power plant cost	**Levelized water cost, $\$/\mathrm{m}^3$**					
Attachment III -15%	0.74	0.62	0.59	0.54	0.79	0.69
Attachment III	**0.77**	**0.65**	**0.62**	**0.57**	**0.81**	**0.70**
Attachment III +15%	0.81	0.68	0.64	0.59	0.82	0.72
	Variation from base case, %					
Attachment III -15%	-3.9	-4.6	-4.8	-5.3	-2.5	-1.4
Attachment III	—	—	—	—	—	—
Attachment III +15%	5.2	4.6	3.2	3.5	1.2	2.9

5.4.7. Labour cost

As can be seen in Table 39, the cost of water is relatively insensitive to labour costs. Over a wide range in labour cost, for all power and desalination options, the maximum impact is about 3%.

TABLE 39. SENSITIVITY OF LEVELIZED WATER COST TO LABOUR COST

Sensitivity Parameter	**Power plant and desalination plant options**					
	PWR-600		**PHWR-600**		**CC-600**	
	MED	**RO**	**MED**	**RO**	**MED**	**RO**
Average management (labour) salary, $/y	**Levelized water cost, $\$/m^3$**					
160 000, (80 000)	0.79	0.66	0.63	0.58	0.82	0.71
110 000 (55 000)	**0.77**	**0.65**	**0.62**	**0.57**	**0.81**	**0.70**
66 000 (30 000)	0.76	0.63	0.60	0.56	0.79	0.69
Average management (labour) salary, $/y	**Variation from base case, %**					
160 000, (80 000)	2.6	1.5	1.6	1.7	1.2	1.4
110 000 (55 000)	—	—	—	—	—	—
66 000 (30 000)	-1.3	-3.0	-3.2	-1.7	-2.5	-1.4

5.4.8. Seawater TDS and temperature

Although seawater temperature and TDS were treated, in effect, as though they were a single parameter in the regional study, they have been dealt with separately in the sensitivity study. Table 40 reflects both variations in TDS at a constant temperature and variations in temperature at a constant TDS. The results for MED and RO desalination systems are markedly different. As would be expected for a distillation system, there is no change in water costs with seawater TDS, and very little change due to temperature variation.

For RO systems, there is a significant change (in the order of 8–11% depending on energy source) for changes in both temperature and TDS. The increase in cost with increasing TDS is an expected result from the DEEP calculations. However, the increasing cost with increasing temperature is not necessarily and expected result. It is well known that the permeability of membranes increases with temperature, allowing higher water production rates. For spiral wound membranes this increase in water production leads to a reduced unit water production cost as temperature increases. However, with hollow fibre membranes the relationship between water production and temperature is more complex, involving potential reductions in operating pressure to accommodate the higher temperatures. As a result, the higher costs with increasing temperature calculated by DEEP, although non-intuitive, may reflect “reality”. Because of these uncertainties some caution should be taken in making comparisons of water costs at various temperatures for distillation systems.

TABLE 40. SENSITIVITY OF LEVELIZED WATER COST TO SEAWATER CONDITIONS

Sensitivity parameter	Power PLANT AND DESALINATION PLANT OPTIONS					
	PWR-600		PHWR-600		CC-600	
	MED	RO	MED	RO	MED	RO
Variations in TDS at 20ºC ppm	**Levelized water cost, \$/m^3**					
38 000	**0.78**	**0.62**	**0.63**	**0.55**	**0.82**	**0.67**
45 000	0.78	0.69	0.63	0.60	0.82	0.72
Variations in TDS at 20ºC ppm	**Variation from base case, %**					
38 000	—	—	—	—	—	—
45 000	0.0	11.3	0.0	9.1	0.0	7.5
Variations in temperature at TDS of 38 000 ppm	**Levelized water cost, \$/m^3**					
20	**0.78**	**0.62**	**0.63**	**0.55**	**0.82**	**0.67**
30	0.76	0.69	0.61	0.60	0.79	0.72
Variations i Temperature at TDS of 38 000 ppm	**Variation from base case, %**					
20	—	—	—	—	—	—
30	-2.6	11.3	-3.1	9.0	-3.7	7.5

5.4.9. Back-up system for heat supply

An additional partial sensitivity analysis has been carried out to assess the contributions of the back up heating system to the water production rate and cost. Only nuclear units in Region 1 for 240 000 m^3/d plants have been studied. The impact on electrical power production cost was also investigated, and in all cases was found to be negligible. The results of this analysis are shown in Table 41.

TABLE 41. COST IMPACT OF BACK UP HEAT SOURCE

Parameter	**Back up heating system**	**Desalination process**	
		MED	**RO**
Water production PWR M^3/d	+	215 500	215 500
	-	174 300	215 500
	Δ, %	23.6	0
Water production PHWR M^3/d	+	217 100	217 100
	-	206 000	217 100
	Δ, %	5.3	0
Water cost PWR-600 $/$m^3$	+	0.83	0.61
	-	0.77	0.61
	Δ, %	7.8	0
Water cost PHWR-600 $/$m^3$	+	0.65	0.54
	-	0.62	0.54
	Δ, %	4.8	0
Water cost PWR-900 $/$m^3$	+	0.82	0.60
	-	0.75	0.60
	Δ, %	9.3	0
Water cost PHWR-900 $/$m^3$	+	0.62	0.52
	-	0.59	0.52
	Δ, %	5.1	0

\+ Back-up heat source is included in the plant.
\- No back-up heat source.
Δ Percentage cost increase due to the addition of a back-up heat source.

The table shows that the contribution of the back-up system to the annual water production is significant for PWR and modest for PHWR, reflecting their availabilities. In spite of the increased water production the extra expenses (capital and operating) associated with the back up energy source increases the cost of desalted water by 0.06–0.07 $/$m^3$ for PWR and 0.03–0.06 $/$m^3$ for PHWR. The differential cost of the additional water produced is about 1.10–1.20 $/$m^3$, or roughly 40–50% higher for PWR and 90–100% for PHWR, respectively.

Other comparisons can also be drawn from this table, such as economy of scale of the power source, PWR versus PHWR and MED versus RO. However, all such comparisons have to be carefully considered, as they depend on specific input data and include some second order approximations in the analysis program.

5.4.10. Evaluation of sensitivity analysis results using the C_W cost ratio

As was previously noted, the competitiveness of nuclear desalination is largely determined by the balance between the relatively high capital costs for nuclear plants (coupled with low fuel costs) and the relatively high fuel costs for fossil fuel plants (coupled with low capital costs). The objective of this section is to assess, on the basis of the sensitivity analysis results, to what extent the identified general competitiveness of nuclear desalination can be affected by possible variations in the costs of fossil fuels or in the capital costs of nuclear plants.

The comparisons are made using the C_W ratios defined previously, where:

C_W = cost of water with a nuclear option/cost of water with a fossil option.

5.4.10.1. Impact of changes in the price of fossil fuel

Table 42 presents the results of the calculation of C_w ratios for three options (using the RO desalination technology): PHWR-600, PWR-600 and CC-600. The same information is presented graphically in Figure 11.

It should be noted that the two selected nuclear options are understood, in these comparisons, as Nuclear-1 and Nuclear-2, rather than PHWR and PWR, because the uncertainty of capital cost estimation is high in both cases and later assessments can noticeably change the numbers assumed here. However, the difference between Nuclear-1 and Nuclear-2 can be interpreted as an indication of the range, within which current cost estimates for new nuclear power plants vary. As to the use of CC-600, this option plays in the comparisons the role of the best fossil fuel option.

TABLE 42. EFFECT OF FOSSIL FUEL PRICE VARIATIONS FOR THE RO OPTION

Fossil fuel price	**C_W ratios**		**Water costs, \$/m^3**		
\$/boe	**Nuclear-1/CC-600**	**Nuclear-2/CC-600**	**PHWR-600**	**PWR-600**	**CC-600**
10	0.92	1.05	0.569	0.65	0.62
20	0.84	0.96	0.569	0.65	0.68
25	0.81	0.93	0.569	0.65	0.70
30	0.78	0.89	0.569	0.65	0.73

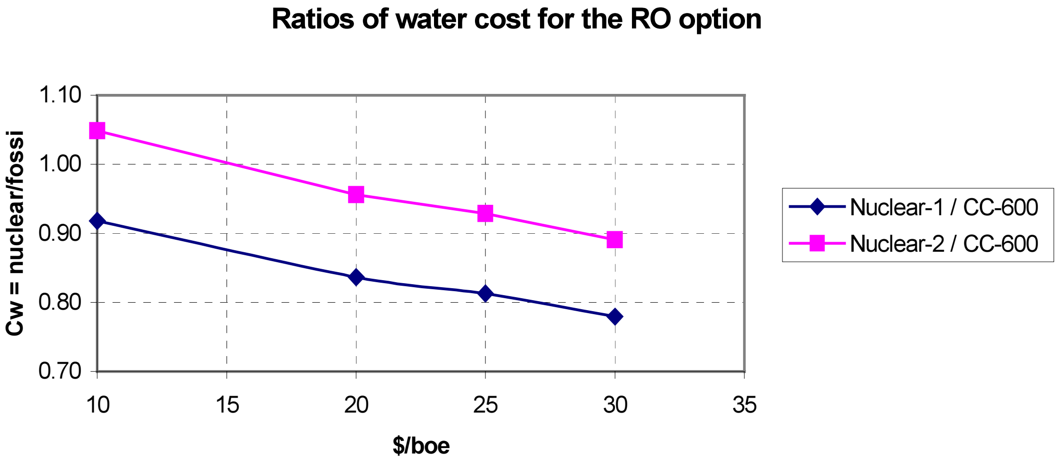

FIG. 11. Effect of fossil fuel price variations for the RO option.

As Figure 11 illustrates, there is an obvious trend to the deterioration of the competitiveness of nuclear desalination with decreasing the price of fossil fuel. For the more conservative nuclear option (Nuclear-2), nuclear desalination becomes uncompetitive at about 15 \$/boe. However, for the more optimistic Nuclear-1 case (with lower capital costs first of all), nuclear desalination remains competitive even at the price of fossil fuel of 10 \$/boe and even lower.

Similar results can be obtained for the MED technology as well, as shown in Table 43 and Figure 12. The only small difference is that Nuclear-2 becomes uncompetitive at a slightly higher price of fossil fuel –20 \$/boe.

Thus, it can be concluded that, in general, at the prices of fossil fuel above 20 $/boe nuclear desalination has rather good chances to be competitive (all other factors being equal and in accordance with the assumptions of the study). However, lower prices are likely to jeopardise nuclear competitiveness, especially if the capital costs for nuclear plants are relatively elevated.

TABLE 43. EFFECT OF FOSSIL FUEL PRICE VARIATIONS FOR THE MED OPTION

Fossil fuel price	C_W ratios		Water costs, $/m^3		
$/boe	Nuclear-1/CC-600	Nuclear-2/CC-600	PHWR-600	PWR-600	CC-600
10	0.92	1.08	0.609	0.71	0.66
20	0.82	1.00	0.615	0.75	0.75
25	0.76	0.95	0.618	0.77	0.81
30	0.73	0.94	0.621	0.8	0.85

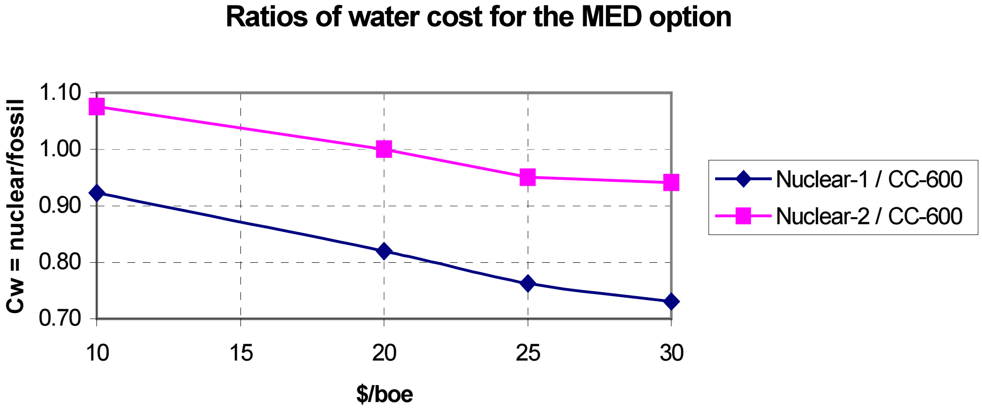

FIG. 12. Effect of fossil fuel price variations for the MED option.

5.4.10.2. Impact of changes in the capital costs of nuclear power plants

The results of similar analysis for the capital costs of nuclear plants are given in Table 44, Table 45, Figure 13, and Figure 14. For this analysis, it was assumed that only the cost of nuclear plants varies, while the capital cost of CC-600 remained as it was in the base case.

These results show that, in general, the competitiveness of nuclear desalination can become questionable if the capital costs of nuclear plants increase by about 15-20% (this is assuming the cost of fossil fuel being 25 $/boe and the relatively high capital costs of the Nuclear-2 case). Lower nuclear costs (as in the Nuclear-1 case) would allow nuclear to remain competitive even after such increases; however, this would not be the case if an increase in the capital costs coincides with fossil fuel prices being lower than 25 $/boe (see Section 5.4.10.1 above).

TABLE 44. EFFECT OF CAPITAL COST VARIATIONS FOR THE RO OPTION

Capital cost variation	**C_W ratios**		**Water costs, $/m^3**		
%	**Nuclear-1/CC-600**	**Nuclear-2/CC-600**	**PHWR-600**	**PWR-600**	**CC-600**
15	0.84	0.97	0.59	0.68	0.7
0	0.81	0.93	0.57	0.65	0.7
-15	0.77	0.89	0.54	0.62	0.7

TABLE 45. EFFECT OF CAPITAL COST VARIATIONS FOR THE MED OPTION

Capital cost variation	**C_W ratios**		**Water costs, $/m^3**		
%	**Nuclear-1/CC-600**	**Nuclear-2/CC-600**	**PHWR-600**	**PWR-600**	**CC-600**
15	0.79	1.00	0.64	0.81	0.81
0	0.77	0.95	0.62	0.77	0.81
-15	0.73	0.91	0.59	0.74	0.81

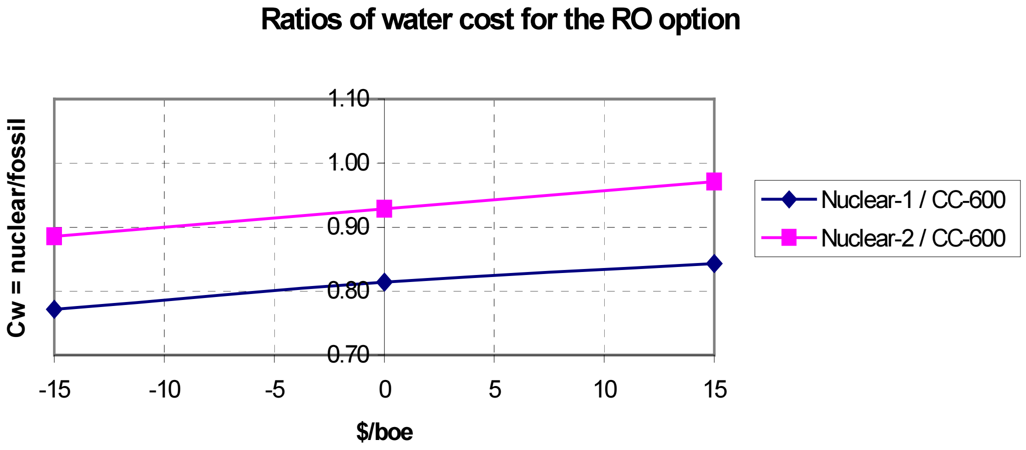

FIG. 13. Effect of capital cost variations for the RO option.

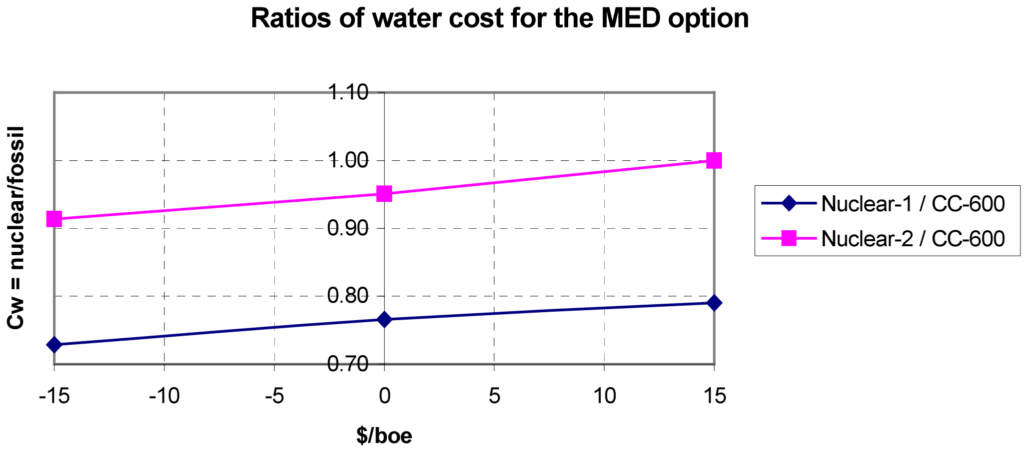

FIG. 14. Effect of capital cost variations for the MED option.

5.4.10.3. Impact of changes in the discount rate

Finally, the impact of changes in the discount rate was evaluated. Although this factor affects both nuclear and non-nuclear options, its impact on the costs of nuclear desalination should be larger due to the higher importance of capital costs for nuclear plants. The results of the analysis of the effect of the discount rate are presented in Table 46, Table 47, Figure 15 and Figure 16.

As can be seen, for the Nuclear-2 case nuclear desalination becomes non-competitive at the discount rates of 10–11%, while for the Nuclear-1 case with its lower capital costs the results do not show a limiting value of the discount rate. Again, it should be noted that this result is implicitly affected by the assumed baseline cost of fossil fuel of 25 $/boe. At lower fossil fuel costs, the competitiveness boundary of nuclear desalination would come down, too.

TABLE 46. EFFECT OF DISCOUNT RATE VARIATIONS FOR THE RO OPTION

Discount rate	**C_W ratios**		**Water costs, $/m^3**		
%	**Nuclear-1/CC-600**	**Nuclear-2/CC-600**	**PHWR-600**	**PWR-600**	**CC-600**
5	0.74	0.85	0.46	0.53	0.62
8	0.81	0.93	0.57	0.65	0.7
10	0.84	0.96	0.65	0.74	0.77

TABLE 47. EFFECT OF DISCOUNT RATE VARIATIONS FOR THE MED OPTION

Discount rate	**Cw ratios**		**Water costs, $/m^3**		
%	**Nuclear-1/CC-600**	**Nuclear-2/CC-600**	**PHWR-600**	**PWR-600**	**CC-600**
5	0.69	0.90	0.48	0.63	0.7
8	0.77	0.95	0.62	0.77	0.81
10	0.81	0.99	0.72	0.88	0.89

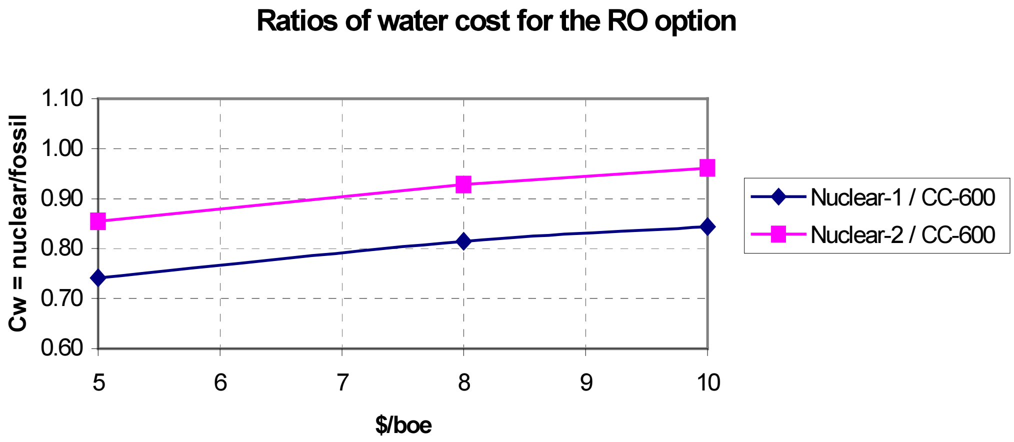

FIG. 15. Effect of discount rate variations for the RO option.

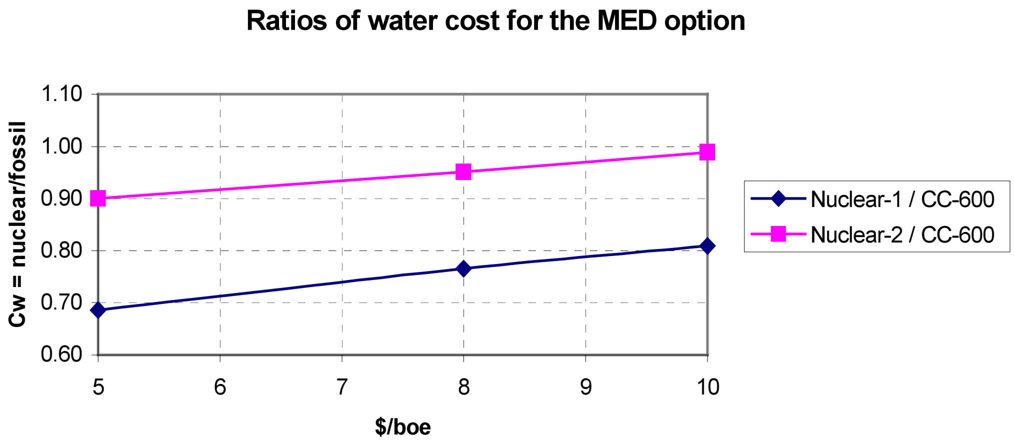

FIG. 16. Effect of discount rate variations for the MED option.

6. ANALYSIS OF DEEP RESULTS FOR SMALL INNOVATIVE REACTORS

6.1. The economics of nuclear desalination using small reactors

There are a number of innovative new reactor designs being developed in the small size range (generally considered to be below 300 MW(e) for dual purpose plants). These reactors are being developed aiming at enhanced safety features, with design innovations specifically intended to reduce energy production costs, and in some cases with a focus on heat production specifically for desalination. The HR-200 and the HTR-100 have been included in this study as examples to evaluate the economics of these small innovative reactors for nuclear desalination. In doing so, it is emphasized that the findings are valid and meaningful only as generic results; that is, they are the result of the adoption of certain technical and economic input data and assumptions that do not necessarily reflect the conditions of a specific project in any particular Member State.

6.2. The HR-200 nuclear heating reactor

The HR-200 can produce a maximum of 140 000 m^3/d of potable water when coupled with MED. Hence it was suitable for inclusion in this study for the 60 000 and 120 000 m^3/d water production capacities. The HR-200 was considered only in Regions 2 and 3.

Water costs for the HR-200 reactor coupled to MED and MSF systems, analyzed under the economic assumptions of the S_N scenario, are given in Table 48. Results for the S_F economic scenario are given in Table 49.

It can be seen from these tables that as with the higher power dual-purpose reactors, water costs for systems coupled with MED are substantially lower than for systems coupled with MSF in both Regions 2 and 3 and for both water production levels. As would be expected, water costs for economic conditions favouring nuclear power are less than for conditions favouring fossil power.

TABLE 48. SCENARIO S_N LEVELIZED WATER COSTS BY REGION

Water production costs for HR-200 nuclear heating reactor
\$/m^3

Region	**For HR-200 coupled to MED**	
	60 000 m^3/d	**120 000 m^3/d**
Region 1	—	—
Region 2	1.76	1.08
Region 3	1.76	1.08

Region	**For HR-200 coupled to MSF**	
	60 000 m^3/d	**120 000 m^3/d**
Region 1	—	—
Region 2	2.15	1.76
Region 3	2.15	1.76

TABLE 49. SCENARIO S_F LEVELIZED WATER COST BY REGION

Water production costs for HR-200 nuclear heating reactor
$/m^3

Region	For HR-200 coupled to MED	
	60 000 m^3/d	120 000 m^3/d
Region 1	—	—
Region 2	2.15	1.31
Region 3	2.15	1.31

Region	For HR-200 coupled to MSF	
	60 000 m^3/d	120 000 m^3/d
Region 1	—	—
Region 2	2.60	2.12
Region 3	2.60	2.12

6.3. The HTR-100 pebble bed reactor

The HTR-100 has been included in this study as an indicator of the cost impact of design innovations intended to reduce the capital cost of the reactor, and hence its energy production costs. This focus on cost reduction is a major thrust in the future direction of nuclear reactor design, and is likely to have a significant benefit in their use in nuclear desalination.

The HTR-100 has been coupled only with the RO desalination process in Region 1 for this study. It is projected to have very low electricity costs, and as a result it is an attractive option for the production of water. Water costs for both the S_N and S_F scenarios are shown in Table 50.

6.4. Analysis of bounding results

A comparison of bounding results was carried out using the methodology described in Section 5.3.2.1 for the advanced reactor HTR-100 and for the dedicated heating reactor HR-200. The results are presented in Table 51 and Table 52 for HTR-100 and Table 53 and Table 54 for HR-200.

The HTR-100 is considered only for RO in Region 1. The HR-200 is considered for Regions 1 and 2. Since in these cases there is only one nuclear power plant being considered, it has been compared with both the F_B and F_W cases to generate I_1 and I_2 indices. The I_3 index is not included, since it is identical to I_1.

Analysis of the data presented in these tables provides the following simple assessments of competitiveness for these two reactors. These results should be viewed within the context of limitations introduced by the performance and cost input data and assumptions on which the DEEP calculations were based. While this is, of course, true for all of the data evaluated in this document, it may have more relevance for these two systems. From the results, it can be seen that:

— The HTR-100 is always the best option (i.e., most economical) for all conditions considered.
— The HR-200 is not competitive with fossil under any of the condition considered.

TABLE 50. LEVELIZED WATER COST FOR THE RO PROCESS

Water production costs for HTR-100 coupled to an RO system
\$/m^3

Region	For economic scenario S_N		
	120 000 m^3/d	240 000 m^3/d	480 000 m^3/d
Region 1	0.47	0.44	0.42
Region 2	—	—	—
Region 3	—	—	—

Region	For economic scenario S_F		
	120 000 m^3/d	240 000 m^3/d	480 000 m^3/d
Region 1	0.58	0.55	0.53
Region 2	—	—	—
Region 3	—	—	—

TABLE 51. STUDY BOUNDING RESULTS (HTR-100 – REGION 1)

	Levelized electricity cost US \$/kW·h		Desalination plant size m^3/d	Levelized water cost, US \$/m^3 RO	
	S_N	S_F		S_N	S_F
HTR-100	0.015	0.024	120 000	0.47	0.58
			240 000	0.44	0.55
			480 000	0.42	0.53
F_B	0.046	0.041	120 000	0.60	0.66
			240 000	0.57	0.63
			480 000	0.55	0.60
F_W	0.059	0.045	120 000	0.66	0.68
			240 000	0.63	0.65
			480 000	0.61	0.62

TABLE 52. COMPARISONS OF BOUNDING RESULTS (HTR-100 – REGION 1)

	C_E		Desalination plant size, m^3/d	C_W RO	
	S_N	S_F		S_N	S_F
I_1 (HTR-100/F_B)	0.33	0.59	120 000	0.78	0.88
			240 000	0.77	0.87
			480 000	0.76	0.88
I_2 (HTR-100/F_W)	0.25	0.53	120 000	0.71	0.85
			240 000	0.70	0.85
			480 000	0.69	0.85

TABLE 53. STUDY BOUNDING RESULTS (HR-200 – REGION 2, 3)

	Levelized electricity cost US$/kW·h		Desalination plant size m^3/d	Levelized water cost, US \$/m^3			
				MED		MSF	
	S_N	S_F		SN	SF	SN	SF
HR-200	—	—	60 000	1.76	2.15	2.15	2.60
			120 000	1.08	1.31	1.76	2.12
F_B	—	—	60 000	0.93	0.93	1.70	1.66
			120 000	0.86	0.85	1.65	1.60
F_W	—	—	60 000	1.00	0.97	1.79	1.74
			120 000	0.94	0.90	1.75	1.70

TABLE 54. COMPARISON OF BOUNDING RESULTS (HR-200 – REGION 2, 3)

	Ce		Desalination plant size, m^3/d	Cw			
				MED		MSF	
	S_N	S_F		SN	SF	SN	SF
I_1 (HR-200/F_B)	—	—	60 000	1.89	2.31	1.26	1.57
			120 000	1.26	1.54	1.07	1.33
I_2 (HR-200/F_W)	—	—	60 000	1.76	2.22	1.20	1.49
			120 000	1.15	1.46	1.01	1.25

7. ANALYSIS AND FINDINGS FROM SELECTED NATIONAL STUDIES

In addition to the work reported in the previous sections of this report, some organizations belonging to Member States actively involved in nuclear desalination programmes have carried out their own economic evaluations using the DEEP methodology. Those evaluations were both intended as an instrument for an assessment of the DEEP 1.1 program, and to provide preliminary indications on the economic feasibility of nuclear desalination in the respective countries.

These papers give the details of the techno-economic evaluation of nuclear desalination in the countries. The information given in the papers was analysed and is presented in Table 55. The table gives the details of type/size of nuclear power plant and desalination plant adopted for the national studies. With some exceptions, Table 55 also provides the investment costs for nuclear plants as well as desalination plants.

Over the wide range of economic boundary conditions and specific assumptions applicable to the projects presented in the national papers, the results obtained lead to the conclusion that in all cases the projects warrant further pursuit.

TABLE 55. TECHNO-ECONOMIC EVALUATION OF NUCLEAR DESALINATION: NATIONAL STUDIES

Country	**Type of nuclear reactor**	**Reactor rating**	**Specific investment cost for nuclear**	**Capacity of desal. unit m^3/d**	**Type of desal. unit**	**Specific investment cost for desal. plant $\$/(m^3/d)$**	**Water cost $\$/m^3$**	**Electricity costs $/kW·h**	**Remarks**
Canada	PHWR-600	660	CDEE default	240 000	RO Spiral Wound	CDEE default	0.63	0.05	The study results include the calculated performance effects of increasing feedwater temperature and various economic options
India	PHWR-220	170 MW(e)	-	4500	MSF	1432	1.48	0.0375	The present power cost is low because the plant was built about 15 years ago with low capital investment. Interest rate: 12% Interest during construction 18%.
				1800	RO	1864	1.50	0.0375	
				60 000	MSF	1000-1071 (GOR 9-12)	1.5-1.35 (GOR 9-12)	0.0587	Power cost used is from most recently commissioned nuclear power plant. In spite of low capital investment on desalination plants, product cost is high (due to high loss of power for withdrawing steam from the turbine of the power station).
Morocco	NHR-10	10 MW(th)	2050 $/kW$_t$	8000	VTFE (MED)	1944	2.79	0.12 (purchased)	The power for desalination is purchased at high cost. Water cost is quite high for coupling with small heat only reactor. GOR: 21.6. New evaporative technique. Total investment: 38 US$M.
	NHR-200	200 MW(th)	486 $/kW$_t$	160 000	VTFE (MED)	1023	0.998	0.12	

TABLE 55 (cont.).

Country	Type of nuclear reactor	Reactor rating	Specific investment cost for nuclear	Capacity of desal. unit m^3/d	Type of desal. unit	Specific investment cost for desal. plant \$/(m^3/d)	Water cost \$/m^3	Electricity costs \$/kW·h	Remarks
Republic of Korea	SMART	100 MW(e)	2442 \$/kW$_e$	40 000	MED	900	0.84	0.055	Worked at brine temperature of 10°C. The water production cost consists of: Fixed charges: 44.6% Heat cost: 22.3% Others: Balance For variation of overnight cost from 1800-2442, the water production cost varied from 0.80 - 0.84 \$/m^3. Possibilities exist to reduce water production cost by increasing water production capacity above 40 000 m^3/d
Russian Federation	KLT-40C	148 MW(th) x 2 32.5 MW(e) x 2	310 \$/kW$_e$	43 100	MED	900	0.98-1.31	0.013 to 0.099	Min. water cost is for discount rate of 5%. (Most sensitive to discount rate, construction cost; less sensitive to interest rate, O&M cost, specific nuclear fuel cost.) Construction costs are modified by DEEP for the plant size utilized.
				45 500	SA-RO	800	0.77-1.02		
				56 000	C-RO	800	0.72-0.94		
	NIKA 70	70 MW(th) 14 MW(e)	4125 \$/kW$_e$	12 000	MED	900	1.12	-	Total capital investment on desalination plant essentially does not change with maximum brine temperature in the desalination plant (60-120°C, GOR 12-21). Lowest water costs are for C-RO.
				48 000	MED	900	1.03		
				12 000	SA-RO	800	1.08		
				12 000	SA-RO	800	0.87		
				12 000	C-RO	800	0.92		
				12 000	C-RO	800	0.84		

7.1. A technical and economic evaluation of the CANDESAL approach to nuclear desalination as applied to severe seawater conditions (Canada)

7.1.1. Objective

The objective of this study was to examine the technical, performance and economic characteristics of a large scale reverse osmosis (RO) seawater desalination plant coupled with a CANDU 6 nuclear power plant, operating under severe seawater conditions. In this context, “severe seawater conditions” are understood to mean high seawater temperatures and TDS (total dissolved solids), as these are conditions under which it is typically most difficult for RO systems to meet specified requirements on water production and water quality.

7.1.2. Summary of input data and findings

The focus of nuclear desalination studies in Canada since 1993 has been to address two of the most critical issues facing nuclear desalination as a commercially viable technology — energy utilization and the cost of water production. It was recognized that improvements in the efficiency of energy utilization could be achieved by taking advantage of waste heat normally discharged from the reactor through the condenser cooling system. Use of the condenser cooling water as preheated feedwater to the RO system improves the efficiency of the RO process, thereby increasing potable water production for a given plant size and energy consumption, with a corresponding reduction in the unit cost of water production. Studies have also shown that further improvements could be achieved by adopting a sophisticated approach to optimizing the RO system design.

Improvements in the efficiency of water production and the associated reductions in the cost of water were investigated under conditions of high seawater temperature and TDS using the IAEA’s CDEE cost calculation model.

Since CDEE/DEEP does not include a cost evaluation for the feedwater preheat case, it was necessary to modify CDEE specifically for this purpose. This required a number of detailed changes to the spreadsheet, including the addition of a new section to carry out the calculations for RO systems with feedwater preheat (RO-PH). A new section was added rather than modifying the existing calculations so that a direct comparison could be made of the effect of moving from a stand-alone system to a contiguous system to an integrated desalination/cogeneration system incorporating preheated RO feedwater.

The following data have been used for this RO system design evaluation. These data have been selected to represent conditions typical of a seawater site having relatively high temperature and TDS.

—	Average annual sea water temperature	29°C
—	Average Total Dissolved Solids (TDS) of sea water	40 000 ppm
—	Required potable water production capacity	240 000 m^3/day
—	Required potable water quality	500 ppm
—	Cooling water temperature rise across the condenser	10°C
—	Reactor power production	660 MW(e)
—	Cost of financing the capital investment (interest rate)	8% and 10%
—	Amortization period (plant economic lifetime)	20 years and 30 years
—	Cost of purchased electrical power	0.05 \$(US)/kW·h
—	Cost of generated electrical power	0.04 \$(US)/kW·h
—	Labour costs for RO plant staff	Used default values from IAEA economic model

Based on the results of the CDEE evaluation, the estimated capital cost of the plant meeting the above conditions is on the order of US \$236 million, with a cost of water production of about US \$0.63/m^3 (based on standard economic assumptions used by the IAEA in their economic analyses). The cost of water from a stand-alone RO plant under these same conditions is about US \$0.74, or about 17% higher, illustrating the significant economic benefit of feedwater preheat and design optimization.

When comparing various economic scenarios, water costs are seen to change in the direction that would be generally expected. However, regardless of the economic conditions assumed, the study has shown that a careful system design optimization and the use of feedwater preheat always leads to reduced water production costs relative to either stand alone RO or contiguous RO plants.

Based on the results of this work it can be concluded that a nuclear desalination facility based on the integration of the CANDU 6 reactor with a reverse osmosis desalination plant can be configured to operate effectively and efficiently even under high seawater salinity and temperature conditions. Modifications to the CDEE/DEEP code are required to properly represent the effects of preheat and design optimization.

7.2. Techno-economics of nuclear desalination in India

7.2.1. Objective

The objective of this study was to assess the economic feasibility of using nuclear power for desalination of seawater both for industrial and domestic purposes.

7.2.2. Summary of input data and findings

India's nuclear power program is primarily based on pressurized heavy water reactors. At the present time approximately 1840 MW(e) of electricity are produced from PHWRs of 200 MW(e) capacity. Future plans envisage additional generation capacity consisting of both 220 and 500 MW(e) unit sizes.

A considerable amount of research and development (R&D) work has been carried out in India both on thermal and membrane desalination processes. Based on the results obtained, a 6300 m^3/d MSF-RO Nuclear Desalination Demonstration Plant (4500 m^3/d MSF and 1800 m^3/d RO) is being set up at Madras Atomic Power Station (MAPS) site at Kalpakkam. The MSF unit will derive steam from the power station after the high-pressure turbine. Pumping power for the MSF and RO units is also expected to be taken from MAPS.

The Indian study describes the coupling of a 6300m^3/d MSF-RO plant to the existing nuclear power station in India (Madras Atomic Power Station).

Cost details have been presented for the 6300 m^3/day unit separately for MSF and RO portions of the plant.

The study shows that water production cost from the small size MSF plant (4500 m^3/d) using energy from the existing PHWR is 1.48 \$/m^3 and for an 1800 m^3/d RO plant it is 1.50 \$/m^3. The power cost used in the study is low — 0.0375 \$/kW·h. (This value is quite low as the power cost is based on an old investment). The steam cost is worked out on the basis of loss of saleable power from MAPS and the existing cost of power.

The capital investment for desalination plants is 1432 \$/(m^3/d) and 1864 \$/(m^3/d) for the MSF and RO units, respectively. Capital investment figures do not include design costs and profit margins. The values of capital investment given in the Indian study are significantly lower even for small capacity as compared to values used in DEEP, whereas the RO capital investment is significantly higher. Therefore, since MSF has the advantage of lower initial capital investment, water production cost is almost the same as for RO. If the membrane life (5 years) is taken to be correct, with the increase of desalination plant capital cost RO is likely to have lower specific capital investment as compared to MSF, and RO. water production costs will be lower.

Cost estimates were also carried out for a large capacity MSF plant (60 000 m^3/d) based on specific capital investment values that were drastically lower than the figures used in DEEP for MSF. Water production costs decreased in this case to 1.35 \$/m^3.

The cost estimates for the 60 000 m^3/d unit are based on a power cost of 0.0587 \$/kW·h, the power cost for the nuclear plants commissioned in recent years. Capital investment for a 60 000 m^3/d MSF plant varies over a range from about 1000 to 1071 \$/(m^3/d) as the GOR of the MSF plant is varied from 9 to 12. These cost figures are considerably lower than the cost figures assumed by DEEP. Water production cost decreases from 1.5 to 1.35 \$/m^3 of product water as the performance ratio. increases from 9 to 12, indicating that MSF plants in India should be designed for higher performance ratios. Steam cost accounts for nearly 50%, of the water production cost, power for about 10% and fixed charges for about 30%. The steam cost is high due to the loss of saleable power from the nuclear plant.

As the interest rate on the capital investment is increased from 4 to 16% the water product cost increases by about 30%.

7.3. Pre-project study on demonstration plant for seawater desalination using a nuclear heating reactor in Morocco

7.3.1. Objectives

The objectives of the pre-project study being carried out in Morocco are to:

- Specify the conceptual design of the reactor and the desalination plant.
- Verify the safety of the demonstration plant.
- Estimate the investment, operation and maintenance costs of the project and assess the potable water produced.
- Draw a comprehensive conclusion regarding the safety, technical feasibility and economical viability of the project to provide to decision-makers.

7.3.2. Summary of input data and findings

Morocco is cooperating with China to carry out a pre-project feasibility study of a nuclear desalination demonstration plant to be sited in Morocco. The project is based on using a low power (10 MW(th)) heating reactor (the NHR-10 Chinese heat-only reactor) coupled to a vertical tube high temperature MED plant (MED-VTE) with 8000 m^3/d capacity.

The study has been carried out using CDEE, the predecessor to DEEP, to evaluate the economic characteristics of such a project. The main performance and economic inputs to the calculation are presented in Table 56.

The capital investment for the desalination plant is 1944 \$/(m^3/d), which is quite high as compared to the MED capital cost figure of 900 \$/(m^3/d) adopted in DEEP.

The results of the analyses indicate that a nuclear desalination plant should be economically competitive with a fossil fuelled plant under the conditions prevailing in Morocco. The cost of water produced by the 10 MW(th) demonstration plant was calculated to be 2.79 \$/m^3. If the discount rate is reduced from the reference value of 10% to 8%, the cost of water production decreases to 2.53 \$/m^3.

In addition to the calculations for the NHR-10, a study was also carried out to assess the economics of a commercial scale production plant using a scaled-up system consisting of an HR-200 nuclear reactor, combined to a 60 000 m^3/d MED-VTE plant.

TABLE 56. INPUT DATA FOR DEEP ANALYSIS

Parameter	Description
Heat source	NHR-10 (10 MW(th) nuclear heating reactor)
Steam temperature	105–130°C
Desalination plant	VTE-MED with 2 units
Capacity of the plant	8000 m^3/d
Number of effects	28
GOR	21.6
Economic lifetime	30 years
Discount rate	10%
Reference currency	US Dollar

In this case, the reactor cost has dropped drastically from 2050 \$/kW(th) to only 486 \$/kW(th) with the scale up of the reactor size. As a result, the water production cost was reduced from 2.79 $\$/m^3$ to 0.998 $\$/m^3$. Also the capital investment for the desalination plant was reduced from 1944 to 1023 $\$/(m^3/d)$ due to scale up of the desalination plant capacity from 8000 m^3/d to 60 000 m^3/d.

It was also found in the study that if the duties and taxes for import materials (which are normally quite high for Morocco) can be eliminated, a reduction in water production costs of about 0.16 $\$/m^3$ can be realized relative to the reference case.

7.4. Economic evaluation of seawater desalination using SMART (Republic of Korea)

7.4.1. Objective

The objective of this study was to carry out a preliminary economic assessment of nuclear desalination using the SMART nuclear reactor.

7.4.2. Summary of input data and findings

The DEEP code was used to do the economic analysis. The MED process was the only one considered for coupling with SMART.

The basic input data for the power plant are as follows:

- Net output of SMART is 100 MW(e).
- Thermal power of SMART is 330 MW(th).
- Planned outage rate and unplanned outage rate is 0.06 and 0.04 respectively.
- Overnight cost is estimated to be 2.442 \$/kW(e).
- O&M cost is 12.50 \$/MW·h
- Fuel cost is 10.30 \$/MW·h.
- Decommissioning cost is 1.00 \$/MW·h.
- Discount rate is 8%/year.

Almost all of the input data for the MED plant came from the default information listed in DEEP. In the study, particularly, estimates were made of the relationship between GOR and maximum brine temperature (T_{mb}), and of the relationship between base unit cost and GOR. Through these estimates, it was found that there is a trade-off relation between water costs and GOR (or in other words, T_{mb}).

The water production cost obtained in this study lies in the range of 0.83–0.84 \$/m^3 for the reference overnight cost of SMART. The results indicated that the optimum value of T_{mb} is in the range of 60–70°C for this water cost. The results also indicate that the water cost can be decreased as the water capacity increases from the base scale of 40 000 m^3/d. Thus, increasing the desalination capacity can be one of the important factors contributing to the further enhancement of economic competitiveness of water produced using SMART.

7.5. Using DEEP 1.1 for the economic evaluation of a nuclear desalination plant based on the floating power unit with small reactors (Russian Federation)

7.5.1. Objectives with respect to KLT-40C reactors

The objectives of this study were to carry out:

- An evaluation of economics and cost parameters for a nuclear desalination plant based on the Floating Nuclear Power Unit (FNPU) equipped with KLT-40C reactors.
- A sensitivity analysis with variations of important input data (such as discount rate, specific construction cost, O&M and fuel cost) within the range of 25–30% up and down.
- Comparative calculations for MED and RO desalination technologies.
- A detailed analysis of performance and applicability of DEEP 1.1.

7.5.2. Summary of input data and findings with respect to KLT-40C reactors

The economic assessment of the FNPU was carried out using the DEEP code, with the following basic input assumptions:

- Base power plant net output was assumed to be 65 MW(e).
- Water plant production capacity of 48 000 m^3/d was defined based on:
    - Utilization of ~50 Gcal/h of heat from turbine steam extractions available for the current NFPU project.
    - 115°C was specified as maximum brine temperature for MED taking into account the extracted steam parameters (~3 MPa, ~130°C).

Calculations were carried out for two locations:

- North Africa (Region 2)
- South East Asia (Region 3).

Optional desalination unit size (one of the DEEP defaults that can be modified by the user) was specified to be 10 000 m^3/d for RO and 12 000 m^3/d for MED.

Cost data for FNPU for the base case were roughly defined based on FNPU project data. Cost and performance data for the desalination plant were based on DEEP default data.

Over the range of input parameters used for this study, the DEEP calculations gave water production costs within the range of 0.98–1.35 \$/m^3 for MED and 0.80–1.10 \$/m^3 for RO. The RO option resulted in lower water costs for all cases considered. the cost of product water from the MED process fell below 1.00 \$/m^3 only for the case of a low discount rate (5%).

The Influence of site conditions is important for RO (~10%), but was found to be essentially negligible for MED. The most important parameters influencing the water cost are discount rate and construction cost. Further refinement of these data is required for a more accurate site-specific cost evaluation.

7.5.3. Objectives with respect to NIKA-70 reactors

The objectives of this study were to carry out:

- An assessment of the economic characteristics of a nuclear seawater desalination complex for future generation based on the NIKA-70 (a small floating integrated PWR with enhanced safety and operational performance characteristics).
- A study of the important characteristics of the DEEP program.

7.5.4. Summary of input data and findings with respect to NIKA-70 reactors

The study has been carried out using DEEP, to evaluate the economic characteristics of a nuclear desalination complex based on the NIKA-70 reactor. The main performance and economic inputs to the calculation are presented in Table 57.

TABLE 57. INPUT DATA FOR DEEP ANALYSIS

Parameter	**Description**
Thermal power of the core	70 MW(th)
Net electrical power	14 MW(e)
Specific cost of construction	4125 US $/kW·h
Specific O&M cost	6.0 US $/MW h
Specific nuclear fuel cost	25 US $/ MW h
Specific decommissioning cost	1 US $/ MW h
Operating availability	0.8
Power plant economic life	30 years
Interest rate	8%
Distillation plant base unit cost	900 US $/(m^3/d)
Membrane plant base unit cost	800 US $/(m^3/d)

All remaining input data assumed the default values in DEEP.

The findings from the NIKA-70 study fall into two broad categories: those related to the use of the DEEP code and those related to the results of the economic evaluation carried out for the NIKA project.

With respect to the DEEP code, the following observations were made:

- The minimum unit of installed water plant capacity is 12 000 m^3/day. Because DEEP bases the number of units on multiples of this value it tends to overestimate the number of units required. By inputting a slightly smaller value, say for example 11 999 m^3/day, a lower water cost would be calculated.
- There is no capability to consider an additional safety circuit in DEEP for creating a potential pressure barrier for leakage between the second reactor circuit and the primary circuit of the desalination plant when using of heat from NSSS for desalination, i.e. at the coupling of an NPP with an MED plant, a C-RO plant or hybrid desalination plant. It is possible to model such an additional safety circuit by increasing the value of condenser approach temperature/steam temperature drop ΔT_{ca} (cell N55 in DEEP). The value of this temperature difference should be chosen giving consideration to the temperature drops between the secondary circuit of the reactor and additional circuit, and between the additional circuit and the primary circuit of the desalination plant. The value 10°C was set for this temperature drop in the NIKA-70 study.

— The calculation scheme for the MED process with power reactor makes use of a flash chamber at the first stage of distillation. There is no option for producing vapour for distillation by evaporation. It would be desirable to include an additional option for this case in DEEP. Such an approach could lead to more economical water production.

With regard to the results of the economic assessment carried out using DEEP, the following observations can be made:

— An inappropriate selection of input water plant capacity can cause an over-estimate of the water cost by as much as 50% for distillation plants.

— The optimum maximum brine temperature T_{mb} would be 80°C for the NIKA-70 case. However the DEEP value of T_{mb} for 90°C was accepted for further calculations, as such a temperature is acceptable for MED plants produced in Russia.

— For a NIKA-70 based nuclear desalination complex, average daily water production ranges from 12 000 to 62 000 m^3/d for MED, from 12 000 to 72 000 m^3/d for C-RO, and from 12 000 to 67 000 m^3/d for a hybrid plant with 50% production by MED and 50% by C-RO.

— Water costs for the NIKA-70 complex is very competitive for such low capacities, and drop with increasing of capacity. The water costs range from 1.12 to 1.02 \$/m^3 for MED, from 1.00 to 86 \$/m^3 for SA-RO, from 0.92 to 0.80 \$/m^3 for C-RO and from 0.93 to 0.87 \$/m^3 for a hybrid plant.

The conclusions of the economic evaluation of the nuclear seawater desalination complex based on the small floating advanced NPP NIKA-70, carried out using DEEP were that DEEP is a good instrument for economic evaluation of nuclear seawater desalination. Nevertheless, the present version of the programme has some features, in particular the discrete input of the water plant capacity that should be taken into consideration in using the program. In the future it would be desirable to improve the programme to correct some of the shortcomings described above.

8. SUMMARY AND CONCLUSIONS

8.1. Objective

In 1998, after releasing its Desalination Economic Evaluation Program (DEEP, version 1.1), the IAEA contracted the Institute of Nuclear Energy Technology (INET), China, to carry out a series of detailed economic calculations of desalination by a wide range of fossil and nuclear energy sources, coupled to selected desalination technologies.

The basic objective of this TECDOC is to present the results of these calculations and provide the conclusions regarding their analysis and assessment. These were also used to determine the extent of validity and the limitations of models used in DEEP 1.1.

Due to the highly site-specific nature of many of the factors influencing the cost of water production, and to the actual state of assumptions and approximations used in DEEP, it is not intended that this work provide a definitive cost of desalted water but, rather a relative comparison of a large number of design alternatives on a consistent basis. The results are thus expected to be a source of information and guidance for business leaders and decision makers in Member States facing severe water shortages and considering seawater desalination as one of the potential solutions.

8.2. Desalination processes

There are many proven desalination technologies available commercially. A large majority of them are described in detail in IAEA-TECDOC-574 [3] and IAEA-TECDOC-666 [4].

The desalination technologies selected for this study (Table 58) are: multi-stage flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO). These processes are industrially mature and have been in use for many years in commercial large-scale desalination plants.

TABLE 58. DESALINATION PROCESSES AND THE CAPACITIES CONSIDERED

Process	Abbreviation	Description	Capacities (m^3/d)
Distillation	MED	Multi-effect distillation	60 000, 120 000, 240 000, 480 000
	MSF	Multi-stage flash	60 000, 120 000, 240 000, 480 000
Membrane	RO	Reverse osmosis	60 000, 120 000, 240 000, 480 000

Desalination is an energy intensive process, and the specific energy consumption may vary widely depending upon the plant design, unit size and site conditions. The RO process requires only mechanical energy (usually in the form of electricity used primarily for pumping). The total energy requirement for RO is on the order of 4–5 kW(e)·h/m^3.

For the MED and MSF processes, the energy input is mainly in the form of low temperature (< 130°C) heat (generally steam) and some electricity used primarily for pumping. The electrical energy required is roughly 2 and 4 kW(e)·h/m^3, respectively, for MED and MSF. The heat requirements, which depend on temperature of the heat source, as well as factors such as those mentioned above, are 30–120 kW(th)·h/m^3 for MED and 55–120 kW(th)·h/m^3 for MSF, respectively.

8.3. Energy sources

Nine different combinations of energy source and power level were considered for this study, as indicated in Table 59.

These represent a range of power plant options that include existing technologies (PWR-900, PHWR-600, PC-600, PC-900, CC-600, and GT-600) as well as prospective next generation nuclear power supply concepts (PWR-600, PHWR-900, HTR-100 and HR-200).

TABLE 59. ENERGY SOURCES CONSIDERED

Energy source	Abbreviation	Description	Power level	Technology status
Nuclear	PWR-600	Pressurized light water reactor	600 MW(e)	Being developed
	PWR-900	Pressurized light water reactor	900 MW(e)	Existing
	PHWR-600	Pressurized heavy water reactor	600 MW(e)	Existing
	PHWR-900	Pressurized heavy water reactor	900 MW(e)	Being developed
	HTR-100	High temperature reactor	100 MW(e)	Being developed
	HR-200	Heating reactor (steam or hot water)	200 MW(th)	Being developed
Fossil	PC-600	Superheated steam boiler, pulverized coal	600 MW(e)	Existing
	PC-900	Superheated steam boiler, pulverized coal	900 MW(e)	Existing
	CC-600	Combined cycle gas turbine	600 MW(e)	Existing

8.4. Input data and assumptions made

The studies carried out consisted of a set of DEEP calculations for three broad regions as defined in Table 60.

TABLE 60. INPUT DATA ASSUMPTIONS FOR REGIONAL CALCULATIONS

Region	Approximate geographic area	Seawater conditions		Personnel costs	
		Temp. ºC	TDS ppm	Management $/year	Labour $/year
Region 1	Southern Europe (South of France, South of Italy, Greece, Spain)	20	38 000	160 000	80 000
Region 2	North Africa, Red Sea, South East Asia	25	41 000	60 000	30 000
Region 3	Arabian Sea	30	45 000	60 000	30 000

Within each region, the studies considered various combinations of the four types of nuclear power plants, two types of fossil fuelled plants and the appropriately coupled desalination technologies, as described above. For each of these combinations, two different economic scenarios were considered:

— The S_N scenario: favouring nuclear, with discount rate 5%, fossil price 30 $/boe, lower range nuclear power plant specific construction costs and higher range fossil plant specific construction costs.

— The S_F scenario: which favours the fossil option, with discount rate 8%, fossil price 20 $/boe, lower range fossil power plant specific construction costs and higher range nuclear plant specific construction costs.

In addition to region-by-region studies, a sensitivity analysis was carried out to permit the evaluation of desalination options as a function of plausible variations in key parameters.

As an additional input to the assessment, five independent national studies (using DEEP 1.1), carried out in Canada, India, the Republic of Korea, Morocco and the Russian Federation, were reviewed. A brief summary of the studies is included as Section 7 of this TECDOC.

8.5. Main findings

A large number of calculations, using DEEP 1.1, were made, covering a wide range of desalination and power options. The analysis of the results obtained has already given confidence in DEEP. These results, based on the input data provided, would lead to the following main conclusions.

However, taking into account the assumptions made and the input data provided, care should be taken as regards the interpretation of these conclusions:

- Desalination costs range from 0.40 \$/m^3 to about 1.90 \$/m^3 depending upon the water plant type and size, energy source, specific region and economic scenarios.
- Over a wide range of power sources and regional conditions, the differences between the water production costs by RO and MED tend to be small as compared to the large differences introduced by changes in discount rate.
- Independent of the energy sources and regions considered, in all investigated cases water production costs from MSF appear to be systematically higher than those from RO or MED.
- If a relatively less stringent drinking water standard, such as WHO rather than EU, is adopted then whatever the energy source, the required desalination capacity or the region, water costs from RO are systematically lower than from other desalination processes.
- There appears to be a relatively significant economy of scale as plant capacities increase. This effect is more pronounced for lower sized plants. For higher capacities, the economics of scale are only a few percent of the water production costs.
- Water production costs in Regions 2 and 3 are higher than in Region 1, mainly because of the predominant effect of higher discount rates in Regions 2 and 3.
- For the S_N scenario, favouring nuclear, the nuclear option appears to be particularly advantageous with both RO and MED.
- For the S_F scenario, favouring the fossil option, costs from nuclear and fossil options are comparable.
- Water production costs with small reactors dedicated to heat production only are systematically higher compared to larger dual-purpose nuclear reactors. Thus for example, for the MED process the water production costs from the heat-only reactor are about 30-40% higher than those from the dual-purpose reactor with the highest water costs, mainly because energy costs are higher roughly by a factor of 2.
- Nuclear desalination with PWRs would be less competitive than fossil desalination for fossil fuel prices below 15 \$/boe. With innovative nuclear reactor options with significant capital cost reductions (as in the case of PHWR and HTR-100, for example) nuclear desalination would remain competitive even for fossil prices below 10 \$/boe.
- The competitiveness of the nuclear option could become questionable if, assuming fossil cost to be 25 \$/boe (or lower), the capital costs of nuclear power plants are increased by 15–20%.
- The existing nuclear power plants would not be competitive for discount rates above 11%. There does not appear to be a limiting value for discount rate with innovative nuclear reactors.
- The results of calculations, using DEEP1.1, and analyses made independently by five countries in the context of specific national programmes yields trends which are in line with the above conclusions.

8.6. Overall conclusion

The use of nuclear energy for electricity and potable water production is an attractive, technically feasible and safe alternative to fossil energy options.

In general, the economics of nuclear desalination are driven by the same factors as those for the economics of nuclear electricity generation. Lower power generation costs, with enhanced safety, coupled to the increased importance of environmental considerations would lead to a better competitive position for nuclear energy in comparison with fossil powered plants. Nuclear desalination, in consequence, would also be a competitive option.

Additional factors, specific for desalination, may further slightly enhance the competitiveness of nuclear desalination as compared to desalination by fossil energy systems: higher load factors, larger amounts of heat and the possible reduction of final vapour moisture.

Analysis of results already obtained indicates that the competitiveness of the nuclear option would be significantly increased if the capital cost could be reduced, as currently envisaged for innovative reactors under development.

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ABBREVIATIONS

boe	barrel of oil equivalent
CC	combined cycle (gas turbine + steam turbine)
C-RO	contiguous reverse osmosis
FNPU	floating nuclear power unit
GT	gas turbine (open cycle)
HR	heating reactor
HTR	high temperature reactor
MED	multi-effect distillation
MSF	multi-stage flash [distillation]
NPP	nuclear power plant
O&M	operating and maintenance
PC	pulverized coal (superheated steam boiler)
PHWR	pressurized heavy water reactor
ppm	parts per million
PWR	pressurized water reactor
RO	reverse osmosis
RO-PH	reverse osmosis with feedwater preheat
SA-RO	stand-alone reverse osmosis
S_F	calculation scenario with economic conditions favouring fossil energy
S_N	calculation scenario with economic conditions favouring nuclear energy
TDS	total dissolved solids
T_{mb}	maximum brine temperature
VTE	vertical tube evaporator

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