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Future vision of using nuclear energy for desalination plants in Egypt

Mohamed K. Shaat, Loula A. Shouman, Dalia A. Fadel*

Egyptian Atomic Energy Authority, Nuclear Research Center, Reactors Department, P.O. 13759, Cairo, Egypt, emails: dalia_shaaban@windowslive.com (D.A. Fadel), m_shaat3073@yahoo.com (M.K. Shaat), loula.shouman5@gmail.com (L.A. Shouman)

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ABSTRACT

Egypt entered the nuclear age. The first nuclear power plant (NPP) is now under construction at El-Dabaa Marsa Matrouh governorate, Egypt. In this study, the use El-Dabaa nuclear reactor (VVER-1200) as a source of heat energy for desalination plant to provide fresh water to El-Dabaa area is investigated. Both multi-effect distillation (MED) and reverse osmosis (RO) are used in the desalination plants. The Desalination Economic Evaluation Program (DEEP) is used to calculate the performance of VVER-1200 with MED or RO plants. The influence of the desalination plant product on the performance of the NPP and the net output power to the grid is investigated. The study presents the impact of using waste heat from nuclear plant condenser to heat feed seawater to save power. Seawater input temperature can increase by 5°C and 10°C with the use of the condenser's wasted heat and the results show power savings of around 8.1% and 27%, respectively. The study also investigates using small modular reactors (SMRs) to provide electricity and fresh water in new residential area. The results show that, the use of the SMRs plant totally as energy source to the desalination plant can produce up to 600,000 m^3/d.

Keywords: Nuclear power plant; Desalination plant; VVER-1200; El-Dabaa; Small modular reactors

1. Introduction

Egypt suffers from water shortage problem due to the rapid growth in population, industry growth, agriculture and construction of new cities in the desert. With limited fresh water resources (Nile River) and after Al Nahda dam in Ethiopia, the crisis of water in Egypt has increased. As a result, adequate solutions to the water situation are required for a comprehensive explanation of sustainability [1,2]. Seawater desalination is utilized to address water shortages in Egypt. During the preceding 7 y, 82 desalination plants with a total capacity 917,000 m^3/d have been erected. A new 14 plants with a 518,000 m^3/d capacity are currently being done so and the government is targeting 6.4 million m^3 by 2050 [3].

Desalination is a technique that uses energy to convert large amounts of seawater or brackish water into fresh water by removing the appropriate amount of salt and other minerals. The most widely used desalination systems are reverse osmosis (RO), multi-effect distillation (MED) and multi-stage flash (MSF).

The price of desalinated water has changed dramatically in recent decades taking into account the technology employed, plant size, location, capacity, pretreatment requirements, feed water quality, and power cost. The use of more sustainable and cleaner energy sources is becoming more popular as a result of problems with fossil fuel supplies due to the global crises caused by the Ukrainian war. Nuclear energy is a sustainable form of energy that can be used in desalination plants, as it emits no greenhouse gases. Nuclear desalination looks to be a valuable and promising alternative for powering desalination facilities at a low cost [4,5]. The energy released from nuclear power plant (NPP)

* Corresponding author.

is used to operate thermal desalination procedures as a cogeneration system to generate electricity [6–8].

The International Atomic Energy Agency (IAEA) has extensively studied the application of nuclear energy in desalination since the 1960s [9,10]. The IAEA various publications on nuclear desalination areas were covering, technical issues [11,12], safety considerations [13], and economic evaluations [14,15].

Several studies on cogeneration of desalination and power plants had been represented. Nuclear desalination plants (NDP) based on the MED-TVC (thermal vapor compression) process was dynamically modeled and analyzed by Dong et al. [16]. The modeling verification was provided with a comparison to the design data, also the open-loop results for stepping the input seawater flow rate were presented.

Kim et al. [17] explored three different systems as intermediary systems to avoid the leaking of radioactive material into the desalinated water.

A nuclear desalination plant using ultrafiltration (UF)-RO combined with low temperature evaporation MED was presented by Khamis and El-Emam [18]. The treated water from the UF unit and the output hot stream from condenser are combined to pre-heat the supply for the RO unit.

Low temperature desalination and hybrid technologies were proven to be good choices that operate at reduced cost with greater recovery ratios. Tai et al. [19] proposed a water-heat combined supply system based on waste heat from a coastal nuclear power plant, and its thermodynamic features, energy-saving ability, environmental advantages, and economic effectiveness were examined.

Around the world, several nuclear reactor configurations are in operation [20]. The most common nuclear reactors used in conjunction with desalination processes were mentioned in [21,22]. Small modular reactors (SMRs) and fast neutron reactors are the most promising technologies for the near future [23].

In the Middle East and North Africa (MENA) area, Khan et al. [24] undertook an economic study for the coupling of SMRs (CAREM and SMART) with MSF, MED, RO, and hybrid desalination systems.

Jung et al. [25] study the feasibility of a small sized nuclear heat-only plant dedicated for desalination in United Arab Emirates. The analysis revealed that running a nuclear heat-only plant beside a thermal desalination plant will significantly increase safety and economics without reducing desalination performance.

A parametric study was carried out by Ingersoll et al. [26] to link NuScale plant to a range of desalination systems. The most advantageous economics are offered by a NuScale unit connected to RO desalination plant.

Two distinct nuclear hybrid energy systems were linked to (SMR) models and simulations by Hills et al. [27]. The first system uses freeze desalination, and the second uses RO to produce clean water. From results, the systems can meet peak electricity demand, and RO product was around six times more than freeze desalination.

Many thermo-economic studies of NDP were conducted. Jamil et al. [28] presented a review of cost balance calculations for significant desalination components.

Locatelli et al. [29] provided systems potentially suitable for coupling with NPPs. The results show that, desalination might be technically and economically feasible. Sadeghi et al. [30] created a novel computer algorithm to assess the economics of various hybrid desalination methods linked with NPPs.

Schmidt and Gude [31] provided a feasibility study of nuclear energy driven cogeneration plant for water and power production in Homestead, Florida. The analysis evaluated the water and power cost of hybrid desalination configurations.

The IAEA developed Desalination Economic Evaluation Program (DEEP) to estimate the installation and operating costs of nuclear desalination plants built using various desalination techniques and energy sources. The results obtained by Mansouri and Ghoniem [32] showed that DEEP software has enabled the comparison between different scenarios for water desalination using different desalt technologies coupled with nuclear or fossil energy technologies. This comparison demonstrates that, Saudi Arabia's nuclear alternatives are more economical than its fossil fuel options, making them economically beneficial for the nation.

Using the DEEP, Rezaei et al. [33] economically assessed the coupling of the Qeshm island desalination plant with six energy sources. The estimated annual electrical costs indicated that, the optimum fossil power plant with combined cycle was 97.72 $/kWh, which was 30% higher than 67.42 $/kWh in pressurized water reactor.

Khan and Khan [34] used simulation models DEEP & DE-TOP to conduct a techno-economic analysis of Karachi nuclear power plant for various desalination technologies. This study showed that MED could be an implementable solution.

Kavvadias and Khamis [35] conducted a sensitivity analysis to examine the interactions between main parameters and to evaluate the uncertainty for different nuclear desalination alternative scenarios. The water cost was estimated in the analysis using Monte–Carlo simulation integrated DEEP.

This study's goal is: first, show the visibility of coupling desalination units with the El-Dabaa nuclear reactor (VVER-1200) by using extracted steam as energy source to the MED plant and electric power to the RO plant. While condenser waste heat from the power plant is used to preheat the feed seawater for the desalination plant, the study will look at the implications of raising the feed temperature on electricity savings. Second goal is to investigate the small modular reactors (SMRs) that can be coupled with the desalination units in new cities or coastal areas.

2. Modeling using DEEP software

DEEP was used in this study to simulate and determine the performance cost of coupling the VVER-1200 El-Dabaa nuclear reactor with either the MED or RO plants. The software of DEEP is explained in numerous references, and its manual that showing how to use it is available, therefore it won't be discussed upon here; only a brief note is described.

The DEEP package is a three-part Excel module that includes a power plant, a desalination plant, and a coupling system. The user has a choice of eight accessible energy sources when it comes to the kind of power plant cycle.

Several different forms of distillation technologies can be used to determine the desalination plant's characteristics. DEEP is also used to evaluate other technologies such as desalination capacity, water salinity (TDS), distillation process type, maximum brine temperature, and seawater temperature. The nuclear power plant is recognized as the type of power plant chosen at the conclusion by the intermediate loop. A number of economic conclusions, including capital costs, operating expenses, and fuel costs can be obtained. All details of the DEEP illustrated in the Manual of the software [36,37].

3. Coupling El-Dabaa plant with desalination unit

Egypt's first nuclear power plant (NPP), El-Dabaa power plant is now under construction at El-Dabaa city at the North coast and located 130 km northwest of Cairo. Four 1,200 MWe pressurized water reactor (PWR) units, each based on the Russian VVER-1200 (AES-2006) design, built at the El-Dabaa NPP site. Connecting a desalination plant with one of the PWRs will provide potable water for El-Dabaa area and the north coast. The technical data of the VVER-1200 is presented in Table 1.

Either MED or RO can be employed, or both can be used simultaneously (hybrid system). The advantages of employing the coupling are investigated using DEEP software.

The MED in this study operates with assumptions, gain output ratio 11, number of effects 14, maximum brine temperature 70°C, and the product salinity 25 ppm. For MED unit the reduction in the net electric power delivered to the grid based on calculating the power lost due to the extracted steam from the low-pressure turbine as well as the electrical energy used to run the desalination unit.

Fig. 1 illustrates the schematic diagram of coupling of MED with the NPP, where steam at 78°C, 26 bar is extracted from the turbine and delivered to an intermediate loop. The intermediate loop is used as heat exchanger; transferring heat from turbine steam to evaporate the flow entering MED first effect.

Heat pipes is a type of heat exchanger used in intermediate loop, and they were used in solar and nuclear desalination processes [38,39], providing a number of benefits. They do not need pumps to work, and the temperature differential between their hot and cold components serves as a good signal of potential difficulties [40]. In cogeneration plants, the nuclear reactor steam and saltwater stream are physically isolated from the product water, so using the heat pipes reduces the potential of contamination. Heat pipelines, rather than the traditional nuclear-desalination intermediate loop [41].

Table 1
Technical data of VVER-1200 (AES-2006)

Parameter	Value
Reactor thermal output (MWth)	3,200
Power plant output, net (MWe)	1,082
Primary coolant material	Light water
Steam flow rate at nominal conditions (kg/s)	1,780
Core coolant inlet temperature (°C)	298.2
Core coolant outlet temperature (°C)	328.9
HP turbine inlet pressure (MPa)(a)	6.8
HP turbine inlet temperature (°C)	283.8
Condenser pressure (KPa)	4.9

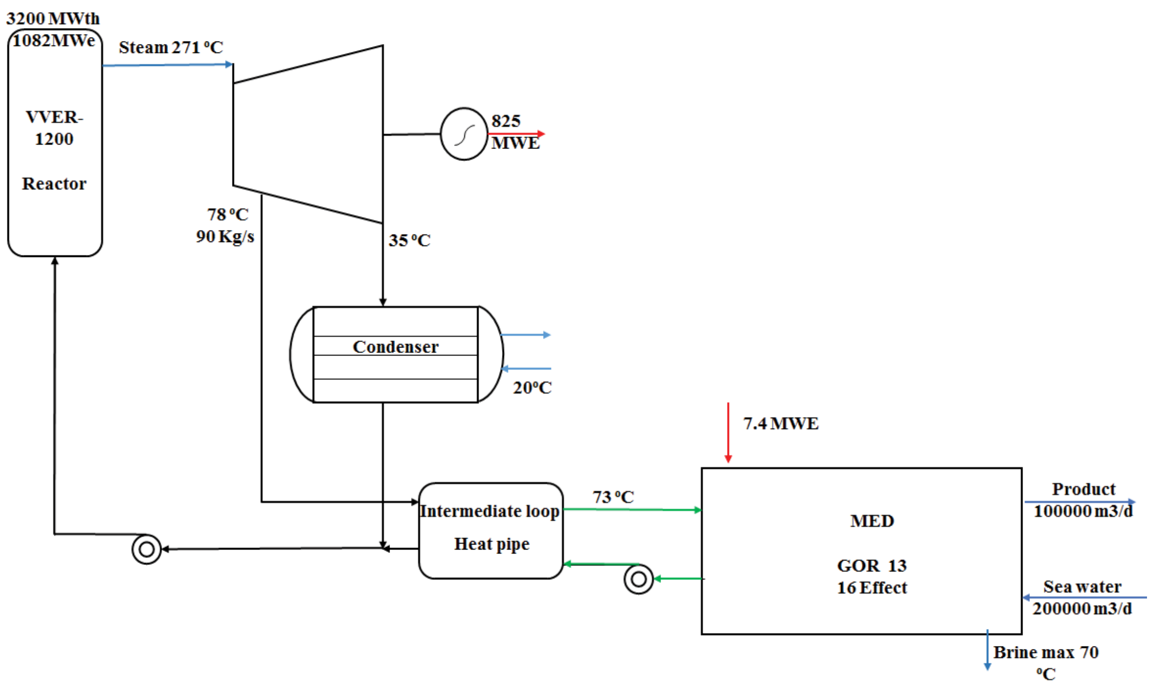

Fig. 1. Flow diagram of nuclear plant VVER and multi-effect distillation desalination plant.

For RO unit the net electrical power to the grid is reduced by the electrical energy consumed to run the unit. The operating conditions of RO are recovery ratio 42%, maximum membrane pressure 69 bar and the product salinity 199 ppm.

The effect of the desalination plant water production on the net electic power delivered to the grid for both MED and RO plants at seawater temperature 20°C and salinity 38,000 ppm is shown in Fig. 2. The increase of the water product reduces the electric power provided to the grid. The production of 500,000 m^3/d from MED or RO will reduce the net power delivered to the grid to 711 and 776 MWe, respectively.

Therefore, the water product of desalination plants at the same net output power from El-Dabaa plant is calculated and presented in Table 2. RO productivity is higher than MED, but this does not conclude that RO is preferable than MED. Several factors must be calculated to decide what type of desalination unit is used, the economic factors are quite important, the capital cost of the unit, operation cost, which include pre and post water treatment, membrane replacement for RO as well as energy cost.

The waste heat from power plant condenser can be utilized in heating the seawater feeding the desalination plants [18]. Heating the feed seawater will lead to higher recovery ratio and thus to higher productivity and lower energy consumption in RO plant [19]. The RO plant consumed 14 MWe to produce 100,000 m^3/d, when seawater feed temperature is increased 5°C the product will be 108,000 m^3/d. This increase in product is calculated as saving in power and presented in Table 3.

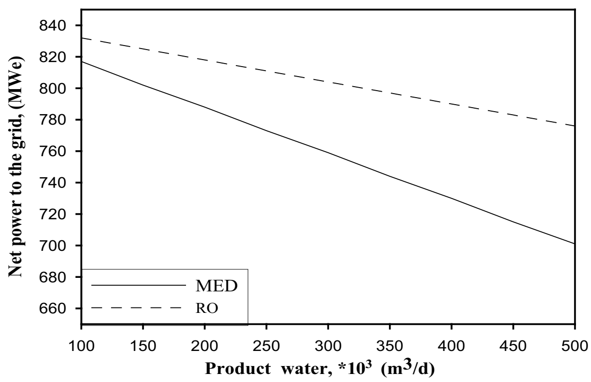

Fig. 2. Effect of water production capacity on El-Dabaa net output power.

Table 3 illustrates the saving in power that can be achieved with increasing the feed seawater temperature for desalination plants. At productivity 100,000 m^3/d, for both MED and RO units the consumed power saving are 8.1% and 7.8%, respectively if the seawater temperature increases 5°C. As the seawater heated 10°C the saving in the power consumed can reach 27% for MED and 14.3% for RO.

The influence of the feed seawater temperature on the net electricity delivered to the grid by the NPP is shown in Fig. 3. As shown in the figure, for 500,000 m^3/d, the provided electric power to the grid is increasing 11.5% and 15.7% when feed water heated 5°C and 10°C, respectively.

4. Small modular reactors with desalination plants

According to the IAEA, there will be 96 SMRs throughout the world by 2030. Small modular reactors (SMRs)

Table 2
Production of multi-effect distillation and reverse osmosis units at different net output power of El-Dabaa plant

Net electric power to the grid (MWe)	MED production (m^3/d)	RO production (m^3/d)
820	89,000	186,000
800	158,000	325,000
780	228,000	47,000
760	297,000	615,000

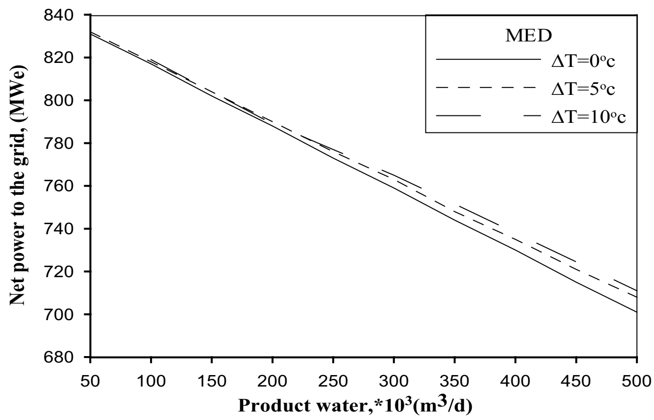

Fig. 3. Effect of increasing seawater temperature on the net power output.

Table 3
Saved power consumption for multi-effect distillation and reverse osmosis due to feed temperature increase

Nuclear plant (MWe)	Desalination plant	Temperature increase (ΔT), °C	Desalination power consumed (MWe)	Power saving
VVER-1200 (AES-2006)	MED 100,000 m^3/d	–	7.4	
		5	6.8	8.1%
		10	5.4	27.0%
	RO 100,000 m^3/d	–	14	
		5	12.9	7.8%
		10	12	14.3%

are nuclear fission reactors that produce no more than 330 MWe of electrical power [42]. SMR has various benefits, including inherent safety heaters taking up less space, being more cost-effective and safer to operate, and taking less time to build, resulting in lower costs [43]. They're now in use or under construction in a number of countries throughout the world. Examples of such plants, the KLT-40 in Russia, SMART in Korea, IRIS in the United States, and CAREM in Argentina. The IRIS, NuScale designed by the United States and the SMART designed by Korea, and the HTR-PM designed by China [44–48].

SMR facilities are designed to use in industrial applications, so desalination systems can be combined with SMRs in cogeneration mode. The SMR-based nuclear desalination facilities are more deployable and may be situated close to the load centers to save transportation costs because of the excellent nuclear safety of SMRs.

As an example, in this study two kinds of the SMRs have been chosen to be coupled with desalination plants SMART-330 and NuScale-160.

The SMART is integral PWR that, 330 MWth and 100 MWe with light water moderator and coolant, and system pressure 15 bar. Its distinguishing features are coupling of the desalination system or process heat application [45].

A NuScale design consist of 1–12 independent modules, each module includes an integral pressurized light water reactor, system pressure 8.7 bar. NuScale

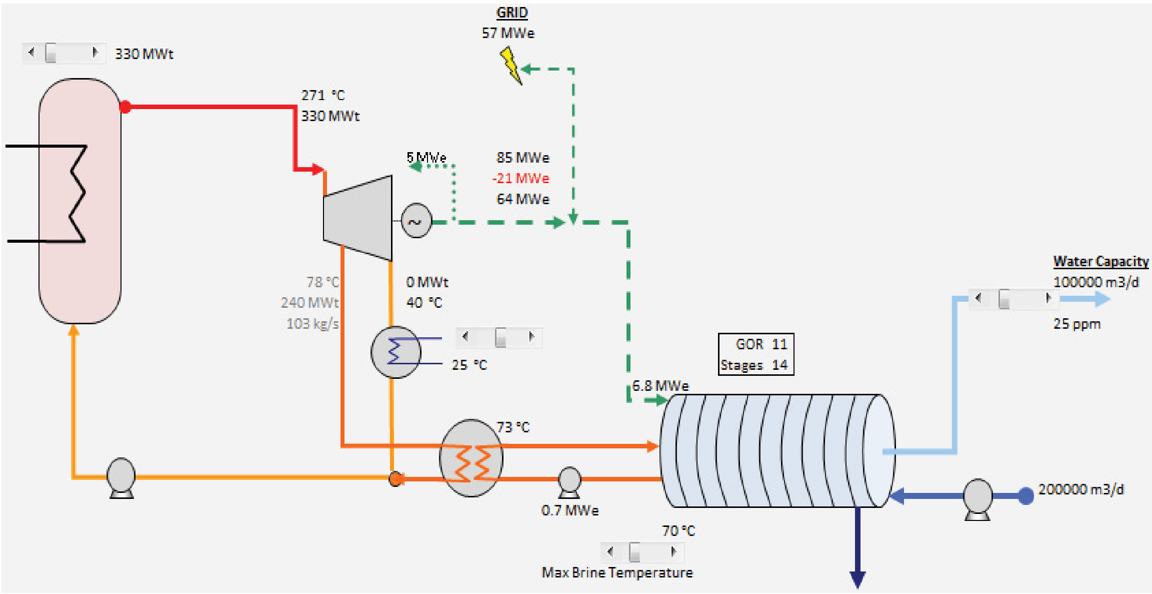

Fig. 4. Flow diagram of nuclear plant SMART and multi-effect distillation plant.

Table 4
Water production and net electrical power for SMART-330 and NuScale-160

Reactor	Desalination plant	Net electric power to the grid (MWe)	Productivity (m³/d)
Korea, SMART-330 (MWth)	–	85	0
	Multi-effect distillation	71	50,000
		57	100,000
		0 (Heat only)	134,000
	Reverse osmosis	71	100,000
		57	200,000
		29	400,000
		0	600,000
USA, NuScale-160 (MWth)	–	41	0
	Multi-effect distillation	36	20,000
		26	53,000
		0 (Heat only)	73,000
	Reverse osmosis	34	50,000
		27	100,000
		0	293,000

developed to supply energy for electricity, district heating, and desalination with 45 MWe, 160 MWth [45].

A schematic diagram of MED unit coupled with SMART to produce 100,000 m^3/d is shown in Fig. 4. The thermal energy input to MED is 240 MWth, and output power from the power plant is 64 MWe, where 6.8 MWe is used to operate MED equipment and the net output power is 57 MWe can be provided to the grid or used for another purpose in the site.

Results at Table 4 show the decrease in net power produced from the plant due to coupling with desalination plant. The ratio between the product water and electrical energy generated from the plant depend on the site requirements. If the power plant is totally operated to produce water (heat only) all thermal energy of the SMR will be directed to the MED units. In case of RO units, the total electric energy generated by power plant is directed to the RO plant.

For SMART and NuScale Plants, the maximum product will be 600,000 and 293,000 m^3/d in coupling with RO units and 134,000 and 73,000 m^3/d when it is coupled with MED units.

As presented in Table 4, results reveal that, coupling RO unit produce more product water than MED if the nuclear power plant energy is totally used in water production.

5. Conclusion

This study discusses the possibility of coupling the El-Dabaa nuclear reactor (VVER-1200) as a source of heat energy with a desalination plant to produce fresh water. The performance of the VVER-1200 with MED or RO plants is determined using the Desalination Economic Evaluation Program (DEEP). To conserve energy, the impact of heating feed seawater by waste heat from nuclear plant condensers is being studied. The results indicated that, the rise of the seawater feed temperature 5°C and 10°C due to the coupling result in saving desalination energy consumption approximately 8.1% and 27% respectively. Fresh water provision in new residential areas utilizing SMRs as source of electric power and fresh water are being researched. When the SMART of 330 MWth is coupled with desalination plants the maximum water product 134,000 m^3/d for MED and 600,000 m^3/d for RO plant. Also, the SMR (NuScale) 160 MWth is used to produce water, with maximum productivity 73,000 m^3/d with MED and 293,000 m^3/d for RO.

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