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Assessment of the integrated nuclear plant for electricity production and seawater desalination in Iran

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ABSTRACT

Like many other developing countries, the demand for water is continuously growing in Iran. As an environmental challenge, Water shortage problems are explicitly sensible in the Middle East nations including Iran. In addition to the potable water problems, some central and southern provinces of the country suffer from a remarkable gap between electricity generation and demand, particularly during summer heat waves. To deal with the stated issues, nuclear desalination can be suggested as an alternative option, which has been used successfully by a number of countries. There are several fossil fuel-powered desalination units especially in southern sections of Iran. Fossil fuels destruct the environment, being the dominant reason for air pollution. Therefore, the primary objective of this research is to determine a suitable option for resolving both energy and water difficulties, which promises fewer carbon emissions in comparison to traditional sources of energy. Some important economic factors that are necessary to be examined for Iran are described. Several nuclear and fossil fuel-based desalination scenarios have been examined by using the International Atomic Energy Agency and Desalination Economic Evaluation Program (DEEP). Results of calculations for water and electricity prices of different options are presented and a brief discussion about other useful parameters is given. It has found that the coupling of a gas-cooled nuclear power plant with the multi-effect distillation technology is the most economical option with the desalination cost of 0.711 $/m^3$.

Keywords: Nuclear desalination; Feasibility of nuclear desalination in Iran; Water and electricity shortage in Iran; DEEP economic evaluation program

1. Introduction

Water seems to be the most abundant and cheap resource of our planet. It surrounds us, falls from the sky, covers more than 70% of the Earth's surface and makes it easy to think that it is always plentiful. However, approximately 2.5% of the total water resources are freshwater. In many territories, there is a serious decline in the freshwater availability due to the extension of water-related activities and it is likely to be one of the main difficulties of this century [1,2].

One of the impressive procedures in dealing with the freshwater problems is the seawater desalination, which is an energy-intensive technology [3]. Many countries are using different desalination technologies, which are proven and commercially available from some suppliers. The current desalination processes involving large-scale capacities have been utilized about five decades ago [4]. Considering the fact that desalination plants require great amounts of energy, it is advisable to use cleaner energy sources to protect air quality, decline the production of greenhouse gasses, poisonous

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gases, and acid rain, which are mainly related to the combustion of fossil fuels [5].

During the 60s and 70s, a great global interest directed toward the application of nuclear energy in order to gain electricity [6]. Nuclear power continues to supply considerable amounts of electricity with low carbon emissions. The electricity generation of nuclear reactors in the world was about 2,503 TWh in 2017, which means about 10% of total electricity production in the same year [7]. However, several Nuclear Power Plants (NPPs) have been decommissioned in recent years and governments in some countries are planning to decommission some of the operating NPPs.

In order to take advantage of both nuclear power and desalination, the concept of nuclear desalination was implemented in the 1960s, according to the Atomic Energy Agency (IAEA) [6]. The benefits of nuclear desalination can be realized by observing the economic analysis, which shows the competitiveness of nuclear power with fossil fuels [8,9]. Many analysis have been conducted to express that one of the appropriate options for solving both of the electricity and water problems in different regions of the world can be nuclear desalination [10–12].

The main desalination technologies can be subdivided into two techniques of thermal and membrane processes. The method of multi-stage flash (MSF), multi-effect distillation (MED), and vapor compression (VC) are the most popular thermal technologies. The membrane technologies mainly consist of reverse osmosis (RO) and electro-dialysis (ED). Among the desalination procedures, RO processes are leading with 53% of the total world desalination market, thermal desalination techniques 33% and the remaining consists of ED and other processes [13]. It is noteworthy to mention that the desalination processes including MED, MSF, and RO can be coupled to nuclear power reactors as well as several high technology revisions of the traditional processes, which enhance the efficiency of dual-purpose plants [14–16].

In response to the need to shift from fossil fuel, in addition to the nuclear desalination, renewable desalination systems have been proposed by several authors [17,18]. The abundant and clean renewable sources such as solar, geothermal, and wind are promising alternatives for coupling with modern desalination technologies. However, the intermittence and low intensity are the biggest issues in association with some of the renewable energy sources, which may be solved by mixing with other renewable sources or nuclear power [19,20].

The use of nuclear power for desalination in Iran has been evaluated many years ago [21,22]. Iran is among the developing countries, which face water scarcity. In analogy to other Middle East countries, the economy of the nation is mainly based on oil or gas resources. The growth of energy consumption and potable water demand forces the country to investigate mechanisms that are more reasonable. Dual-purpose NPP seems to be appropriate for the country, especially on the southern coasts of Iran. Several studies conducted to find possible procedures for dealing with the stated problems [8,23–26].

Several technical cooperation projects carried out in assessing the feasibility of a beneficial combination of NPPs with desalination units [27,28]. In 2002, an integration of the nuclear heating reactor with the MED desalination plant was carried out [29]. By utilizing a power range of 10–200 MW(t) the desalination plant could produce 8,000–160,000 m^3/d of potable water. In order to increase the thermal efficiency of desalination plants and reduce production costs, the coupling of nuclear reactors with hybrid desalination technologies was studied in 2003 [30]. Two coupling schemes of MED-RO and MED-VC were selected and it turned out that the cost of water with low-temperature MED-VC is relatively low. Other relative assertions are given elsewhere [31–35].

In the scope of feasibility examination, many studies were accomplished for different regions. In 2009, the feasibility of NPP integrated with a desalination plant in Egypt carried out [36]. More recently in 2016, a study has been conducted on nuclear desalination for Saudi Arabia, which explored the economic potential of using nuclear power for desalination [37]. It has found that nuclear power for desalination is relatively more cost-effective compared to fossil fuels. More case studies have been performed recently to techno-economically analyze the integration of nuclear and renewable energy sources with desalination systems [38–45].

As a final introductory remark, it is useful to note the most important objectives of this paper. The primary goal is to determine the most suitable nuclear desalination system, considering techno-economical and other specific conditions of Iran with the hopes that it will find a wider application. Shifting to a sustainable energy source and utilizing it for desalination purposes lead to some major improvements in Iran. It fills the gap between electricity demand and supply, produces potable water and creates jobs, and supports the evolution toward a low carbon future.

2. Status of energy, water, and atmospheric pollution in Iran

2.1. Freshwater shortage

Rapid urbanization, unsustainable development, population growth, mismanagement of water resources, and the expansion of agriculture can be considered as the essential causes of freshwater scarcity in Iran. Moreover, in recent years, the Middle East seems to be affected by the changes in atmospheric conditions and more dryness and relatively less annual precipitation (rain and snow) throughout the year can be seen. The most critical crisis that Iran will face in the next ten years, which in many parts of the country is already threatening the lives of residents, is the water shortage and drought. From 1980, the amount of water usage has grown at least 2 times in Iran [46]. The level of rainfall in Iran is ¼ of the global amount and ¾ of the country is in a zone of dry and semi-dry climate. About 16 Iranian provinces, exceeding half of the inhabitants, are on the verge of tensions in the water sector. It has been proclaimed that in an 8-month period (from September 23, 2017, to May 21, 2018) the country was received 151.5 mm of rain while the long-term averages are 214.6 mm, which indicates a 29% reduction in the mean precipitation nationwide [23].

Throughout the country, several dams have been installed with the purposes of water-storing and electricity generation. It makes Iran be in the list of the countries that have a great number of dams already built or under construction.

Moreover, Iran is examining the eventuality of setting up new dams [47]. In addition to dams, a major portion of needs to the water is being handled by groundwater exploitation, which has led to a disastrous situation in some regions of the country.

The water poverty generally can be resulted by two mechanisms of insufficient inherent water resources or poor management of natural water resources. Nowadays Iran faces both of the stated problems. Unlike other Middle East countries, which are well organized in confronting the water crisis, Iran did not show enough effort in providing practical solutions for either water desalination or water transportation to hotspots. However, the importance of the water problem and its destructive influences has presently forced the government to pay great attention to solve current water difficulties.

2.2. Iran's seawater desalination industry

Iran can be categorized among the countries with high potential for desalinating seawater, whereas large-scale seawater desalination is still at an early stage of development. Currently, there are 73 operating water desalination units in different regions of Iran with a total capacity of 420,000 m^3/d of pure water [48]. The primary desalination plant with a total production of 1,000 m^3/d was installed in 1960 [21]. Initial researches on the establishment of the Chabahar–Kenarak facility were started in 1973. The project arranged to desalinate water using MSF technology with a total capacity of 15,000 m^3/d [23]. Finally, the installation of the plant was accomplished in 2006.

Qeshm island MED desalination plant can be stated as a water-power dual-purpose project, which utilizes the latent heat of the gas turbine. The plant has been constructed in 2013 and has a capacity of 18,000 m^3/d. A gas power plant is providing the energy required for desalination unit with a thermal capacity of 250 MW. The largest desalination plant in Iran has been constructed in Bandar Abbas, with a capacity of 100,000 m^3/d, in December 2018. More information about constructed desalination plants in Iran is given elsewhere [8].

2.3. Potential and incentives for nuclear desalination in Iran

Nowadays the primary energy resources in Iran are the regular fossil fuels and hydropower. However there is a potential for wind and solar energies, they are not being implemented widely and renewable energy sources are not developed considerably. According to the Energy Information Administration, the total electricity net generation in 2015 was 272 TWh and about 92% of the capacity was produced using fossil fuels, which is considerably more than the share of global fossil fuel usage for electricity generation (about 66%). The share of nuclear power for Iran was around 2% and 10.4% for the world. The country's electricity generation data is given in Fig. 1 [49].

Despite the fact that Iran is an energy-rich country, which supplies large amounts of energy resources to a significant number of other countries, it is facing electricity shortfall in recent years. In December 2018, it has been reported that the gap between electricity generation and consumption in the country was about 5,000 MW [50]. Some of the most important reasons for this problem can be [51,52]:

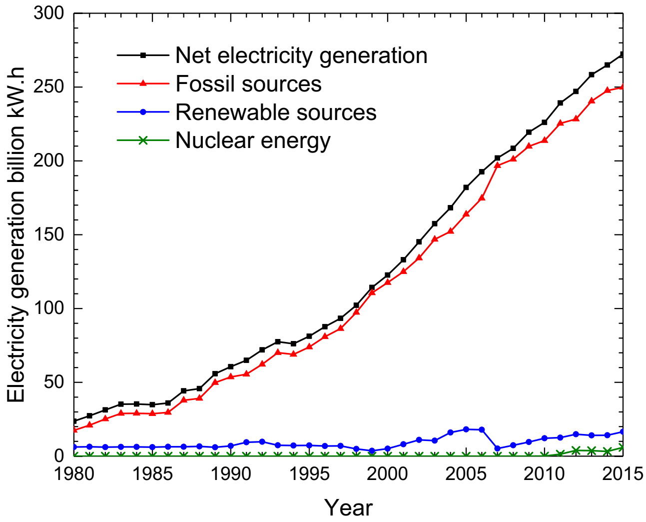

Fig. 1. Total electricity generation in Iran by various energy sources [49].

- Continuous growth of industrial, agricultural, and domestic electricity demands,
- Paying high prices for fuel and energy importing and incomplete investment in the development of non-fossil fuel power plants,
- Low operational efficiency of power plants in the excess demand condition.
- High amounts of energy losses during transmission and distribution,
- Decrease of reserved water level behind the dams (especially in summer), which reduces the hydropower plants output,
- Lack of incentives for non-governmental organizations to invest in the electricity industry.

Despite the existence of concerns in association with the environmental impacts of seawater desalination processes, they have achieved wide applications. The most important concern is about the impact on the habitats and marine environment, caused by discharging huge amounts of highly saline brine into the ocean. In order to minimize these impacts, brine management processes such as deep injection wells, zero-liquid or close to zero-liquid discharge technologies, wind-aided intensified evaporation, and Ohmic evaporator can be implemented, instead of direct disposal of waste reject brine [53,54]. Further, commercial products such as metals, chemicals, and salts can be recovered from the reject brine [54].

Although the use of nuclear energy may have contributed somewhat to the environmental impacts, which result from the long-lived radioactive wastes (spent nuclear fuel) and NPP accidents, it removes some of the impediments for the use of fossil fuel sources in coupling to desalination systems [55]. However, reprocessing and reusing the spent nuclear fuel can yield even more energy and decrease the amount of waste disposal [56]. The requirements for large-capacity, high availability, and stability during normal operation can justify the integration of nuclear power to desalination technologies.

Nuclear energy has been used for desalinating purposes in many countries such as Kazakhstan, India, and Japan and has the possibility for a great extent of utilization [5,57,58]. Several nuclear energy-based desalination plants already operating around the world and many countries such as Saudi Arabia, UAE, Egypt, Algeria, and others express their attentiveness to nuclear desalination technology.

2.4. Atmospheric pollution

The CO_2 emissions can be considered as the most significant factor in the climate changes on our planet [59]. Although some global efforts have been devoted to the CO_2 concentration reducing processes such as the capture and storage technology, the concentration of this pollutant is still at a worrying level [60]. Iran is the world's seventh-highest GHG emitter with about 616,741 million tons of CO_2 emissions [61]. The amount of carbon emission in the country increased drastically between 1990 and 2015 (5% annually), which was about 2.5% more than the global average during the same period. Fig. 2 shows the total CO_2 emissions of Iran through the years. Some of the middle eastern countries are currently 100% dependent on fossil fuels for their particular energy needs.

The most important reason that the Middle East countries are not well-established in modern energy production technologies is their fossil resources. The energy consumption in Iran increased by about 6% per year over the last 30 y, which in turn has increased environmental damages [63].

In some countries, employing renewable energy sources, switching from coal to natural gas, energy efficiency improvements, fundamental changes in the economy and technical developments through the years, have resulted in a decline in the rate at which carbon dioxide pumped into the atmosphere. The amounts of CO_2 emissions per energy production in Iran and some other countries have been shown in Fig. 3 [64]. As can be seen, the amount of Iran's CO_2 emissions per energy production is slightly decreasing throughout the last years, but it is still over the global amounts. In comparison, the lowest and highest amounts of CO_2 emissions per energy production belong to France and China, respectively.

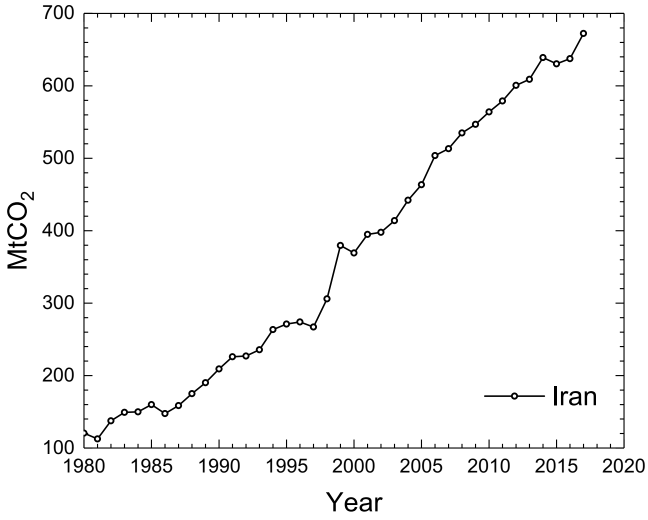

Fig. 2. Data of Iran's total CO_2 emissions through the years [62].

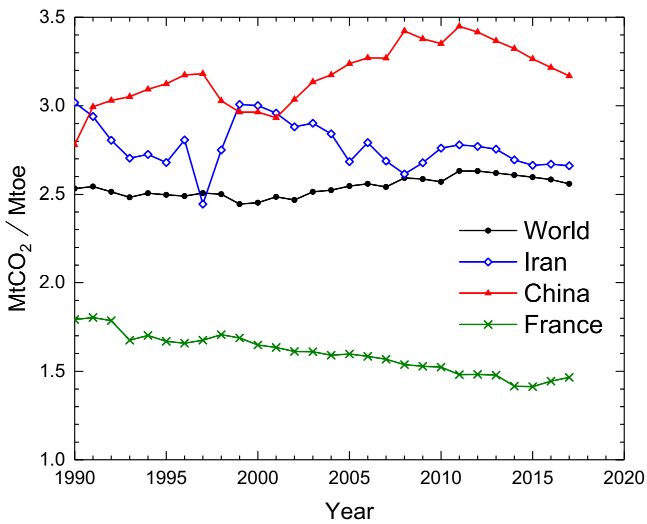

Fig. 3. Ratio of CO_2 emissions to energy production for Iran and some other regions [64].

2.5. Iran's nuclear power plant and nuclear desalination status

Iran had previously attempted to build an NPP at the Bushehr site. The Bushehr site was selected after exploring the potential areas on the southern coasts of Iran. The site has been found to be suitable for constructing several nuclear power blocks. The major characteristics of the site can be categorized as follows:

- Adequate infrastructures for establishing the power blocks.
- Appropriate topography of the site, allowing for suitable protection against hazards.
- Low population density around the site area.
- Suitable access to the electrical network.
- Good location from the outlook of seismic activity of the region.
- Access to the seawater and other international transmission systems.

In 1974, a contract was signed with Germany to construct two reactors. In 1994, a contract signed between Tehran and Moscow to continue the nuclear project by constructing the VVER 1,000 MW(e). The Bushehr NPP is unique in design due to the incorporation of VVER technology into the original German type. Finally, the plant reached full-power operation in March 2012. It has been planned to integrate seawater desalination units with the NPP to reach the capacity of 200,000 m^3/d. The primary capacity has been divided into the capacities of 130,000 and 70,000 m^3/d. Considering the more technical and economic benefits, the construction of 70,000 m^3/d of RO desalination unit was approved. In 2014, the first unit of desalination site came into operation with a capacity of 5,000 m^3/d, which is divided into two parts of 3,700 m^3/d for consumption by the residences of NPP and the rest for industrial consumption. Two new integrated NPPs will be built with the involvement of Russia in Bushehr [65].

3. Type of nuclear reactor and desalination technology

3.1. Nuclear reactor selection

Determination of the type of nuclear reactor, which generally affects the other industries in a country, must be based on more advanced considerations that are necessary for selecting the conventional industrial plant. It has been stated in [66] that for water desalination purposes, there is no exceptional difference between nuclear reactors and any of them can be accompanied by the desalination unit. However, it is highly desirable to state that the need for more electricity in Iran persuades the country to focus on the NPP with medium to high power nuclear reactors. It has been reported that the Iranian grid can accept any size among the available types of NPP to recover the electrical deficiency without any instabilities [65]. From many aspects like safety and system operating reliability, NPP with the capacity of ~600 MW(e) seems to be preferable, however, NPP with the order of 1,000 MW(e) can also be recommended. The main criteria for admissibility of a cogeneration plant to be operated reliably and safely in Iran can be summed up as follows:

- *Financing*: For successful financing of a nuclear power project in developing countries such as Iran, it is significant for the government to commit to the nuclear power program and make an overall financing analysis with economic experts to evaluate the feasibility of the suggested scheme. Another key factor in this topic is financial viability. The manufacturer should guarantee the schedule and cost to prevent the negative influences on the financing viability.
- *Safety and radiation protection*: The put forward NPP should be designed and constructed in accordance with the international fundamental concepts, which are provided by IAEA [67]. The design should aim to minimize the probability of an accident and if any failure happens, the facility must be capable of protecting the public and environment. It is also significant to achieve the highest level of quality in different stages including planning, organization, control, and operation.
- *Fuel supply*: In association with nuclear fuel, a number of distinct manufacturing activities should be done, including front end and backend. The plant should be provided with the fuel until the next refueling date. The manufacturer should give routine services regarding the handling of radioactive wastes with the minimum side risks.

The world market for NPP provides many options for customers offering the latest level of technology. The use of traditional light water reactors is principally more convenient, so they can be selected as the candidate reactors. Coupling these reactors with high capacity desalination units will lead to significant energy loss [10]. There is an alternative, which provides MED desalination without loss of electricity. The utilization of gas-cooled, high-temperature reactors is virtually vacant of thermal energy to be added in the MED process. Considering the design of these types of reactors, the temperature ranges of water in heat exchangers could be 80°C–130°C, which is an ideal range for the MED desalination plant [68].

3.2. Determination of desalination unit

A large number of world's desalination plants are installed in the Middle East and North Africa, including the commercially available technologies RO, MED and MSF. Among them, the desalination plant in KSA can be considered as the largest one with a capacity of 948,000 m^3/d [38].

Some studies already identified the suitable capacity of nuclear desalination plants, for example, a 600 MW(e) PWR can produce more than 300,000 m^3/d desalted water at an appropriate cost and about 517 MW(e) to the grid. If higher amounts are aimed, nuclear desalination is also able to handle 200–500,000 m^3/d output [4]. The southern coastal regions of Iran have the potential of constructing NPPs integrated with desalination systems. Further, a reasonable water networking system can be utilized to resolve the freshwater problems in the central parts of Iran. This, in turn, demands efforts for decision-makers in developing a proper water pipeline scheme to transfer water, considering the economic criteria.

It can be realized from the literature that all available commercial desalination technologies are trustworthy. MED is almost the oldest desalination process, which historically represented its effectiveness. Currently, in some countries, the cost of MSF has declined by up to 20% from 2010 due to technological developments. To compare the economic advantages of different desalination methods, many cost factors and variables should be accurately evaluated [69]. Over the years, along with the development of technology, the membrane prices have reduced and membrane life has increased [70]. These alterations led to the considerable growth of RO usage over recent years. It is also advantageous to consider the country's potential in equipment manufacturing. As an example, for a nation, which already produces membranes (or is in developing level) it is far better to select mostly the RO technology to reduce the initial or long-term (replacement and maintenance) costs. The most important criteria for coupling desalination system with an NPP in Iran can be stated as follows:

- Safety is the highest priority in nuclear desalination projects. It should be assured that radioactive particles will not enter the potable water in any situation and the quality of product water will always be at the top level. It is essential to select a desalination system, for which excellent safety characteristics are proved practically or experimentally. All possible accidental cases should be simulated and their consequences should be determined precisely [71].
- Considering the type of desalination technology, the cost of product water should be at the minimum level. In general, the construction cost of MSF is the highest and RO is the lowest among the desalination techniques. For cost reduction purposes, several technical procedures

are available. For example, in the RO systems, the cost of water can be decreased by using the cooling water of condenser to feed the system.

- One of the most significant criteria, which are directly relevant to public health, is a continuous potable water supply. It is vital to employ a procedure, through which the desalination unit can still operate when the nuclear reactor is shut down for technical or refueling reasons.
- With regard to the permanent growth of water demand, it is more suitable to install expandable desalination units. Subsequently, an obvious difficulty regarding this subject is the unit space, which in turn should be predetermined. Generally, desalination systems are being installed as several stages. In addition to the stated advantage of expandability, this feature can later be utilized to develop and optimize an innovative approach in the desalination procedure.
- In several levels of production, it is very significant for Iran to participate in the project. The participation can be performed by producing some materials or components of the desalination unit. The metallurgy industry of Iran can take part in providing several types of metals and pipelines. In addition, there are experienced companies in the field of production of boilers, steam generators, turbines and other power equipment that will lead to cost reduction. The participation can be configured as the education of specialists. This is beneficial in increasing the assurance about maintenance and renovation in the long term.

A hybrid seawater desalination plant can be categorized as a relatively new approach in the cogeneration of nuclear power and water systems. It is the combination of two or more desalination processes to provide an economical procedure and increase the overall efficiency of the plant. The utilization of hybrid systems allows for feeding the RO plant with higher temperature, which results in improved performance of membranes. By using the combined desalination processes, it is possible to blend the product of RO and thermal plants to yield different grades. It is notable that the discussed superiorities depend also on the power plant type. The environmental impacts of desalination processes can be decreased due to the lower amount of feed water in the hybrid method. Detailed information about the types of hybrid desalination plants and their specifications is given elsewhere [10].

4. Theoretical modeling

4.1. Comparative economic evaluation

In order to compare performance and costs of different desalination configurations, the IAEA Desalination Economic Evaluation Program (DEEP) has been used, which has been improved and validated through the years on performing economic analysis [8,39,72,73]. The software can simulate the common commercial processes for medium- or large-scale seawater desalination systems. Within a given interval of temperature (lower feed water temperature and maximum brine temperature), the maximum water production can be calculated. The required heat and electricity can be evaluated for a specified capacity. There are also some additional parameters, such as lifetime, project availability, interest, construction period, the rate of discount, and fuel escalation, which can be adjusted.

4.2. System description

For the purpose of making an economic comparison between different desalination designs, steam cycle (SC), gas cycle (GC), and combined cycle (CC) power plants have been considered to be integrated with desalination systems. The key point of profitability investigation in this study lies in comparing some main criteria such as power cost, water cost, and capital cost.

The following power plants are included in the economic evaluation: NPP with a steam cycle, gas cycle (NGC), and combined cycle (NCC), oil- and coal-fired steam cycle plants (OSC, CSC), gas-fired gas cycle plant (GGC), and gas-fired combined-cycle plant. Table 1 illustrates the power plant types and the selected desalination options. Considering Iran's demand for electricity, NPPs with the power of 600 and 1,000 MW(e) and the fossil-fuel power plants with the power of 600 MW(e) are assumed. A total capacity of 200,000 m^3/d is considered for the desalination plant. The evaluated desalination processes are MED, RO, and a hybrid MED–RO scheme. The suggested design for a hybrid nuclear-powered desalination system is shown schematically in Fig. 4.

Due to the fact that the MSF method is not economical (in comparison with MED), it does not seem to be reasonable to utilize, so it has been excluded from the assessment. For reducing pumping water directly from the sea to the RO unit, it has been recommended to partially feed the RO from the coupled thermal desalination plant. Thereby, the overall cost of the supply and discharge processes can be reduced to about 25% for a 2:1 ratio of RO to thermal desalination unit product capacity [10].

4.3. Results and discussion

The assumed financial parameters, such as interest rate, discount rate, fuel escalation, and some other input parameters are given in Table 2.

The results of the calculation for power plants along with several desalination technologies are shown in Table 3. As can be seen, the power generation cost for NPP is considerably lower than the other assumed power sources. Steam cycle-based NPP provides power slightly more expensive than gas cycle- and combined cycle-based NPPs. However, the Operating and Maintenance costs for the SC plant are less compared to the other nuclear cases. In comparing the specific capital costs of the power plants, it can be realized that the nuclear plant with the steam cycle is the most expensive one and the GGC plant's capital cost is considerably lower than the other options. The fuel costs of considered fossil-fuel power plants are considerably higher than those for the NPPs, which leads to higher electricity generation prices.

In integration with the SC power plant, the water production cost by the RO process is more economical and MED has the most expensive water cost among considered

Table 1
Considered options for power plant and desalination unit

Nuclear power plant	Type	NSC	NGC		NCC
	Electricity output, MW(e)	600		1,000	
Fossil-fuel plant	Type	OSC	CSC	GGC	GCC
	Electricity output, MW(e)	600			
Desalination plant	Type	MED	RO		MED–RO
	Desalination capacity, m³/d	200,000			

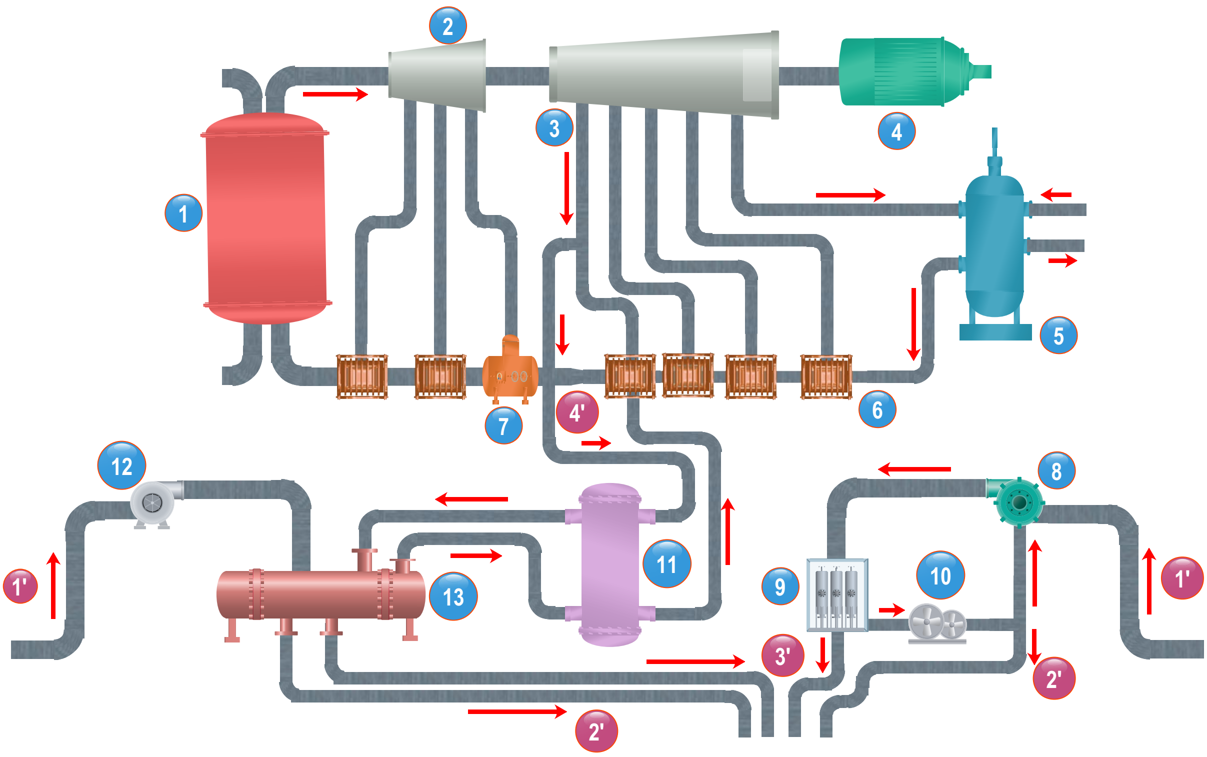

Fig. 4. Schematic drawing of NPP integrated with the hybrid desalination plant. Equipment: (1) steam generator, (2) high-pressure turbine, (3) low-pressure turbine, (4) generator, (5) condenser, (6) preheater, (7) deaerator, (8) high-pressure pump, (9) RO desalination plant, (10) energy recovery system, (11) intermediate heat exchanger, (12) feedwater pump, (13) MED desalination unit. Pipelines: (1′) feedwater, (2′) brine, (3′) product water, and (4′) hot steam.

Table 2
Considered input parameters [8,74,75]

Parameter	Value
Desalination plant operation life, years	25
Interest rate	18%
Discount rate	5%
Fuel escalation	3%
Total dissolved solids, ppm	42,000
Feed water inlet temperature, °C	25
Desalination capacity, m³/d	200,000

procedures. For GC plants, the situation is completely different from the SC plants. The calculations show that the MED technique provides a remarkably lower water production cost by integrating with the GC power plant. The NGC combination with the MED unit is the cheapest desalination option among the considered cases with the cost of 0.711 $ for a cubic meter of water. For GC instance, RO results in the highest water price. For the plants with combined cycles of gas and steam, the water cost of RO is the cheapest and it is slightly less than SC-RO due to the less power cost. Since the fuel price of the OSC option is considerably higher than the other cases, its combination with the MED process results in the highest desalination cost. In comparing the total capital costs of desalination units, it is obvious that RO has the lowest costs and the hybrid technique is a little more expensive than RO.

The values of cost parameters for suggested nuclear desalination plants are illustrated in Fig. 5. It is clear that the base plant overnight costs depend mainly on the desalination method and it is relatively high for the MED case. The main portion of the MED costs is comprised of heat costs for SC and CC cases. The heat cost for MED combined with GC is

Table 3
Levelized electricity and water costs for different cases

Plant type		NSC-1000	NSC-600	NGC-1000	NGC-600	NCC-1000	NCC-600	OSC-600	CSC-600	GGC-600	GCC-600
Nuclear power plant											
Total											
Capital costs	M$	6,874	4,078	5,887	3,530	6,983	4,189	2,093	2,262	432	773
Fuel costs	M$	77	46	61	37	53	32	582	126	488	298
O&M costs	M$	54	33	75	45	84	50	10	10	28	22
Annual cost	M$	493	295	480	288	540	324	828	290	648	434
Specific											
Capital costs	$/kW	7,088		5,887		6,728		3,487	3,866	743	1,263
Fuel cost	$/MWh	12		10		8		198	43	115	74
O&M costs	$/MWh	9		12		12		3	4	7	6
Power cost	$/MWh	79.2		76.8		76.8		282	99.6	153.6	108
Desalination plant											
MED											
Total capital costs	M$	437		437		437		387	387	387	387
O&M costs	$/m³	0.12		0.12		0.12		0.12	0.12	0.12	0.12
Total energy costs	$/m³	0.55		0.14		0.53		1.8	0.63	0.25	0.68
Water production cost	$/m³	1.122		0.711		1.104		2.285	1.167	0.783	1.219
RO											
Total capital costs	M$	366		366		366		366	366	366	366
O&M costs	$/m³	0.20		0.20		0.20		0.20	0.20	0.20	0.20
Total energy costs	$/m³	0.31		0.30		0.30		0.93	0.37	0.54	0.39
Water production cost	$/m³	0.855		0.846		0.848		1.386	0.848	1.009	0.876
MED–RO											
Total capital costs	M$	375		375		375		372	372	372	372
O&M costs	$/m³	0.18		0.18		0.18		0.18	0.18	0.18	0.18
Total energy costs	$/m³	0.39		0.25		0.37		1.16	0.43	0.45	0.46
Water production cost	$/m³	0.928		0.788		0.909		1.615	0.914	0.934	0.952

zero and uses less electricity. This feature makes NGC and MED integration the most economical option for water production among the suggested scenarios.

For any desalination plant, it is noteworthy to identify the critical parameters that impress the product water cost [76]. This approach can help to identify uncertainties, which are quite large in the subject area of nuclear desalination. This procedure is used here to compare the result of fluctuations of various parameters, for example, interest rate, discount rate, and power plant construction cost. In order to manage and overcome uncertainty in parameters, a sensitivity analysis has been performed on some of the parameters. Fig. 6. demonstrates the results for the sensitivity analysis of some nuclear desalination cases among the suggested scenarios. The availability of power plants and the interest rate contribute significantly to the sensitivity analysis for almost all of the cases. The changes in the interest rate for the SC plant with the RO desalination technique mainly alter the final price of product water. Despite the fact that parameters like discount rate, fuel escalation, and specific fuel costs seem to be the least sensible variables, they can make great changes in large-capacity desalination.

5. Conclusions

In this paper, some aspects of nuclear energy powered seawater desalination, to produce electricity and potable water in Iran, have been analyzed. The results obtained by the DEEP economic evaluation program for the integration of some NPPs and fossil-fuel power plants with desalination systems has been compared. Setting up a nuclear desalination system for Iran is a strategic project, which provides constructive feedback for planning future developments. The use of nuclear power to desalinate water for a developing country such as Iran will increase global experience in nuclear desalination technologies, as well as improving the health conditions of the suffering community from water shortage. The significant decrease in CO_2 emissions is one of

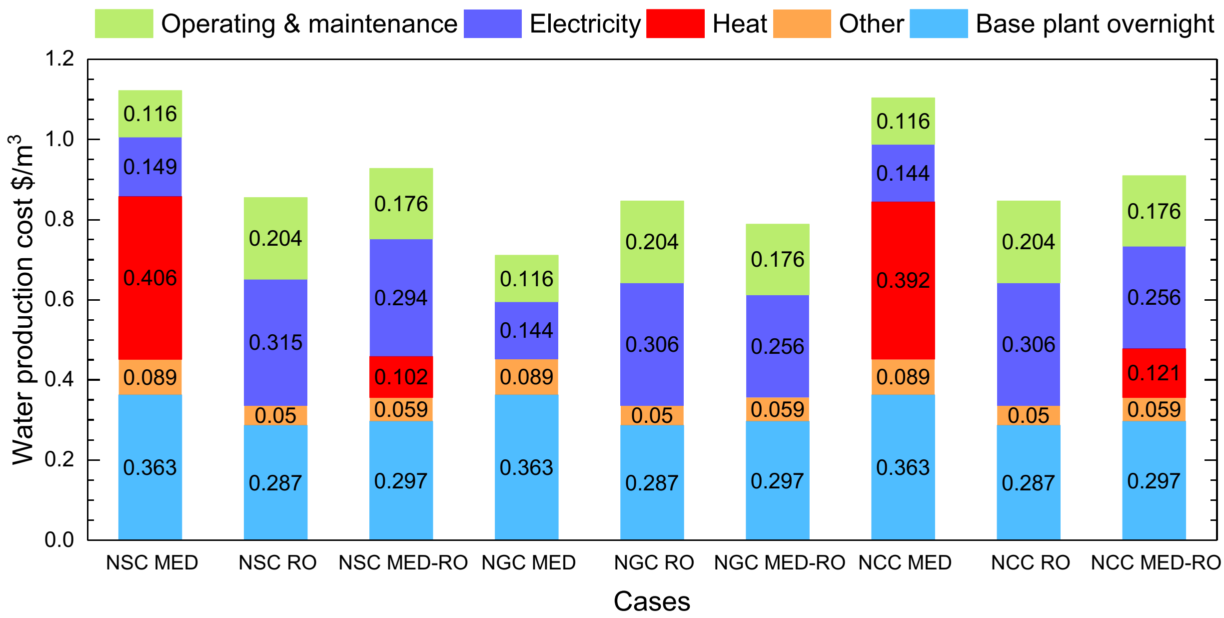

Fig. 5. Comparison of freshwater costs produced by various NPPs.

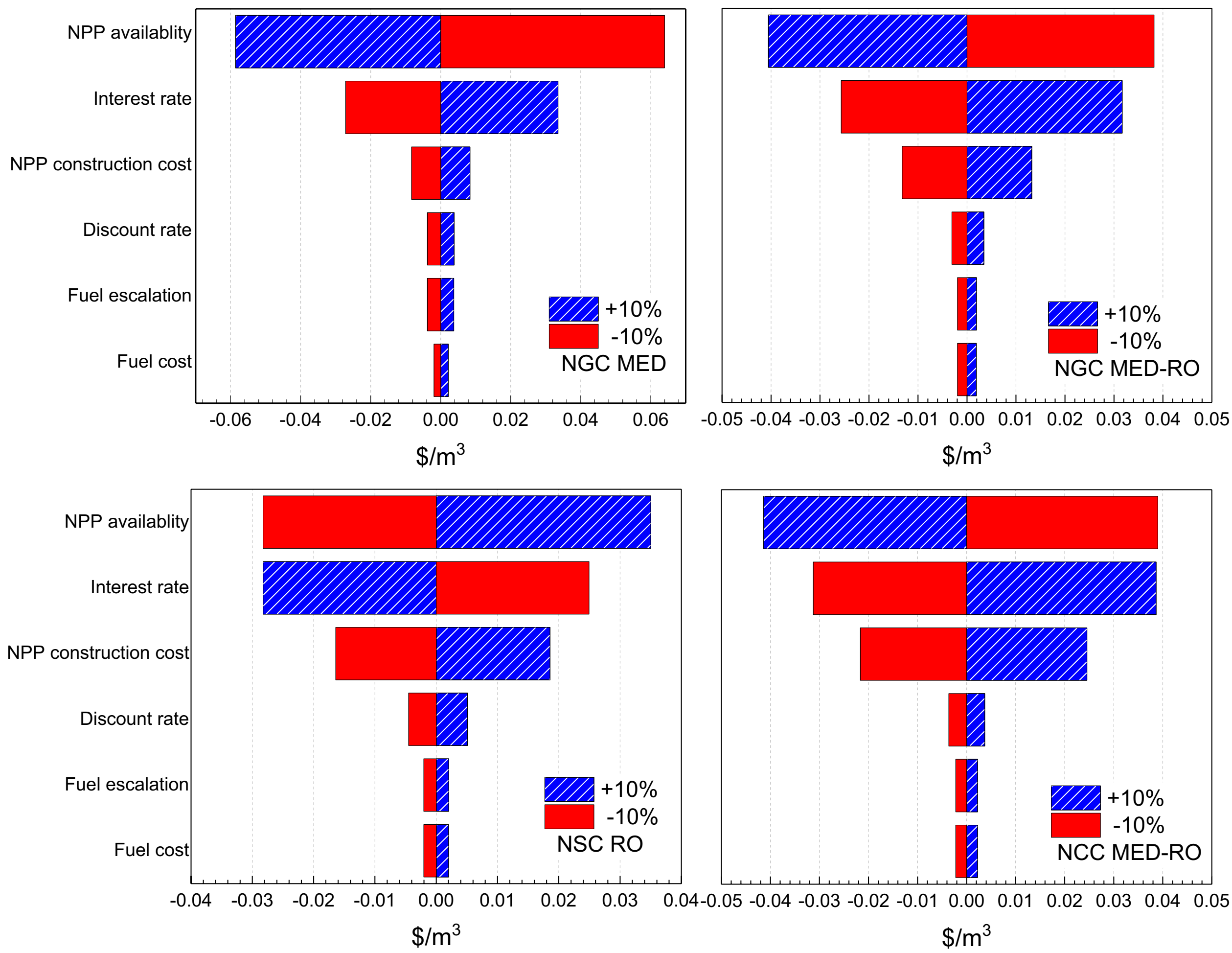

Fig. 6. Sensitivity analysis of different nuclear desalination scenarios.

the key advantages of nuclear-powered desalination systems over fossil fuel-based options. However, a long duration of construction and nuclear waste production can be stated as the specific issues of nuclear-based seawater desalination plants. As a social aspect, setting up a desalination plant with a nuclear reactor will certainly increase the social acceptance of nuclear plants.

In the economic evaluation, the costs of water and electricity for each scenario have been represented separately. The results for economic parameters have been used to make several proper comparisons between considered cases. The lowest nuclear and fossil fuel-based desalination costs are attainable by the MED integration with a gas cycle NPP and gas plant with the prices of 0.711 and 0.783 $/m^3$, respectively. The electricity generation costs of NPPs are considerably less than those for fossil fuel plants. The NGC and NCC plants yielded electricity cost of 76.8 $/MWh, which is about 30% less than the electricity generation cost by CSC plant. Despite the fact that the most economical option is gas-cooled nuclear reactor integrated with MED technology, the global experience in this type of nuclear reactor is far less than for water-cooled reactors. Thus, for a developing country such as Iran, it demands a great venture to select the stated option for electricity generation and freshwater production instead of water-cooled reactors.

In summary, it can be figured out that constructing a nuclear desalination plant is economically justifiable in Iran. Hybrid RO-thermal desalination systems combine the privilege of high desalting performance of thermal processes and lower energy (electricity) consumption of RO membranes. Therefore, it will be beneficial to choose hybrid desalination technology integrated with NPP instead of a 100% RO process. Since the main goal of this work is to evaluate the possible options for nuclear desalination in Iran, the desalination processes using renewable energy sources have not been extensively studied. An interesting area for future work is the assessment of a specific renewable energy powered desalination system in Iran.

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