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Preliminary Feasibility Study Of Coupling Between SMR And Desalination Plant

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ABSTRACT

The aim of the paper is to assess the feasibility of nuclear desalination, which will be obtained using both electricity and heat generated by nuclear power plant to remove salt and minerals from seawater. The integration of a water desalination plant into a small and modular nuclear power plant is described by considering a combination of a variety of seawater desalination co-generation configurations/ techniques (thermal or membrane in single or hybrid mode) to show they are successfully coupled with SMRs (of different types) to produce water and electricity at different scales.

Running SMRs as base load plants is more economical and simpler than requiring them to follow load. Therefore, in a cogeneration mode and while grid load is low, they may run at full capacity even if their capacity exceeds water demands.

The proposed solution was numerically investigated from both thermodynamic and economic points of view using the Desalination Economic Evaluation Program (DEEP) software made available by the IAEA.
The study highlights the role of factors such as site characteristics, plant capacity, feed/product-water quality, energy costs, in affecting the economics of desalination regardless of the energy source used.

The economics of nuclear desalination has been found to be competitive with other desalination techniques driven by other sources of energy. Results show that e.g., for an average per capita electricity consumption of 4.7 MWh/year and 80.3 m^3/year of water, the CAREM25 reactor coupled to a desalination plant could produce electricity for 35,000 inhabitants and water for domestic use for 200,000 inhabitants.

1 INTRODUCTION

Nuclear desalination is gaining interest worldwide, as it is expected that the number of desalination plants will increase in the near future to meet the ever-increasing demand for drinking water by the world population. The need of water resources is expected to increase together with the population growth (Figure 1) and seawater desalination represents an important option for satisfying current and future demands for fresh water in arid and semi-arid regions with close proximity to the sea.

Developing and providing adequate water resources, their conservation and preservation have become fundamental problem. From that it appears how important is to investigate the possibility of (and support for) seawater desalination using nuclear energy. Moreover, desalination achieved with fossil fuel would not be compatible with sustainable development. Nuclear desalination (ND) can instead significantly contribute to achieving the sustainability objectives by minimizing the environmental impact, removing some of the impediments for the use renewable energy sources. ND involves three technologies: nuclear, desalination and their coupling system.

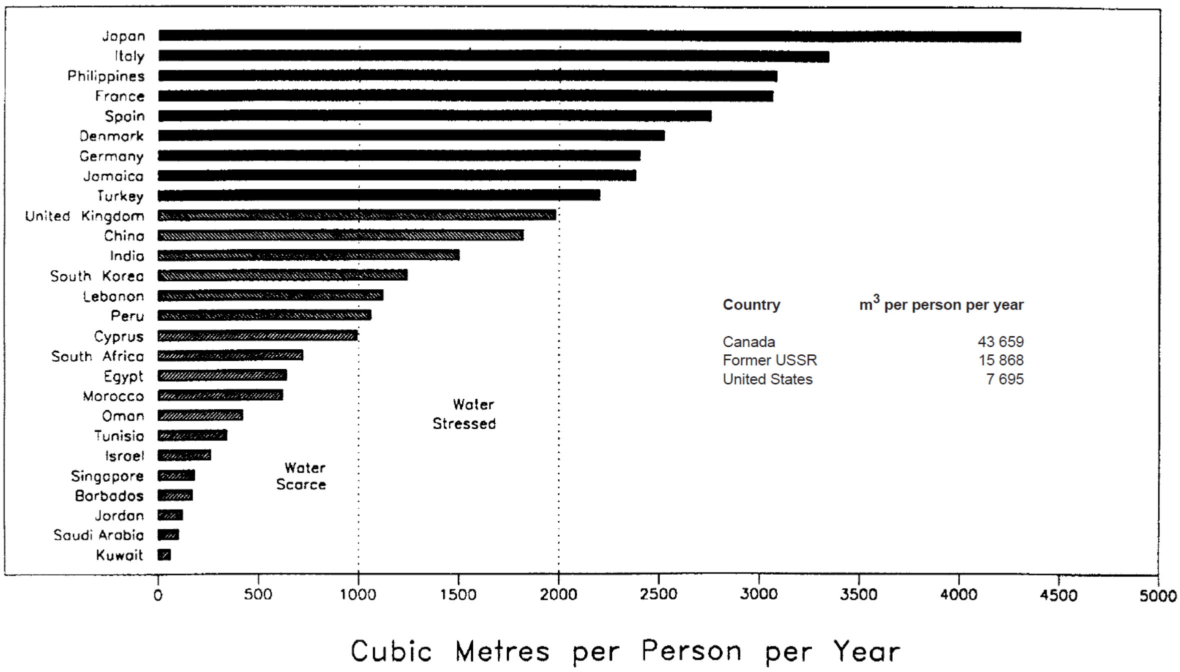

Figure 1: IAEA forecast of hydrologists' concept of Water Stress Index (i.e. approximate minimum level of water required per capita to maintain an adequate quality of life in a moderately developed country in an arid zone,) with illustration of Countries expected to experience water stress or scarcity by 2025 (from [1])

The idea to use nuclear energy for water desalinization is not new as it has been around for almost 50 years. Though sufficient experience was gained over more than 150 reactor-years of experience mainly in Kazakhstan, India, Japan, and USA demonstrating it is technically feasible, ND option was never achieved wider application [2]. Figure 2 represents a generic example of a ND plant.

In this study, the integration of a water desalination plant in a SMR is described. Some seawater desalination co-generation configurations/ techniques are described in section 2.

Section 3 describes the coupling of thermal or membrane (in single or hybrid mode) techniques with SMRs (of different types) to produce water and electricity at different scales.

The analysis of technical and economic feasibility of nuclear desalinization was conducted using the Desalination Economic Evaluation Program (DEEP) software made available by IAEA [3]. The numerical simulations were carried out considering both the CAREM25 and SMART nuclear reactors, having 32 MWe and 100 MWe electrical power respectively.

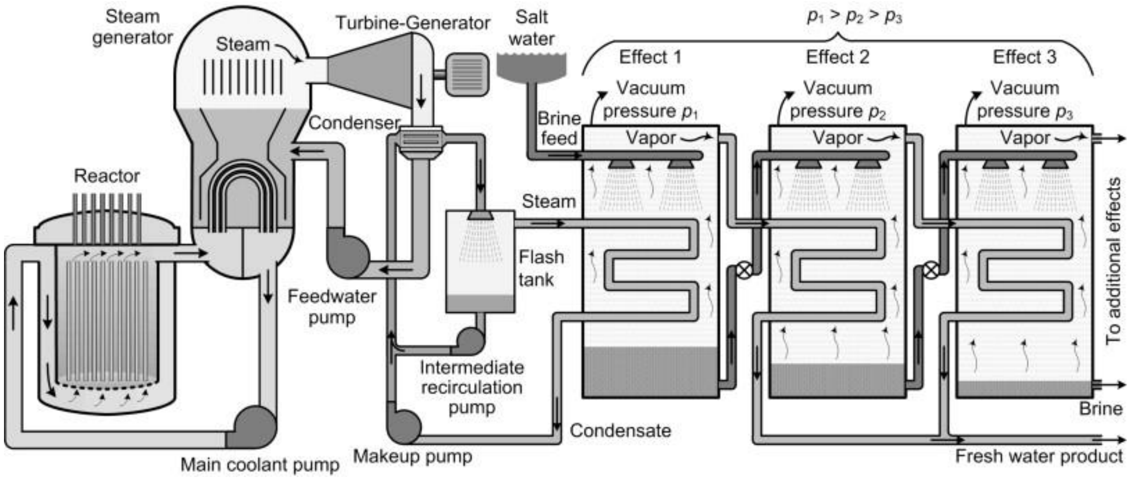

Figure 2: Scheme of desalination plant powered with nuclear energy (courtesy from [4])

2 SEAWATER DESALINATION PROCESS

Desalination consists in the removal of salts present in salt water, i.e., sea water, to obtain fresh water. The desalination plant is a complex plant consisting of seawater intake system, pretreatment system, desalination equipment and associated equipment, product water treatment plant and other auxiliaries. The main desalination plant parameters (Kazmerski & Al-Karaghouli, 2013) are:

- Electrical and Thermal Energy Consumption [kWh/m^3] referred to the volume of the permeate water, which are defined by the ratio between the input electrical or thermal power and the volume of the purified water.
- GOR [-] i.e., Gain Output Ratio, which indicates the ratio between the distilled water flow produced and the required inlet steam flow.
- RR [%] i.e., Recovery Ratio, which is the ratio between the flow rate of desalinated water produced and the flow rate of input water to be desalinated.

The most common conventional desalination technologies are divided in thermal (TP) and non-thermal processes (membrane processes- MP): both are energy-intensive processes. Therefore, they can be listed by the type of energy that drives them into:

a) Thermal Energy processes
   - Simple Stills (SS)
   - Multi-Effect Distillation (MED)
   - Multi-Stage Flash Evaporation (MSF)
   - Thermal Vapor Compression (TVC)

b) Mechanical Energy processes

- Mechanical Vapor Compression (MVC)
- Reverse Osmosis (RO)

c) Electrical Energy process
- Electrodialysis (ED)

In six of these processes, the fresh water is removed from the feed stream, leaving behind a more concentrated brine; the only one that removes the salt leaving behind a purified feed stream is the ED.

The most practiced processes are the MSF and MED and the RO: the formers desalinate water through evaporation and condensation, the latter thanks to reverse osmosis and osmotic membranes that separate the salt from the water making it completely free of mineral salts and solid particles. The obtainable products by means of such techniques are the desalinated water, i.e., permeate, for civilian use and the residual water with a higher concentration of salts, i.e., brine, to be discarded. The MED instead is among the oldest desalination technologies: its main components are preheaters, distillation units and condensers [7]. Typical operating parameters of MSF, MED and RO plants are provided in Table 1.

Table 1: Operating performances of the most practiced desalination plants [3]

	MED	**MSF**	**RO**
Max Brine Temperature [°C]	55 ÷ 70	90 ÷ 120	T_{room}
Thermal energy consumption [MJ/m^3]	145 ÷ 230	190 ÷ 282	-
Electrical energy consumption [kWh/m^3]	2 ÷ 2.5	2.5 ÷ 5	4 ÷ 6
Equivalent Electrical to Thermal Energy [kWh/m^3]	12.2 ÷ 19.1	15.83 ÷ 23.5	-
Total energy consumption [kWh/m^3]	14.45 ÷ 21.35	19.58 ÷ 27.25	4 ÷ 6
GOR [-]	10 ÷ 16	8 ÷ 12	-
Recovery Ratio [%]	35 ÷ 45	35 ÷ 45	20 ÷ 50
Pre-Treatment	Low	Low	High

2.1 MSF process

MSF is almost constructed in combination with a power generating station. Its typical water capacity ranges between 10,000 m^3/d and 65,000 m^3/d.

In MSF a part of sea water vaporizes passing through multiple stages, each of which is operating at high/low pressure and temperature depending on steam thermo-hydraulic conditions. The vapor is produced by heating the seawater close to its boiling temperature and passing it to a series of stages under successively decreasing pressures to induce flashing. Then the vapor produced is condensed (and cooled as distillate) on the outside of seawater tubes of that stage and, thanks to collection tubes, it gets saved properly. Therefore, the incoming sea water is subjected to progressive heating up, passing through tubes that go through the upper part of all evaporation stages, until it reaches the operating temperature, i.e., Max Brine Temperature (MBT), in the Brine Heater (Figure 3) where the vapor extracted typically from one (or more) turbine stage(s) is used to heat the seawater finally up to the MBT. The discharge brine can also be partially injected by the Heat Rejection Stages in the incoming sea water to be desalinized, so that only its remainder gets discharged through the Brine Discharge line.

The components in contact with water, i.e., stages or spray plates, are made of corrosion resistant materials such as copper-nickel alloys, i.e., CuNi 90/10, or austenitic-ferritic steels, i.e., AISI 316 L, due to alkaline corrosion while the connecting pipes and the pre-heater pipes are made of titanium or copper-nickel alloys and the spray nozzles are made of polypropylene. The distilled water leaves the final stage 3°C to 5°C hotter than the initial salt water and with a concentration of total dissolved solids between 2 mg/l and 50 mg/l. The discharged brine has a higher temperature between 8°C and 12°C than the incoming saltwater temperature.

2.2 RO process

The RO process is based on the use of a semi-permeable membrane (made of e.g., cellulose acetate and polyamide) to desalinate under pressure. Seawater is forced to pass through special semi-permeable membranes: pure water is so produced with a lower concentration of salts, on average around 200 mg/l. The operating pressure ranges from 50 bar to 80 bar. The differential pressure must be high enough to overcome the natural tendency of water to move from the low salt concentration side to the high concentration side, as defined by osmotic pressure. A general scheme of RO process is shown in Figure 4.

To increase the membrane lifetime (usually 3 years) and reduce the energy consumption, the pre-treatment phase of the incoming water, i.e., feed treatment, is essential. A post-treatment phase of the water, i.e., product treatment, is also required to remove dissolved gases, i.e., CO_2, stabilize the pH with the addition of calcium or sodium and remove dangerous substances also from the brine. The typical capacities of RO plants vary from 0.1 m^3/d for small installations to 400,000 m^3/d for commercial uses.

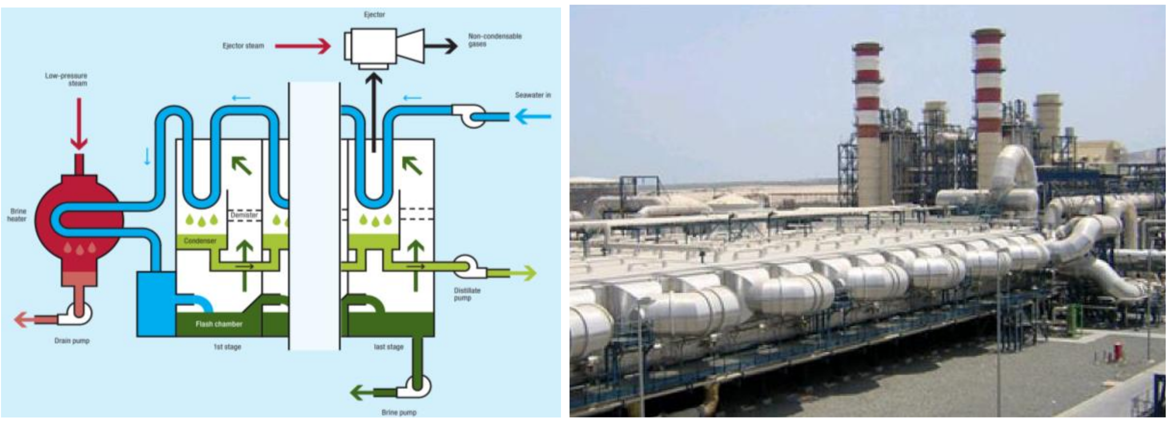

Figure 3: MSF simple scheme [2]

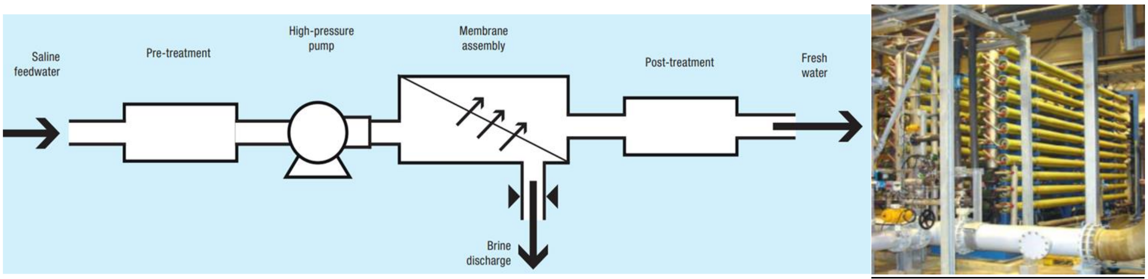

Figure 4: RO process scheme [1]

2.3 Nuclear Desalination Plant

The adaptation of nuclear energy for desalination purposes involves the selection of technology options, which must be appropriate either to produce water and electricity or for the availability of natural and technological resources of the site hosting the plant [8].

Technically any reactor system can be used for nuclear desalinization (ND), although several types, like the light water reactors (LWRs), have been identified as the most practical and probable for this application, because of their advanced state of development (characterized by known, widely available, and well proven technology) and deployment/use. Furthermore, among LWRs, Small Nuclear Reactor (SMRs), producing 300 MWe electrical power per reactor unit are considered as most promising: the coupling with a desalination plant is favoured by the small size, high degree of composability, and maximum flexibility in the choice of the desalination technology. Additionally, from both technical and economic point of view, nuclear desalination is particularly attractive because the continuous technical innovations and advancements may significantly lower the desalination costs (respect to conventional desalination plant).

Many countries have been started nuclear desalination programme. Integrated ND plants have been operated successfully in Japan and Kazakhstan for many years producing feedwater make-up for the steam generators and for on-site supply of potable water. MED, MSF, and RO processes have been used with individual desalination capacities from 1,000 to 3,000 m^3/d.

Figure 5: DP powered with nuclear energy.

Argentina has been working on the development of CAREM advanced small reactor coupled with RO or MED. Canada is developing instead a nuclear desalination/co-generation programme based on the integration between the CANDU reactor and the RO plant. In this latter, the discharged stream from condenser is fed as preheated feedwater to the RO system: the result is a significant improvement in RO system output, thereby reducing both capital and unit water production costs. Korea ND programme is focused on the coupling of MED-TVC with SMART reactor. The target water production capacity will be 40,000 m^3/d and the electricity generation of about 90 MWe. The integrated SMART desalination plant consists of four MED units combined with TVC. China's nuclear desalination programme involves the Nuclear Heating Reactor (NHR-200) coupled to the MED process with production capacity of 160,000 m^3/d [6][1].

The existing and the planned NPPs could be used to produce fresh water using the surplus of a) waste heat (like MED with e.g., PWR, using low pressure steam extraction), b) electricity (RO with any plants, e.g., CANDU-6), and/or c) combination of heat and electricity (e.g., PHWR: steam extraction to MSF and electricity to RO). To make this (thermal coupling) possible we need to install an additional intermediate loop normally consisting of a loop with heat exchanger and a re-circulation pump.

From a design point of view, this circuit should operate at a higher pressure than the NPP secondary loop to ensure that even in a hypothetical and highly improbable double rupture in the steam generator tube and the intermediate heat exchanger tube no contamination (especially tritium gas) can migrate into the desalination system. This is an important radiological safety

[1] Broad description of the ND programme is available in the IAEA Technical Reports Series No. 400 (2000)

constraint to be guaranteed constantly, with a system design avoiding any such risks. Further design limitations refer mainly to the seawater intake and outfall system and the environmental limitations with respect to temperature and salinity of seawater discharge. However, any NPP can accommodate almost any size of DPs.

The coupling [5] between a nuclear plant and a desalination plant must be realized also in such a way as to seek the optimal thermodynamic and economic conditions, and not to impact the safety of the plant in all operating conditions (normal and accidental). Figure 5 shows the coupling scheme of a PWR with MED system: the vapor extracted from one (or more) turbine stage(s) is fed to a heat exchanger where the temperature of incoming water increases up to 70-90 °C. Then the hot water passes through a flash tank where it is partially evaporated. This vapor is used to heat up the fluid in the first MED effect so that the MED process gets started.

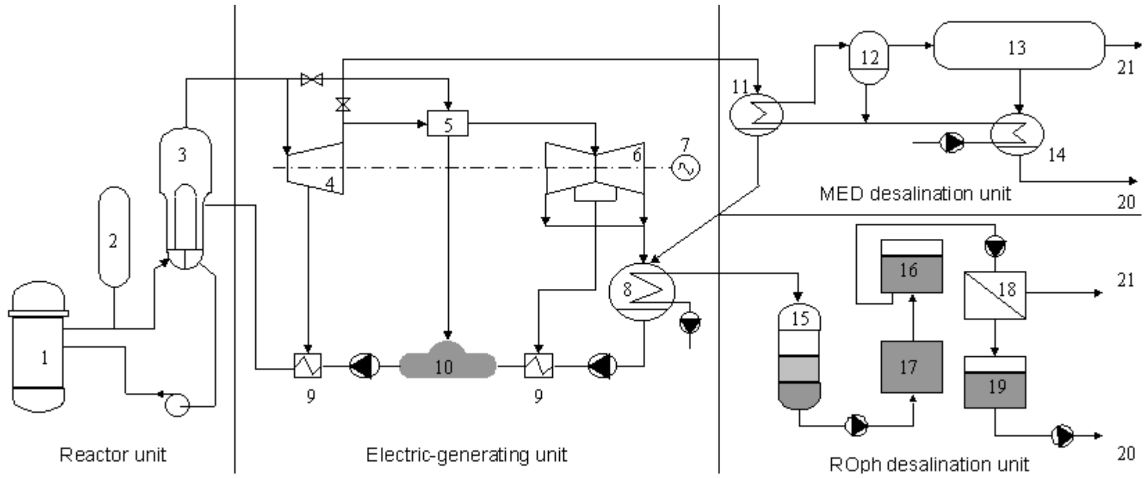

Figure 6: Scheme of PWR-MED coupling: numbers correspond respectively to 1: Reactor core, 2: Pressuriser; 3: Steam generator; 4: High pressure turbine; 5: Intermediate steam heater; 6: Low pressure turbine, 7: Generator, 8: Main condenser, 9: Pre-heaters, 10: De-aerator; 11: Seawater heater;12: Flash tank, 13: MED plant, 14: MED output condenser, 15: Prefilter, 16: Chlorified water tank, 17: Ultra-filtration membrane, 18: RO membrane, 19: desalted water tank, 20: Fresh water out, 21: Brine out-fall (courtesy from [9]).

3 SMR-DP: COUPLING AND PLANTS INTEGRATION

In the past two decades a lot of studies have been focused on the feasibility of nuclear desalination [10], particularly on reliability, efficiency, cost analysis and safety aspects, since it is recognised as one of the most efficient and promising options to produce fresh water and generate power. The choice of the most appropriate DP to integrate with a nuclear plant depends on the size and type of reactor, the characteristics of the desalination process and the possibility to produce electricity [11]-[14], particularly:

- Siting conditions,
- Plant capacity and expected availability,
- Availability of water resources (quantity and quality),
- Energy resource (e.g., residual steam, waste heat, electricity), that affects the cost of energy,
- Co-generation scheme, that is selected based on technical and economic considerations,
- Materials,
- Overall cost of distribution,
- Safety,
- Quality of product water, and
- Environmental impact assessment.

In this paper, the ND feasibility of CAREM25 and SMART reactors was investigated numerically by DEEP software.
CAREM25 is an advanced and flexible SMR based on modular new design solutions involving the electrical and thermal coupling of desalination technology. It is characterised by an integral design of the primary circuit; the flow rate in the reactor primary systems is maintained by natural circulation [12]. CAREM plant has a standard steam cycle: steam is superheated under all plant conditions and no super-heater is needed.

SMART is an integral reactor system as well, with 330 MWth thermal power. It differs from the loop-type reactors for the arrangement of its primary components. The main interest in the coupling SMART to DP is related to the utilization of steam rather than electricity: ND would produce 40 000 m^3/day of desalted water (sufficient for a population of 100,000 people) [13].

3.1 DEEP Evaluation

The feasibility analysis of ND with the CAREM25 and SMART reactors was carried out by means of the Desalination Economic Evaluation Program (DEEP), which is a software developed by the IAEA [15].

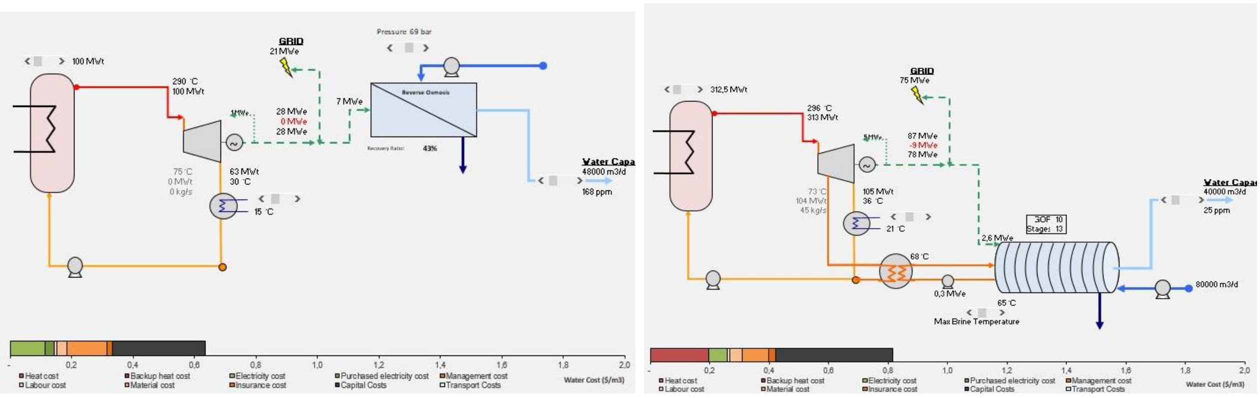

Figure 7: Flow Diagrams of CAREM+RO (left) and SMART + MED (right)

DEEP allows designers and decision makers 1) to compare the performance of several design alternatives on a consistent basis with common assumptions, 2) to estimate approximately the cost of desalinated water and power as a function of quantity and site-specific parameters including temperatures and salinity, and 3) to identify the lowest cost options for providing specified quantities of desalinated water and/or power at a given location.

The desalination options of the DEEP software include MSF, MED, RO and hybrid systems MED+RO e MSF+RO with separate inlets, while power options include nuclear, fossil and renewable sources. Both co-generations of electricity and water as well as water-only plants can be modelled. The input data are the desalination configuration, power, and water capacities as well as values for the various basic performance and costing data. The results obtained from technical-economic analyses include the power and water production performance and the resulting/associated costs (e.g., levelized cost of electricity and desalted water as a function of site-specific parameters, energy source, amount of power produced).

In what follows the performed study focused on the economics of nuclear desalination is presented. The input data of the analyses we carried out are provided in Table 2, while Table 3 and Table 4 provide some of the important data of coupled plants. Figure 8 shows the comparison of several possible coupling scenario provided by DEEP. Lastly, Table 5 summarises the main results obtained.

Concerning the CAREM25 case of study we observed that the thermal power produced is not sufficient for the required water capacity using thermal desalination processes. Therefore, the only way to guarantee the expected water production is through RO desalination process.

Concerning the SMART case of study, we note the variation of the electrical power that can be dispatched to the electricity grid due to the withdrawal of part of the steam from the power cycle according to the type of desalination plant connected to the reactor.

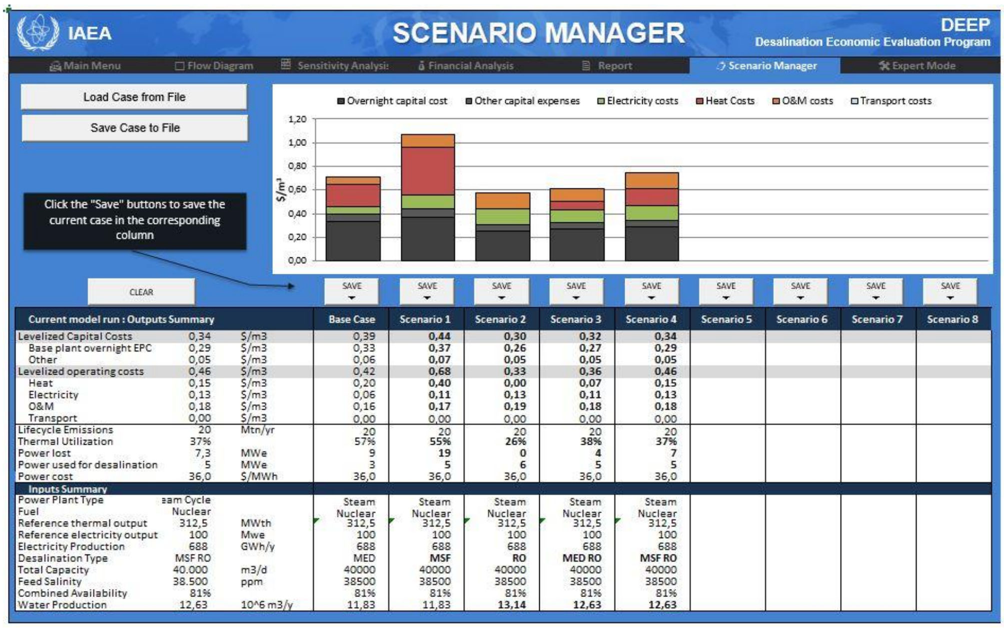

Figure 8: Comparison between the different type of coupling of the SMART reactor

Table 2: Input data

Input value	CAREM25	SMART
Reference Thermal Power [MWth]	100	312.5
Reference Net Efficiency [%]	32	32
Water Salinity [ppm]	34000	38500
Water Temperature [° C]	15	21
Water Capacity [m^3/d]	48000	40000
Discount Rate [%]	6	6
Interest Rate [%]	6	6
Fuel Escalation [%]	-	-

Table 3: SMR input data

Input Data	CAREM25	SMART
Main Steam Temperature [° C]	290	296
Auxiliary Loads [%]	5	5.3
Specific Construction Cost [$/kW]	1500	1714
Specific Fuel Cost [$/MWh]	7.2	8
Specific O&M Cost [$/MWh]	9.4	5.59

Table 4: DP main input data

Desalination Plant	RO	MED	MSF
Max Brine Temperature [° C]	-	65	110
Membrane Pressure [bar]	69	-	-
In/Outfall Specific Cost Factor [%]	7	7	10
Operational Availability [%]	90	90	90
Base Unit Cost [$/m^3]	900	900	1000

Table 5: Main results from the DEEP analysis

	CAREM25	SMART				
	RO	RO	MED	MED+RO	MSF	MSF+RO
Power Grid [MWe]	21	81	75	79	63	74
Power Cost [$/MWh]	35.9	36	36	36	36	36
Water Production [Mm^3/y]	15.77	13.14	11.83	12.63	11.83	12.63
Water Cost [$/m^3]	0.64	0.63	0.81	0.68	1.12	0.8
Water Salinity [ppm]	168	221	25	150	25	150
Lifecycle Emissions [Mtn/y]	6	20	20	20	20	20
Combined Availability [%]	81	81	81	81	81	81
Power for Desalination [MWe]	7	6	3	5	5	5
Power Lost [-]	-	-	9	3.5	19	7.3
Gor [-]	-	-	10	10	9	9
Stages [-]	-	-	13	13	31	31
Recovery Ratio [%]	43	36	50	50 36	50	50 36

4 SUMMARY

This paper describes the various aspects of nuclear desalination processes including the different nuclear reactors used, the trends, and economic assessments for on-site ND plants.

It was described and demonstrated that the nuclear desalination is possible by coupling and integrating SMR, which are receiving a considerable attention for the several advantages they offer over large reactors (e.g., moderate space for installation, shorter time for construction, economical construction, and safe operation) with DPs.

ND could guarantee the production of large amount of water even with a lower power reactor, like the CAREM25, and of large quantities of electricity and water, for industrial and domestic use, with a higher power reactor, like the SMART.

Effectively if we consider the average per capita consumption of electricity and water, respectively estimated at 4.7 MWh/y and at 80.3 m^3/y, and the preferred desalination method of producing domestic water, i.e., RO technique, we can say that CAREM25 reactor coupled to a RO desalination plant can produce electricity for 35,000 inhabitants and water for domestic use for 200,000 inhabitants. SMART reactor coupled to a RO desalination plant can produce instead electricity for 130,000 inhabitants and water for domestic use for 160,000 inhabitants.

In addition, it has been proven that for the same amount of electricity and fresh water to be produced and desalination methods, the annual lifecycle emissions produced by a plant having a SMR reactor as power unit are clearly lower, about 150 times lower, compared to a similar plant having the widely used gas-fired combined cycle plant as power unit. Therefore, it can be stated that the coupling between SMR nuclear power plant and desalination plant is an appropriate solution to satisfy the water and energy needs of cities, or industrial districts, of average size in a short time.

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