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# The Prospect of Nuclear Power Integrated Desalination Plants in Saudi Arabia

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**Abstract** – Despite the amount of water on our planet, water scarcity is a crucial problem facing the world. Thus, many countries resort to seawater desalination to solve this problem. Some of the most popular desalination technologies in the world are Reverse Osmosis desalination (RO), Multi Effect Desalination (MED) and Multi-Stage Flash desalination (MSF). These technologies are operated by heat and electricity, which are conventionally provided through fossil fuels. The world's largest desalinated water producer by a significant margin is Saudi Arabia. Consequently, with the prospect of reducing the dependence on fossil fuels and shifting to more environmentally friendly sources, nuclear desalination will be a contributing factor. This study discusses the process of coupling Nuclear Power Plants (NPPs) with RO desalination plants in Saudi Arabia. As well as provide valuable recommendations to utilize the country's new nuclear ventures in its already existing desalination infrastructure.

**Keywords:** Desalination; Vision 2030; Nuclear energy; Reverse Osmosis; Development; Economy; Environment.

## I. Literature Review

The demand for innovative desalination technologies has increased because of the expanding global population and growing water scarcity. To address the growing demand for freshwater, desalination technologies have emerged as a crucial solution.

The most used desalination technique is that of reverse osmosis because of its effectiveness and adaptability. By driving seawater through a semi-permeable membrane, only water molecules can pass through while salts and other contaminants are rejected. Recent developments have concentrated on improving membrane components, namely graphene-based membranes that have higher permeability, better selectivity, and increased fouling resistance. Additionally, energy-saving methods like pressure recovery units and isobaric chambers have gained popularity, reducing operating expenses and promoting the long-term viability of RO.

MSF, a well-known thermal desalination process, evaporates seawater in stages using heat produced by either fossil fuels or renewable energy sources. Despite having a lengthy history, MSF is still relevant today due to advanced low-temperature multi-effect distillation (LT-MED) setups and ongoing development in heat exchanger technologies. Higher energy efficiency, lower carbon emissions, and cheaper freshwater production are all made possible by these innovations.

To desalinate saltwater, MED makes use of the idea of heat transfer and several phases of evaporation. Recent research has highlighted the potential of hybrid MED systems that use waste heat, geothermal energy, or other renewable energy sources to power the process. Hybrid MED systems have shown promising results in lowering energy use and environmental effect by utilizing low-grade heat.

In addition to the conventional techniques, several new desalination technologies show potential. Due to its potential for high efficiency, low energy consumption, and little negative environmental impact, membrane distillation, capacitive deionization, solar desalination, and nuclear desalination are among those that are gaining popularity.

## II. Introduction

With the Kingdom of Saudi Arabia's urban and industrial expansion, the Kingdom's natural renewable water resources are insufficient to supply the Kingdom's need for freshwater due to its geographical location and desert environment. The World Bank's Freshwater Development Indicators estimate that Saudi Arabia has an internal renewable freshwater resource of 2.4 cubic kilometers per year and that Saudi Arabia withdraws about 21.2 billion cubic meters of freshwater annually [1]. With a significant disparity between domestic renewable freshwater supply and increasing demand for freshwater, the Kingdom of Saudi Arabia is challenged with a situation that necessitates long-term solutions to meet the country's growing water demand. One of the solutions in which the Kingdom of Saudi Arabia has invested heavily is the desalination of seawater and converting it into fresh water suitable for human use.

Saudi Arabia has invested in desalination and relied on it as the country's primary supply of fresh water due to its economic capacity to fund seawater desalination plants and its 3,400 km coastline on the Arabian Gulf and the Red Sea. The main entities Saudi Arabia relies on for desalination are the Saline Water Conversion Corporation (SWCC) and the Saudi Water Partnerships Company (SWPC). Together, they produce approximately 8,442,272 cubic meters per day of fresh water. The Saline Water Conversion Corporation in Saudi Arabia produces approximately 5,900,272 cubic meters per day, while the Saudi Water Partnership Company produces approximately 2,542,000 cubic meters per day [2, 3]. Desalination facilities in Saudi Arabia utilize a variety of processes, with multi-stage flash distillation (MSF) accounting for 57.8% of domestic Saudi production, multi-effect distillation (MED) accounting for 13.2%, and reverse osmosis (RO) accounting for 29% [4]. However, according to Sustainable Development Goals (SDGs) provided by SWCC, the dependency on reverse osmosis will increase by Replacing thermal plants with environmentally friendly reverse osmosis plants in the near future [5].

Despite its accomplishments in water desalination, Saudi Arabia is constantly trying to expand its capability and improve its sustainability to fulfill the growing demand for fresh water. According to the SWCC Sustainable Development Goals (SDGs), to accomplish the objective of sustainable cities, desalination plants must be equipped with cutting-edge technology to meet the requirements of a sustainable generation of electricity and the desalination industry [5]. The Sustainability Report presented by the SWCC also emphasizes the continuous need for development to ensure compliance with the requirements of the Kingdom's Vision 2030 [5]. Among the primary goals of the Kingdom's Vision 2030, which the kingdom's desalination plants must comply with, is to reduce carbon emissions to 278 million tons annually by 2030 and to reach net zero emissions by 2060 [6]. These goals drive Saudi Arabia to search for solutions to the carbon emissions of desalination plants and to try to find sustainable and reliable solutions for decades to come.

The problem of carbon emissions in desalination facilities has several possible solutions, one of which is nuclear energy. We can define nuclear desalination as a description of when a nuclear reactor is utilized to operate a desalination plant that provides drinkable water from seawater or brackish water. Nuclear power has been successfully implemented in desalination and is being promoted as an alternative option to reduce fossil fuel use and carbon dioxide emissions [7]. Nuclear water desalination has also proven to be the most feasible in terms of economic cost, as proven in studies conducted by The International Atomic Energy Agency (IAEA) [7]. The growing demands for nuclear energy and the danger posed by carbon emissions from fossil fuels used in desalination plants prompted countries to consider nuclear desalination as a possible solution and alternative to ensure water security for decades to come without risking the nation's environmental future.

## III. Economics

Many studies have been developed on integrating desalination plants with renewable energy sources such as solar PV and wind. However, recently, the focus on nuclear desalination has increased dramatically. The use of integrated desalination and nuclear plants has shown, in addition to low carbon emissions, a substantial reduction in the cost of water. As the largest country in the field of desalination, the consumption of energy is dramatically increasing due to the increase in demand. Consequently, the establishment of alternative, less costly sources of energy is essential. Moreover, conventional sources of energy and some renewable sources are unreliable. Therefore, the use of nuclear desalination is the most appropriate approach to mitigate this issue. Table 1 shows the energy consumption per day for some of the RO desalination plants along with their capacity in Saudi Arabia. The distillation processes the energy demands of MSF and MED are higher than those of the RO and include both thermal and electrical energy. Primarily electrical energy is required to power the system in RO, and little heat energy is used. Consequently, the technology focused on in this analysis is RO technology. Furthermore, the vision of Saudi Arabia is to shift all the focus to the RO desalination plants.

**Table 1: Capacity and Estimated Energy Consumption of Some Desalination Plants in KSA [8,10,11].**

| Region/ City | Technology | Capacity (m3/day) | Energy consumption (MWh/day) | Power consumption (MW) |
|---|---|---|---|---|
| Khobar | RO | 210,000 | 1050 | 43.75 |
| Jeddah 3 | RO | 240,000 | 1200 | 50 |
| Khafji | RO | 60,000 | 300 | 12.5 |
| Yanbu 4 (2023) | RO | 450,000 | 2250 | 93.75 |
| Jubail 3 (A) (2022) | RO | 600,000 | 3000 | 125 |
| Jubail 3 (B) (2024) | RO | 570,000 | 2850 | 118.8 |
| Rabigh 3 | RO | 600,000 | 3000 | 125 |
| STPC-IWP | RO | 250,000 | 1250 | 52.08 |
| SEPCO -IWP | RO | 150,000 | 750 | 31.25 |
| SqWEC -IWPP | RO | 212,000 | 1060 | 44.17 |
| Shuqaiq 3 | RO | 450,000 | 2250 | 93.75 |

The plant's ability to produce water, the location's features, the type of energy used, and the desalination technology are only a few of the variables that affect the overall cost of water. However, the capital cost of the water module, the O&M cost, and the cost of energy are often added together to get the overall water cost [8]. A factor of 5 (kWh/m3), was taken as an average value for the consumption of electricity per meter cubed of desalinated water from [9], was used to approximate the consumption of each desalination plant in table 2, where E is the energy consumption (MWh/day), C is the capacity of the plant, divided by a factor of 1000 to convert from kWh to MWh.

### III.A Conventional Desalination Plant

Conventional desalination plants normally use natural gas and Liquid fuels such as crude oil, heavy fuel oil (HFO), and diesel to get electric power. [12], using the data for the capacity of the desalination plants, as well as the average electricity consumption factor specified earlier the Levelized Cost Of Water (LCOW). The LCOW represent the final cost of a meter cubed of desalinated water. Using the relation in equation 1 the LCOW was calculated to be 0.4$/m$^3$, where the value 0.3 SR/kWh represents the cost of electricity in KSA [13]. To check the validity of the LCOW calculated for the technology, it must be comparable to the data provided by SWCC. Table 2 shows a comparison between the theoretical value estimated and the values provided by the SWCC. the estimation, provides reasonable error margins when compared to actual plants data. This validates the theoretical approach to be a benchmark in further comparison between using nuclear vs conventional power in sea water desalination.

$$LCOW = \frac{5\ (\mathrm{kWh}/m^3) * 0.3\ (SR/\mathrm{kWh})}{3.75\ (SR/\$)} \qquad (1)$$

**Table 2: Conventional LCOW Literature vs Theoretical**

| Region/City | LCOW ($/m3) (for conventional power plant) (literature) | LCOW ($/m3) (for conventional power plant) (theoretical) | %Difference |
|---|---|---|---|
| Yanbu 4 (2023) | 0.464 | 0.4 | 14 |
| Jubail 3 (A) (2022) | 0.411 | 0.4 | 3 |
| Jubail 3 (B) (2024) | 0.424 | 0.4 | 6 |
| Rabigh 3 | 0.531 | 0.4 | 25 |
| Shuqaiq 3 | 0.52 | 0.4 | 23 |

### III.B Nuclear Desalination Plant

For nuclear desalination plants, equation (2) represents the cost of water relative to the LCOE for each nuclear technology, Where LCOW is in $/m3.

Table 3 shows the LCOE for different nuclear power plants technologies. Those costs were estimated for the advanced technologies present in recent years. Table 4 shows the LCOW for different nuclear technologies coupled with RO technology, assuming a discount rate, a measurement of the value of future outcomes relative to immediate ones, of 5%. Nuclear power generation was much less expensive than the substitutes in every country at a discount rate of 3%; at 7%, it was equivalent to coal and still less expensive than Combined-Cycle Gas Turbine (CCGT); and at 10%, it was like both [14]. In line with the US Federal Reserve's move, the Saudi Central Bank increased both of its repo rates by 75 basis points to 4.5 %. The Saudi repo rate is higher than

the 3.1% inflation statistic from September 2022. Due to the Riyal's tie to the dollar, Saudi Arabia normally adheres to Fed policies (see figure 1) [9]. Therefore, based on the maximum and minimum values of the discount rate within the last 22 years, the value of the discount rate will not affect the competency of the nuclear desalination.

$$LCOW = \frac{5\ (kWh/m3) * \mathbf{LCOE}\ (\$/\mathbf{MWh})}{1000} \quad (2)$$

| Table 3: Levelized cost of electricity (5% discount rate) [12] | | | |
|---|---|---|---|
| Nuclear ($/MWh) | | | |
| SMR | EPR | APWR | AP1000 |
| 50 | 56.42 | 48.23 | 36.31 |

| Table 4: Levelized cost of water conventional and Nuclear | | | | | |
|---|---|---|---|---|---|
| Tech | Normal ($/m³) | Nuclear ($/m³) | | | |
| | | SMR | EPR | APWR | AP1000 |
| RO | 0.4 | 0.25 | 0.2821 | 0.24115 | 0.18155 |

To compare the two technologies, all parameters were fixed and a comparison between LCOW was conducted. Table 5 shows that the LCOW was decreased by more than 25% and up to 54.6% when using nuclear power as source of electricity.

### III.C Conventional vs Nuclear

Using the energy consumption calculated before, the LCOW can be calculated and compared between conventional and nuclear desalination. From table 5, it can clearly be seen that the LCOW using nuclear power plants is more economical compared to the conventional plants. However, even with small size and low construction cost, the LCOW of the SMR is not the lowest out of the nuclear technologies. This indicates that for recent designs of SMRs, the technology cannot be utilized efficiently.

## IV. Environmental Impact

### IV.A Paris Agreement

In 2015 Saudi Arabia joined efforts with 195 other parties, to reduce $CO_2$ emissions to limit the increase in temperatures to below 2 °C, compared to pre-industrial levels, and pursue further efforts to limit the increase to 1.5 °C [15]. In 2016, Saudi Arabia submitted its first Nationally Determined Contribution (NDC) which promised to cut $CO_2$-e emissions ($CO_2$-equivalent) by 130 million tons. In 2021 Saudi Arabia, has updated its NDC and increased it to 278 million tons of $CO_2$-e by 2030, which is more than twice the previously declared value [16]. This increase comes due to a change in internal policies and other factors which are outside of the scope of this study. One crucial factor that is essential to this study is the phase out of energy intensive technologies such as MSF and MED, while simultaneously investing more in Sea-Water Reverse Osmosis (SWRO) technology.

| Table 5: | | | | | | | |
|---|---|---|---|---|---|---|---|
| Region/City | Capacity (m3/day) | Energy consumption (MWh/day) (averaged) | LCOW ($/m3) (for conventional power plant) | NPP type | LCOE ($/MWh) | LCOW ($/m3) (NPP) | %Diff |
| Khobar | 210,000 | 1050 | 0.4 | SMR | 50 | 0.25 | 37.5 |
| Khobar | 210,000 | 1050 | 0.4 | EPR | 56.42 | 0.2821 | 29.5 |
| Khobar | 210,000 | 1050 | 0.4 | APWR | 48.23 | 0.2412 | 39.7 |
| Khobar | 210,000 | 1050 | 0.4 | AP1000 | 36.31 | 0.1816 | 54.6 |

### IV.B Current Environmental Impact

To have a better understanding of the change in the environmental impact, an examination of the current state of $CO_2$ emissions is necessary. Due to the current phase out of thermal desalination technologies, little focus will be placed on them in what is to come, while most will be placed on SWRO. There are two ways in which desalination contributes to $CO_2$ emissions, one is through burning of fossil fuels or natural gas, to provide thermal energy. This is used in both MSF and MED. The other is electrical coupling between the grid and the desalination plant. This is done in SWRO.

Table 6 shows the extent to which these different technologies contribute to $CO_2$ emissions. We can see that even though SWRO contributes to what is approximately third of the water capacity in the kingdom, it only contributes to 5% of the total emissions. This is due to low emission factor of $CO_2$, which accounts to, 3.4 kg $CO_2/m_3$. On the other hand, we see an almost 1:1 and 3:4 contributions of MED and MSF, respectively. This is the result of a high emission factor, 18 kg $CO_2/m_3$, 23.4 kg $CO_2/m_3$ for MED and MSF, respectively. Using these emission factors and the yearly capacity of production, one could easily obtain the total $CO_2$ emissions to be, 75.18 million ton/year. This accounts for 18% of the total emissions in the kingdom [4].

**Table 6: Technologies contribution to water capacity and $CO_2$ emissions.**

| Technology | % Water capacity contributed | % $CO_2$ emissions contributed |
|---|---|---|
| SWRO | 29.0% | 5.8% |
| MSF | 57.8% | 80.1% |
| MED | 13.2% | 14.0% |

### IV.C Future Environmental Impact

Nuclear power generation is known for its high-volume electricity generation and low $CO_2$ emissions. These emissions are mainly due to transportation, nuclear fuel cycle, and construction & decommissioning. However, those parameters differ from one reactor design to another. The reactor designs to be considered for the coupling process with SWRO are, SMR, AP1000, EPR. The emission factor for these designs differs due to the different sizes and electricity output. Table 7 shows the emission factors for the respective designs compared to the grid averaged value for SWRO. To show the extent of this reduction in emissions, table 8 shows what if some of the current SWRO plants were operated on nuclear energy instead of fossil fuels. It can be seen that a reduction of 2.85 Mton of $CO_2$/ year in the case of Rabigh 3 can be achieved. Well, what if this transformation is carried out on all operating desalination plants with a total capacity of 3.08E09 $m^3$/year? Taking a non-conservative approach by choosing the SMR emission factor as basis (As shown in equation 3).

$$3.08 \times 10^9 \ \frac{m^3}{Year} * SMR\ emission\ factor \frac{kgCO_2}{m^3} = \frac{kgCO_2}{year}. \quad (3)$$

Then, 0.111 Mton of $CO_2$/year is produced. Comparing this to the current value of 79.34 Mton $CO_2$/year, we can see a reduction of 99.86% of all emissions. This would help in decreasing the desalination sector's contribution to the kingdom's $CO_2$ emissions from 18% to 0.03%.

**Table 7: Emissions factors for the grid and different nuclear technologies. [17]**

| | Grid average value (current) | EPR | SMR | AP1000 |
|---|---|---|---|---|
| $CO_2$ emission factor from SWRO ($kgCO_2/m^3$) | 3.4 | 0.018 | 0.036 | 0.033 |

**Table 8: Change in emissions, before and after nuclear conversion. [4]**

| Region/City | Capacity (m3/day) | Energy consumption (MWh/day) (averaged) | NPP type | Current emissions (Fossil fuels) in Mton co2/yr | Nuclear energy emissions. In Mton co2/yr |
|---|---|---|---|---|---|
| Khobar | 210,000 | 840 | AP1000 | 0.9 | 2.58E-03 |
| Haql | 17,000 | 68 | SMR | 0.01 | 2.26E-04 |
| Rabigh 3 | 600,000 | 2400 | EPR | 2.86 | 4.03E-03 |

## V. Lifetime

The lifetime of electricity production plants is one of the most critical variables influencing decision-makers' decisions to invest in and develop new technologies that differ from those currently in use. Electricity production plants that rely on oil and natural gas derivatives are currently used in the Kingdom of Saudi Arabia, for a variety of reasons, including the Kingdom of Saudi Arabia's ability to provide sufficient oil derivatives and gas used in electricity production, as well as to ensure production sustainability. The other reason is that oil and gas-based electricity production plants can continue to produce electricity if suitable maintenance and human resources are provided for up to 30 years for gas-powered electricity production stations and up to 43 years for stations producing electricity with oil derivatives [18].

When we talk about nuclear power plants, one of its most important features is the plant's long production period, which may exceed 60 years, and this makes nuclear power plants an alternative that many industrialized nations rely on to create electricity [19][20][21]. However, the data can often be misleading. Although there haven't been any nuclear power plants that have operated for 60 years, it is true that this is their expected lifespan. To operate for 60 years, the highest maintenance requirements must be followed. Additionally, you must uphold these standards for 60 years and provide the greatest possible training for engineers and technicians. Although nuclear power reactors are widely acknowledged to be extremely dependable, they also come with a variety of regular maintenance, training, and safety regulations, this pushes decision-makers to examine several alternatives before excessively depending on them.

## VI. Safety

Before desalinated water is transported to be used, it must comply with strict quality specifications, which are compatible with the World Health Organization (WHO) guidelines. SWCC monitors the quality of the water thorough their network through collecting samples from pumping stations and tanks. These samples are tested for pH, turbidity, chlorine dioxide residues and electrical conductivity [3]. This requires the desalination plants to have rigorous safety procedures to ensure the safety of their output water. Thus, ensuring constant water quality. Similarly, a Nuclear Power Plant has the containment of radioactive materials as one of its three main safety concerns. Therefore, a great deal of effort has been made to ensure the safety of both industries individually. In terms of design and operation, the challenges to be considered are solely ones that arise from the coupling of a Nuclear Power Plant with a sea water desalination plant. On the other hand, in terms of public opinion, mentioning nuclear desalination would present unwarranted safety concerns. Tackling these safety concerns would benefit from an easy-to-explain solution for the design safety.

Unlike other desalination technologies such as MSF and MED, that use thermal energy as well as electrical energy, which along with the power they generate, complicates safety and comparison. RO requires only electricity to function properly. This presents a uniquely simplified coupling scheme. The electricity can be delivered from the NPP to the desalination plant either directly through a connection to the NPP, or indirectly through a connection to the power grid. A direct connection would be valid for remote desalination plants that require little energy. This task can be handled by an SMR type reactor fittingly. The larger types of reactors such as the EPR and AP1000, should have an indirect connection due to the excess power they provide. In this manner, the electricity not used by the desalination plant will transfer to the power grid directly. Furthermore, this simplified scheme -a wire connection for electricity- presents the needed easy-to-explain coupling process to trivialize the unwarranted concerns of the lay person.

## VII. Recommendations

After analyzing the data and discussing the results, several decisions are clear to be the best fitting for Saudi. The first, which is due to the plan to phase out thermal desalination technologies, is to focus on electrical based desalination technologies such as RO. This will simplify both comparing and justifying the use of NPPs. For a lay person, the concept of using nuclear power to desalinate water might wrongfully come across as dangerous. This is a further incentive to use RO technology as a simple connection to electricity would be the best for public acceptance and further normalize the use of nuclear energy in the public eye.

The deciding factors in desalination through conventional means against nuclear are the levelized cost of water (i.e., the least expensive) and CO2 emissions (i.e., more environmentally conscious). For the first factor we recommend using an AP1000 reactor, as it provides the cheapest power for the desalination process at 0.18155 $/m3 which is more than 50% cheaper than conventional. For the second factor, all technologies reduced CO2 emissions by more than 99% per meter cubed. SMRs had the highest emissions of the three technologies considered, with the EPR having the least emissions.

## VIII. Conclusion

In conclusion, the switch from conventional desalination to nuclear desalination offers several favourable benefits. The simple coupling method of a RO/SWRO desalination plant with an NPP does not depend on water quality or plant efficiency. The deciding factor is purely the levelized cost of electricity of the NPP. Thus, the analysis depends only on the NPP, but the results include all RO desalination Plants. By switching to nuclear desalination, Saudi Arabia could save up to 37.5%, 29.5%, 39.7% or 54.6% on the price of desalinated water using a SMR, EPR, APWR or an AP1000, respectively. Furthermore, the use of NPPs will also lower CO2 emissions from desalination plants per meter cubed by 99.93%, 99.87%, and 99.86%when coupled with an

EPR, AP1000 or an SMR, respectively. This will be a significant step in the country's vision of zero emissions, reducing desalination-based emissions from 18% to at least 0.03%of the total emissions.

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