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Economic evaluation of Qeshm island MED-desalination plant coupling with different energy sources including fossils and nuclear power plants

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ABSTRACT

The coupling of the Qeshm island desalination plant with different energy sources was economically evaluated by using a Desalination Economic Evaluation Program (DEEP) package. The capacity of this plant was 18,000 m^3/day and its energy source was 250 MW (th) gas power plant. Six energy source plants, namely, coal, oil, gas, combined cycle (CC), pressurized water reactor (PWR), and pebble-bed modular reactor (PBMR), were coupled with this desalination plant. The estimated annual electrical costs indicated that the optimum fossil power plant was CC with 97.72 $/kWh, which was 30% higher than 67.42 and 64.63 $/kWh in PWR and PBMR power plants, respectively. The total annual water costs and the total annual costs of coupling with the desalination plant of CC, PWR, and PMMR plants were approximately 1.78, 1.49, and 0.77 $/$m^3$, and 94.74, 49.23, and 49.1 m$, respectively. The construction costs of these power plants are approximately 131, 510 and 553 M$, respectively, On the basis of the contraction times, costs, and lifetimes of these power plants 25, 40 and 60 years for CC, PBMR and PWR, we concluded that CC, PBMR and PWR are short-term, medium-term and long-term strategy to generate electricity and couple with desalination plants, respectively.

1. Introduction

Water is a component essential for human existence and development. Earth contains approximately 1 billion km^3 of water that covers roughly 70% of this planet, but the total global water consumption does not exceed 2100 km^3. Although this condition seems promising, approximately 97.5% of available water is unpotable because of its saltiness or brackishness. Almost 70% of the remaining 2.5% is in the form of ice. Another large part of this percentage is underground water whose usage is limited. Consequently, only 0.007% or approximately 70,000 km^3 of the total water sources is accessible. Several parameters, including uneven distribution of water, rapid increase in population, development of new living standards, and industrialization and development of irrigation agriculture, lead to global water crisis [1]. Todays, electricity and water resources are two fundamental parameters of sustainable development. The conception of sustainable development involves economic, environmental and social approaches. So finding the appropriate solutions to overcome water crisis is necessary for a complete description of the sustainability [2,3].

Water crisis and potable water shortage are resolved through an important process named seawater desalination. Seawater desalination technologies have been established since the mid-20th century in many countries, especially in the Middle East and South Africa [4,5]. In seawater desalination, the total dissolved solids (TDS) of seawater are reduced and freshwater is produced. TDS is used to describe all types of inorganic salts and any small amounts of organic matter present in a water solution. TDS mainly comprise cations, such as calcium, sodium, magnesium, and potassium, and anions, such as hydrogen carbonate, carbonate, sulfate, chloride, and nitrate [6,7]. The salinity of freshwater usually measures < 1500 ppm, while the salinity of seawater ranges from 10,000 ppm (Baltic Sea) to 45,000 ppm (Persian Gulf). A simple classification of natural water and different TDS values are presented in Table 1 [7].

Although the seawater desalination technologies are vital for the human civilization, they are not environmentally friendly. They produce harmful brine discharges which have a higher TDS about 50–60 g/l [14]. There are three approaches to dealing with brine discharges from desalination plants which are included (a) zero liquid discharge, (b) injection to deep well and (c) seawater discharge. In the first method, the desalination plant components are designed so that seawater brine discharge is higher than 150 g/l which is suitable for reprocessing into salts' products. The floating solution is an alternative opportunity for the third method because of many reasons such as less cost of seawater collecting, protecting the coastal environment, low utilization if the fresh water request is to be reduced, the ability to move easily to another area upon request etc. [8–10].

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Table 1
Water classification based on salinity content.

Type	Total dissolved solids (TDS)	Note
Fresh water	Up to 1500	Variable chemical composition
Brackish water	1500–10,000	Variable chemical composition
Salt water	> 10,000	Variable chemical composition
Sea water	10,000–45,000	Fixed chemical composition
Standard sea water	35,000	Fixed chemical composition

In an industrial scale, desalination generally involves two techniques, namely, (A) distillation and (B) membrane processes. Distillation requires electricity and heat, whereas membrane processes employ electricity only. The two major processes of distillation are multiple-effect distillation (MED) and multi-stage flash (MSF) [11].

In MED and MSF, seawater is heated and evaporated. The evaporated steam is then condensed and freshwater is subsequently obtained. The major technique of membrane processes is reverse osmosis (RO) [12,13]; in this technique, a semi-permeable membrane is used to allow the passage of freshwater from the low-pressure freshwater side and prevent the passage of high-pressure salt water [1,4,14]. MSF and RO are applied to more than three-quarters of the capacity of desalination plants. MED has also been widely utilized [15]. The largest MED plant with a total capacity of approximately 36,000 m^3/day was constructed in the Middle East [16].

Selection among MSF, RO, and MED involves two important factors, namely, total capacity and gain output ratio (GOR). GOR is the index performance of thermal desalination and defined as the amount of produced freshwater per unit amount of heating steam. Depending on plant design and conditions, GOR usually ranges from 8 to 10 for MSF and from 10 to 12 for MED [16]. Other comparable parameters of desalination processes are heat and electricity consumptions. Total energy consumption is a function of many variables, such as temperature and salinity of seawater and maximum brine temperature and flow rate of desalination plant capacity. Table 2 shows the typical specific heat and electricity consumptions that suggest MED as suitable for a desalination plant. Thermal vapor compression (TVC) is an additional process that can be coupled with MED to increase GOR [17]; as a result, TVC under normal circumstances can be increased up to 16 GOR in a unit MED [1,12,16,18].

The required energy for desalination plants can be of any form, such as heat energy for distillation or electrical and mechanical energies for pumps to transport seawater across membranes. Fossil power plants (gas, oil, and coal) are major sources that supply heat or electricity required for desalination plants. However, limited resources of fossil fuels and their use in other industries have remarkably increased the price of fossil fuels. Therefore, other alternative energy sources should be developed to compensate for the lack of energy sources [19]. Solar energy is another alternative energy source among all energy resources which has a high potential to provide energy for desalination plants [20]. Desalination plants with solar energy exhibit considerable economic advantage due to relatively low operating costs, use of free energy, the simplicity of assembly and operation, and low cost of repairs and maintenance [21]. Despite the mentioned advantageous, the solar energy based desalination plants have some disadvantages. The important subject related to the use of solar energy for desalination plants is the availability of solar radiation. Solar desalination plants are most favorable at geographical places where there is considerable solar radiation. The geographical and weather conditions are played the significant role in the solar plant operation. As well as, due to low efficiency, the solar energy plants are coupled with much lower capacity desalination plants [21–23]. Nuclear energy is a new and sustainable energy that can be an alternative source of energy in desalination plants and other industries due to non-emission of greenhouse gasses, which is in accordance with the concept of sustainable development [24–26]. At today's prices, the cost of electricity generated by a solar power plant is about 45% more expensive than a nuclear power plant. With reducing solar cell prices and continuing trend to the solar energy, it is expected the cost of solar units become only 10% more expensive than nuclear units at the end of this decade [22].

Table 2
Average energy consumption in desalination processes.

Process	Specific heat consumption kWth·h/m^3	Specific electricity consumption kWe·h/m^3
MSF	100	3[a]
MED	50	2[a]
RO	–	4.5

[a] Some electricity is required to run the pumps and other auxiliary systems in MSF and MED.

> 16% of the world electricity is provided by nuclear energy [14]. Feasibility studies on the use of nuclear energy as an energy source in desalination plants were first requested by five North African countries with severe water shortages from the International Atomic Energy Agency (IAEA) in 1989 [14]. Therefore, IAEA aims to enhance and accelerate the contribution to related subjects and thus facilitate the combined application of nuclear technology to related industries, such as seawater desalination. IAEA has provided consideration and support to any activities in the field of nuclear desalination over the last decades. In this period, several papers and reports have been published under the IAEA on nuclear desalination fields, including technical aspects [27,28], safety consideration [29], and economic evaluation [4,30–32] of nuclear desalination. One of the key outcomes of economic evaluation is the preparation of DEEP developed to estimate the installation and operation costs of nuclear desalination plants constructed by various desalination systems and various energy sources, including fossil and nuclear energy. DEEP as software is continuously developed and verified; this software can calculate water and power costs by solving a detailed economic model [33,34].

Since the development of DEEP in 1998, the coupling of nuclear technology and desalination plants has been economically evaluated. Ho Sik Kim and Hee Cheon No prepared the technical and economic review of coupling high-temperature gas reactors (HTGR) and MED plant. They concluded that the cost of freshwater production through this technology is approximately 62% less than that through MED-gas combined cycle (CC) units [35]. Yong Hun Jung et al. investigated the safety and economic evaluation of nuclear desalination plants in the United Arab Emirates. They proposed that the optimum option for drinking water preparation is the coupling of a small nuclear heat-only plant (SNHP) and a MED desalination unit. SNHP is a pressurized water reactor (PWR) technology that generates heat [16]. S. M. Gómez de Soler et al. examined the feasibility and economic evolution of replacing a CAREM reactor (PWR) for a gas CC power plant in a desalination plant in Argentina. They revealed that the production cost of 48,000 m^3/day of water by their nuclear desalination plant is 0.66 \$/day, which is lower than the cost of 0.69 \$/day by the CC power plant [36]. A. H. El Desoky et al. estimated the production cost of drinking water from three types of desalination plants, including MED, MSF, and RO coupled with a 1000 MW PWR reactor. The estimated production costs of 140,000 m^3/day were 1.48 \$/m^3 for MSF, 0.89 \$/m^3 for MED, and 0.65 \$/m^3 for RO; this estimation shows that in thermal desalination (MED and MSF), MED is reasonably less expensive than MSF [37]. S. Nisan economically compared three MED-coupled desalination plants, including PWR, HTR, and CC, and they found that the costs of water production by PWR and HTR are 46% and 42% lower than those of CC, respectively [38]. To solve water shortage in Shandong, China, S. R. Wu et al. proposed and compared the economically evaluated costs of coupling nuclear technology and MED with that of transferring water