Nuclear desalination in Iran, current status and perspectives

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Abstract. Nuclear power can be categorized as a clean energy source for producing electricity and supplying the required energy to a desalination plant, promising less atmospheric emission in comparison to fossil fuels. Considering the fact that fresh water-related issues are acute in many countries of the world, the utilization of desalination technologies seems to be the key solution to these problems. Desalination processes are known to be “energy-intensive”, emphasizing the potential advantages of its integration to a nuclear power plant in medium- to large-scale seawater desalination projects. The demand for electricity and fresh water in Iran compels the country to search for a feasible option. We suggest nuclear desalination as a suitable alternative, in which the recovered heat can be used in thermal desalination systems. In this article, the status of currently operating desalination plants and future developments are described. Several possible schemes for coupling nuclear power plant and fossil fuel-based plants with desalination technologies are suggested and some thermo-economic analysis (based on the specific characteristics of the country) are presented. Results of calculations reveal some advantages of nuclear desalination complex and its competitiveness with other options. It should be noted that the research has been conducted by cooperation of two SPbPU PhD students with Iranian citizenship.

1 Introduction

Seawater desalination can be counted as one of the most feasible solutions for fresh water stress, which is already turned to a significant global challenge in many regions around the world. Since the 1950s, the industry of desalination has been implemented and nowadays it is playing a crucial role in supplying the required fresh water of some countries [1]. There are several compelling reasons that make countries to implement desalination technologies: in arid climates, the demand for fresh water is continuously increasing by growth of population, the industrialization, metropolization, and other developments rise the per capita demand for fresh water, water pollution and also groundwater over drafting cause to water crisis [2].

Among the energy sources, the nuclear power, which has already illustrated its unique proficiencies and potential advantages through many years (with more than ten thousand reactor years of performing in more than 30 countries of the world), can be considered as one of the clean options for supplying electricity or heat to desalination plant [3]. It is worth noting that nuclear reactors are the only options for providing required energy of large-scale desalination projects in the future [4]. Nuclear reactors are not directly causing hazardous emissions unlike fossil fuels, which discharge tons of carbon and other atmospheric emissions. For providing desalination plant required energy, fossil fuels are the dominant utilized energy sources due to their simplicity of use and availability. Fortunately, nowadays there is a

great interest shown by many countries in investigating other sources of energy and methods, which are more sustainable and environmentally friendly [5,6].

The aridest and semiarid areas, which have extremely affected by the lack of safe drinking water access are located in Middle East and North Africa (MENA). It is reported that the quantity of accessible fresh water in MENA was cut in half in the period between 1975 and 2001 [7]. It is also anticipated that the future status of fresh water in MENA will become worse due to the ongoing growth in population and climate change impacts. Considering all the above-mentioned problems, discovering an alternative in MENA countries and also in other poor regions in terms of water resources is urgently required.

Among the MENA countries, Iran can be stated as one of the countries with a good experience of taking the advantages seawater desalination technology, dating back to 1960 [8]. The country is located in arid to semiarid zone of Earth with a relatively great climatic diversity. The average rainfall is about one-third of the global average. Most of the installed desalination systems are fossil fuel-driven, implying that it is necessary to shift into sustainable energy sources for future desalination projects. Currently, the water stress is very serious in some central and southern lands of Iran. Notwithstanding the foregoing, the water management situation of the country is unsatisfactory. To offer just an example, the use of non-developed agriculture technologies has led to high amounts of water waste in some regions of Iran. On the other hand, uncommon

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high losses of water in industrial and household consumption decline the water resources.

As well as the fresh water issues, the country's electric energy demand cannot be entirely responded in some periods (on some summer days). It has been reported that for preventing the power outage in the summer of 2019 (during the peak time of electricity consumption) an amount of about 9,000 to 10,000 MW should be planned to be handled [9]. Considering this, the construction of Nuclear Power Plant (NPP) with the option of cogeneration application (here we consider seawater desalination technologies) will be advantageous in solving both the energy and fresh water issues. In this regard, the country has short- to long-term plans for persuasion of students, specialists, and researchers to investigate for the best options of coupling of power plants to desalination systems. Several studies in this concern have recently been conducted [8,10-13].

The main objective of this article is to propose and evaluate a suitable nuclear desalination combination as a remedy for both electricity and fresh water difficulties, promising less greenhouse gas emissions. After a brief problem explanation, the status of seawater desalination in Iran will be described in Sec. 2.1. The use of different energy sources for electricity generation and the motivation of the country for nuclear desalination utilization will be stated in Sec. 2.2. Some suggested schemes of nuclear-desalination coupling are given in Sec. 2.3. The results of the thermo-economical assessment are expressed in Sec. 3 and Sec. 4 gives a brief concluding discussion.

2 Method

2.1 Status of seawater desalination industry in Iran

In the past few years, the Middle East is influenced by the atmospheric changes and less insufficient precipitation in cooperation with some other reasons such as rapid urbanization, population density rise in some regions have led to water stress. Considering these facts, it can be said that one of the most unfavorable challenges of Iran in the next 10 years will be the fresh water shortage tensions, for which country should have applicable plans (projects) to deal with. It is reported that more than half of the provinces of Iran currently are facing the fresh water deficit [8].

In Iran, several dams are constructed in order to store the water and use it for electricity generation, listing Iran among the countries with the highest number of installed dams. Despite the several advantages of installing dams, the huge amount of evaporation can be stated as a negative result. Groundwater is also accounted for covering fresh water necessity, which in turn has led to the reduction of water resources in some regions of the country. Annual precipitation can be regarded as the primary water resource of the country, which is about 413 billion cubic meters, ranging from 50 mm to 1000 mm in different regions of Iran [8]. In the past few years the climate changes also influenced the water resources,

which have led to the droughts and several other problems in water management of the country.

The construction of desalination plants needs to be increased to meet the demand for water in some specific parts of Iran. Currently, about 73 water desalination units are operating in different regions of the country, producing total capacity of about 420,000 m³/day of pure water [14]. According to the Ministry of Energy, 39 new desalination systems came to operation from 2013 (mostly on the southern coast of the country) with the total capacity of more than 174,000 m³/day [15]. The growth of global desalination market reflects the fact that this technology is reliable and effective in dealing with the fresh water shortage. Caspian Sea from the north, and Persian Gulf and Sea of Oman from the south are surrounding Iran, which fortunately give a suitable opportunity to take the advantages of desalination technologies. It has been reported that the total capacity of fresh water production of the country will be increased by 300,000 m³/day by the end of 2022 [15].

The conventional desalination technologies, which are commercially available can be categorized into two main groups of thermal and membrane-based (RO) desalination technologies [16]. In thermal desalination methods such as Multi-stage flash distillation (MSF) and Multi-effect distillation (MED), lateral heat from the low-pressure stages of a turbine or heat resulting from fossil fuel burning is implemented to evaporate water and then recover the fresh water after condensing it. In desalination by membranes, the electricity from a power plant drives high-pressure pumps to force water pass through semi-permeable membranes, which leads to the separation of dissolved solids and fresh water. There are also several new technologies on their way to enter the commercial-scale market in future [1,17].

In 1960, the first small desalination plant with a capacity of 1000 m³/day was installed on the island of Khark [8]. This desalination plant was set up with the technology of MSF. Subsequently, several small and medium-sized desalination plants were designed to achieve a total capacity of 50,000 m³/day. Most of the seawater desalination plants for fresh water production are centralized in southern regions of Iran. Initial research on the construction and commissioning of the Chabahar-Kenarak facility was started in 1973. The project planned to desalinate water using desalting technology of MSF with a total capacity of 15,000 m³ / day [8]. Finally, the construction of the unit project was completed in 2006. According to the report of the Ministry of Energy, the second phase of desalination of the Chabahar-Kenarak plant was operated in 2014. It was reported that the total capacity of the plant was increased to 35,000 m³ / day using RO desalination technique.

The construction of Iran's largest desalination plant, which is located in Bandar Abbas, has been completed. The facility has begun operating in December 2018. The project was funded by the private sector for 204 M\$. It will have an initial production capacity of 20,000 m³/day at the first stage using reverse osmosis technology and will be updated to produce 100,000 m³/day of fresh water [18].

2.2 Iran's energy situation and motivation for nuclear power development

The existence of water and energy crisis in some regions of the world make government move steadily toward promising technologies. In this way, it is very essential to explore all the possible options, considering technical and economic factors. The majority of desalination plants are specifically designed to desalinate water only, which require a large amount of energy (about 1 kWh for 100 gallons of fresh water) [19]. It is believed that nuclear power can be implemented for large-scale seawater desalination, promising less environmental footprint in comparison to fossil fuel-driven desalination systems.

Iran can be counted as a resource-rich country considering its huge reserves of oil and gas. The statistical reviews of 2017 revealed that Iran has the most massive natural gas reserves and the fourth greatest

confirmed oil reserves among the countries of the world [20]. The population growth, industrial and economic evolution, expansion of request for transport, and increase of electricity demand are some of the major factors, which have led to the growth of general energy consumption almost twice since 2004. The main implemented energy sources are the natural gas and oil with the considerably less contribution of hydropower, nuclear energy, and renewable energy sources such as wind, solar, and biogas. The share of different energy sources in electricity generation of Iran between 2000 and 2018 years is shown in Fig. 1. Considering the problems concerning the burning of fossil fuels, policymakers are investigating for attractive and creative approaches to reduce the dependence on fossil fuel resources. Therefore, the development of renewable and sustainable energy sources is included in the national sixth 5-year development plan of Iran [20].

Fig.1. Electricity production and consumption of Iran (source: Ministry of Energy)

In shifting from fossil fuels to a clean source of energy, nuclear power can be suggested even though it does not have all the advantages of renewable sources, it does not suffer from the restrictions regarding renewable energy sources. From the point of view of economics, the electricity generated by NPPs is competitive to other energy sources and can be categorized as a sustainable and stable resource. Hence, decision-makers are planning to increase the nuclear energy generation capacity in near future by constructing two new NPPs with the capacity of 1057 MW(e), the operation of which will reduce the emissions of pollutants by 14 million tonnes per annum [20].

The construction of nuclear desalination complex in Iran efficaciously will assist in solving both the fresh water and electricity shortage problems. It is important to notice that the amount of gap between electricity production and demand was about 5,000 MW in December of 2018 [21]. In order to prevent the power

outage in some periods of the year it is necessary to find proper energy options to meet the required capacity. Unfortunately, the renewable energy sources are not decidedly implemented throughout the country, however there is a great potential to take the advantages of them in different regions of Iran.

2.3 The type of nuclear reactor and desalination system

Determination of the reactor type to be constructed involves a complicated process, which generally influences the other industries of a country. Long-term advantages and disadvantages of the selected type must meticulously be considered. In selecting the nuclear reactor the fuel cost of specific type, operation, and maintenance are some of the most significant financial factors. When it comes to the integration to desalination unit, it is critical to examine the possibility of their combination and take into account safety factors. In

principle, all of the nuclear reactors can be used as the source of energy for desalination purposes [22]. Taking this to account, any medium to high power NPP is suitable for Iran, due to the previously stated issues in electricity sector. Iran's electricity network has the capacity of adding electricity generated by a high-power nuclear reactor, reminding the already operating Bushehr NPP of VVER-1000 type.

There is a variety of commercially available nuclear reactors for costumers promising the world's latest technology in design and safety parameters. The proposed complex will serve as a dual-purpose facility to generate electricity and produce fresh water. Due to the fact that world has gained lots of experience with the light water reactors, they can be listed as the high priority candidates in our suggestion, taking into account their approved safety and reliability features. However, comprehensive research should be conducted in order to techno-economically analyze potential advantages of High-Temperature Gas-cooled Reactors (HTGRs) on coupling with thermal desalination units in Iran [23]. The temperature of water in the heat exchangers of the HTGR design is ranged from 80-130 °C, which is suitable to be used as the main heat source of MED or MSF desalination unit [24].

The countries of MENA can be considered as the greatest seawater desalination customers, in which the world's largest desalination plant is located with the daily capacity of 1,030,000 cubic meters [25]. This is because more than 85% of the MENA region is formed by arid and hyper-arid lands [26]. By having a look at the statistics regarding the world's desalination plants, it can be understood that RO technology is the dominant desalination method. However, the thermal desalination processes are still dominant in MENA region with a total capacity of 18.1 million m³/day followed by RO technology with a capacity of 16.0 million m³/day [27].

Being a part of the MENA region, Iran has a good experience with desalination plants. The countries major desalination units are based on membrane technology following by MED and MSF technologies. In fact, proceeding with the seawater desalination is not a complicated manufacturing process for the country, due to the previous experience of the suppliers with desalination systems of Iran. Considering the fact that all of the commercially available desalination techniques are trustworthy, one of the most critical criteria is the economy. On one hand, the cost of desalination by membranes has considerably declined in the past few years, but on the other hand, taking advantage of waste heat of an NPP is economically convincing. It is also advantageous to consider the potentials of the country in manufacturing some required equipment of desalination systems. For example, if the country is already producing competitive membranes (or in levels of development), it is beneficial to mostly utilize RO desalination units, which leads to the general and long-term (operation and maintenance) cost reduction.

A useful method of desalination is the utilization of two or more desalination technologies to take the advantages of both membrane and thermal desalination techniques. One of the advantages of this approach is the

decrease in total water intake, which leads to cost reduction and declines the environmental effects of desalination process. In some cases, the waste heat of MSF plant can be used in MED unit to decrease the overall energy loss. The hybrid scheme of MSF/MED+RO can be suggested in order to decrease or avoid scaling and fouling problems, as well as gaining more production by the same process [28]. In another hybrid approach, the rejected water of membranes can be used as the feed water of thermal desalination methods. It is possible to increase the water quality of RO technology by blending it with the produced water of thermal desalination processes [3].

3 Results

In order to check the superiority and weak points of suggested nuclear desalination system, it is advantageous to utilize some reliable tools. For this purpose, several computer software and tools have been developed through the years to provide the possibility of performance comparison of different desalination scenarios. In our work, we have chosen the IAEA Desalination Economic Evaluation Program (DEEP) to carry out economic analysis [29]. With the aid of this program, several types of power plants such as fossil fuel-driven gas or steam plants as well as water-cooled or gas-cooled NPPs can be modeled. When it comes to desalination systems, all the commercially available medium- to the large-capacity membrane and thermal desalination processes can be examined.

The NPP type is considered to be a Water-Cooled Reactor (WCR) with the net power of 1000 MW(e), which seems to be preferable for Iran. To get a better understanding of nuclear desalination complex's economic indicators two types of fossil fuel-based power plants are also involved in the assessment. One uses oil as the Steam Power Plant (SPP) with the total electrical output of 650 MW(e) and the other uses gas within the Combined Cycle Plant (CCP) with the net power of 500 MW(e). The key point of our analysis is to find out a good approximation to the cost of seawater desalination, by considering exact input data such as interest rate, discount rate, the average value of total dissolved solids in Persian Gulf, specific base cost of desalination plant and other parameters. Some of the most important input parameters are described in Table 1 in the appendix.

The levelized power cost data for power plant options are illustrated in Table 2. The highest capital cost belongs to the NPP, however, its electricity generation cost is the least among other plants. By comparing the fuel costs, it can be realized that the fuel cost of SPP-650 is considerably higher than the other plants. Adding up the fossil fuel environmental damages to this, the unnecessary of implementing this type of energy source will be revealed.

Table 2. Levelized power cost data of different power plant cases

Plant type	Units	WCR-1000	SPP-650	CCP-500
Total costs				
Capital costs	M\$	6,965	2,108	554
Fuel costs	M\$	69	616	252
O&M costs	M\$	54	10	18
Annual cost	M\$	552	768	309
Specific costs				
Capital costs	\$/kW	7,255	3,243	1,103
Fuel cost	\$/MWh	11	194	76
O&M costs	\$/MWh	9	3	6
Power cost	\$/MWh	90	242	93

The results of the economic evaluation of MED, MSF, RO, RO+MED, and RO+MSF desalination plants with the total capacity of 100,000 m³/day along with the assumed power plants are shown in Table 3. As it was expected, the lowest desalination cost can be achieved by implementing RO membrane unit. In all of the cases, MSF method has the highest desalination cost, due to the huge amount of energy usage. Due to the high fuel cost (energy cost) of the SPP plant the desalination costs of all types are considerably higher than that for WCR and CPP plants. Water production cost by the CCP energy source is a bit less than that for WCR in the case of thermal desalination plants. For the RO method, the WCR plant has the least cost of water production, due to its lower electricity generation price. The costs of hybrid desalination processes seem logical, considering their previously stated advantages over the other desalination technologies.

Table 3. The results of water plant economic evaluation

Plant type	Units	WCR-1000	SPP-650	CCP-500
MED				
Total capital costs	M\$	226	200	200
O&M costs	\$/m ³	0.13	0.13	0.13
Total energy costs	\$/m ³	0.62	1.54	0.59
Desalination cost	\$/m ³	1.312	2.191	1.247
MSF				
Total capital costs	M\$	244	218	218
O&M costs	\$/m ³	0.13	0.13	0.13
Total energy costs	\$/m ³	1.28	3.31	1.24
Desalination cost	\$/m ³	2.014	4.012	1.948
RO				
Total capital costs	M\$	129	129	129
O&M costs	\$/m ³	0.21	0.21	0.21
Total energy costs	\$/m ³	0.34	0.84	0.35
Desalination cost	\$/m ³	0.836	1.329	0.839
RO+MED				
Total capital costs	M\$	152	152	144
O&M costs	\$/m ³	0.19	0.19	0.19
Total energy costs	\$/m ³	0.42	1.06	0.41
Desalination cost	\$/m ³	0.954	1.600	0.930
RO+MSF				
Total capital costs	M\$	158	150	150
O&M costs	\$/m ³	0.19	0.19	0.19
Total energy costs	\$/m ³	0.60	1.50	0.59
Desalination cost	\$/m ³	1.150	2.031	1.121

In order to express the cost change trend of each technology of desalination in dependence on the total capacity, the normalized water production costs of each process as a function of capacity are plotted in Fig. 2. It is obvious that the sensitivity of the RO process desalination cost to changes in the capacity is the maximum among the other methods. The desalination cost by MSF process does not change sharply by altering the water production capacity.

4 Discussion

In this study, the feasibility of utilizing desalination plants along with the nuclear and fossil fuel power plants have been assessed. For both the desalination and power plant, general cases have been considered, which seem preferable to be constructed in Iran. It is important to notice that constructing a nuclear desalination system in Iran follows a strategical purpose, which will partially (or completely) remove the fresh water and electricity shortage problems. On the other hand, it can change the public opinion about nuclear power and increase its acceptance, however concerns about the wastes of NPPs still remain.

The results of calculations showed the economic competitiveness of nuclear desalination with the destructive fossil fuel-based desalination systems. However, fossil fuel-driven desalination plants pump thousands metric tons of carbon to the atmosphere, they are being utilized in many countries especially in MENA region. As a cleaner option, nuclear desalination is suggested as an aid for facing water shortage issues. The total efficiency of NPP can considerably be increased by means of integration to thermal desalination plants. Moreover, new generation of HTGRs can be addressed as more compatible nuclear reactors with desalination plants, which can be stated as the topic of future works.

Fig. 2. Normalized water production costs by different desalination technologies

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Appendix

Table 1. Main assumptions and input data

Table 11 Main assumptions and input data															
Power plant															
Plant type	Water-cooled reactor					Steam power plant					Combined cycle power plant				
Electrical output, MW(e)	1000					650					500				
Power plant lifetime, y	50					35					30				
Fuel escalation	3%					3%					3%				
Construction lead time, m	60					36					24				
Desalination plant															
Desalination method	MED	MSF	RO	RO+MED	RO+MSF	MED	MSF	RO	RO+MED	RO+MSF	MED	MSF	RO	RO+MED	RO+MSF
Capacity, m ³ /day	100,000					100,000					100,000				
Thermal/total desalination capacity	-	-	-	30%		-	-	-	30%		-	-	-	30%	
Plant operation life, y	25					25					25				
Total dissolved solids, ppm	42,000					42,000					42,000				
Feedwater temperature, °C	25					25					25				
Interest rate	18%					18%					18%				
Discount rate	5.8%					5.8%					5.8%				