A Feasibility Study of Utilizing Nuclear Energy for an Existing MED-TVC Desalination Plant

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Abstract: This study aims to investigate the viability of using a nuclear heating reactor to supply energy and replace the used fossil crude oil energy supply of an existing MED-TVC (Multi-Effect Distillation-Thermal-Vapor-Compression) desalination plant located in Saudi Arabia. The MED-TVC, with a 91,200 m$^3$/day capacity, was simulated using Aspen Plus$^\text{®}$. The MED-TVC desalination plant was built in a parallel arrangement with oil-fired steam boilers, and it uses Red Sea water with a salinity of about 45,000 ppm. The simulation results of the MED-TVC are in good agreement with the actual data of the existing desalination plant. The heat required to operate the existing MED-TVC was determined to be 169 MW (th). This amount of heat was utilized as an input to DEEP (Desalination Economic Evaluation Program) to evaluate the production cost of fresh water using nuclear energy instead of fossil fuel. An economic comparison between the two energy sources was carried out in this study. The production cost of freshwater was estimated to be USD 1.38/m$^3$ when using a nuclear reactor. In contrast, the estimated production cost was USD 0.95/m$^3$ when using oil-fired boilers at a subsidized oil price of USD 4.4/bbl. The economic analysis has considered the discounted domestic crude oil prices in Saudi Arabia. Nuclear energy is cost-competitive with oil if Saudi Arabia raises the price of domestic crude oil to more than USD 15 per barrel or imposes a carbon tax of at least USD 20 per ton of greenhouse gas emissions.

Keywords: MED-TVC; desalination; nuclear; Aspen Plus; DEEP; simulation; feasibility

1. Introduction

Water is essential to the sustainable development of the world. Human water consumption has increased intensely over the last few decades due to the population's rapid growth and the increase in living standards [1]. Nowadays, around 1–2 billion people worldwide are affected by water scarcity. Shortly, climate change issues will include millions more people living under severe water stress conditions [2]. Seawater desalination is one of the proven key solutions to tackle water droughts in the coming decades. Since the nineteen-seventies, there has been a massive increase in the desalination industry to satisfy the growing water demand in the Arabian Gulf region. Several thermal desalination plants have been constructed using cheap fossil fuels as their energy source [3]. Worldwide, since 2010, the number of desalination plants has been increasing at a rate of 6.8%. In 2020, the total installed desalination capacity for freshwater production was more than 97 million m$^3$/day. Furthermore, contracted projects are expected to come online soon, including an additional freshwater capacity of more than 15 million m$^3$/day [4].

Commercial desalination technologies can be classified as either thermal or membrane desalination. The thermal desalination technologies include MSF (Multi-Stage Flash) and MED (Multiple Effect Distillation). An overview of the worldwide installed desalination capacity shows that the highest share, 69% corresponds to RO desalination, which is used mainly for small to medium-scale plants. The contribution of thermal desalination, which is
used for large-scale plants, is divided between 7% for MED and 18% for MSF [5]. Despite the dominance of membrane desalination systems in recent years, thermal desalination systems, including MSF and MED, still play a significant role in the Arabian Gulf and the Red Sea, where these systems reflect high reliability and performance records, given the high-salinity environment. The MSF and MED use almost the same principle, wherein a source of energy heats the saline water, producing water vapor, which ultimately condenses to form pure distilled water. When comparing thermal desalination technologies, MED outperforms MSF desalination technology since it has better energy efficiency, low-temperature operation, low-grade heat utilization, and more GOR (Gain-Output-Ratio), which is the ratio of the mass of produced distilled water to the mass of heating steam used to produce this fresh water. In this context, low-temperature MED has recently experienced more interest because of its low TBT (Top Brine Temperature). The low-temperature MED effectively solves corrosion and scale formation issues with a TBT of less than 70 °C [6].

Due to the high heat of vaporization of water, thermal desalination technologies consume substantial amounts of energy. The thermal energy that drives the currently running desalination plants is primarily supplied by fossil fuels. In 2018, the share of fossil fuels in the world’s primary energy demand was 81%, with a total of 33.2 Gt of GHG (greenhouse gas) emissions [7]. Thus, to achieve the sustainable development scenario of reducing the share of fossil fuels to 72% by 2030 and 58% by 2040, a bold move must be undertaken by the world’s leading economies to invest more in nuclear and renewable energy. Currently, the continuous surges in fossil fuel prices, along with the growing regulations regarding the control of GHG emissions, have been promoting the use of clean and sustainable energy sources. In this context, Saudi Arabia, as the world’s top crude oil exporter, announced its net-zero emissions target of by 2060 during the Saudi Green Initiative in October 2021. The Kingdom also intends to reduce its carbon emissions by 278 million tons by the year 2030, which can be met by adopting the concept of the circular carbon economy [8].

Nuclear energy is a clean and reliable energy source; nuclear reactors have been contributing to supplying baseload energy to the global energy mix since the nineteen-sixties. The nuclear sector contributed roughly 10% of global electricity generation in 2018 and that share is expected to double by 2030, meaning that nuclear energy is needed for clean energy transitions worldwide [7]. In addition to electricity production using nuclear energy, the heat produced by the nuclear fission reaction can be utilized for other applications, including seawater desalination and hydrogen production. Nowadays, new opportunities can be offered by advanced nuclear technologies such as SMRs (Small Modular Reactors), which are defined as nuclear reactors producing energy of up to 300 MW [9]. On a global scale, there has been a growing interest in SMRs because of the various benefits offered by such technologies, which include flexibility in power generation, improved safety because of the inherent passive safety features, lower upfront capital cost, and lastly, the options of co-generation and non-power applications [9]. Currently, there are more than 70 different SMR designs for different applications, including electricity production, district heating, process heat, and water desalination. Technology readiness for these designs ranges from conceptual design level, passing through all different levels down to a small number of designs currently at the demonstration phase [10]. Nuclear desalination can meet the huge demands for water for in-house and other applications if demonstrated to be feasible and economically competitive without any compromise in the quality of produced water through a properly designed coupling system between a nuclear reactor and a desalination plant. Nuclear desalination has been successfully operated for many years in Japan, Pakistan, and Kazakhstan without any recorded reactor abnormalities or leakage of radioactive materials into the desalinated water [11]. An interesting SMR technology is the nuclear heating reactor, namely NHR-200. The reactor, which was developed by Tsinghua University in China, is a heat-dedicated single-purpose reactor. The NHR-200 is capable of supplying heat in the form of steam at 127 °C and 2.5 bar, which can be used as motive steam for seawater desalination plants [12]. Several studies presented in the literature have
reported water production costs for different nuclear reactor technologies with different production capacities. For a MED desalination plant with a capacity of 100,000 m$^3$/day, Khan and Orfi reported the water production cost as 1.803 USD/m$^3$ [13]. Wu found the cost of producing water using NHR-200 coupled with low-temperature MED to be USD 0.72/m$^3$ for a capacity of 120,000 m$^3$/day [14].

This study aims to investigate the suitability and feasibility of using a nuclear heating reactor to supply steam to an existing MED-TVC desalination plant located in Saudi Arabia. A comparison between the nuclear heating reactor and the conventional oil-fired steam boilers will be conducted. A sensitivity analysis will be performed to determine the price of oil, which makes the nuclear heating source more competitive.

2. Research Methodology

The research is divided into three parts, as shown in Figure 1. In the first part, a simulation of an existing MED-TVC desalination plant in Saudi Arabia is conducted using Aspen Plus®. The results of the simulation are validated with the actual data of the existing desalination plant, and the plant’s heat requirement is determined from the simulation. The required heat to run the desalination plant as well as other design parameters are used as an input in the DEEP program to find the levelized cost of produced water via nuclear energy or through fossil oil. Water costs from both heat sources are obtained where the most sensitive parameters that affect water production costs are considered. Lastly, the carbon emissions resulting from generating the required heat for the existing desalination plant from either nuclear energy, crude oil, or natural gas are addressed and compared.

3. Simulation of MED-TVC Desalination Plant

An existing MED-TVC desalination plant located on the west coast of Saudi Arabia with a water production capacity of 91,200 m$^3$/day and ten effects [15], was simulated using Aspen Plus software. Table 1 shows the desalination plant’s specific information. Figure 2 depicts the flow sheet of the MED-TVC desalination plant. Medium pressure (MP) steam, which is generated using crude oil as a heat source, enters a steam generator (SG) and exchanges its latent heat with the distillate coming from the first effect to generate motive steam at MP condition. The entrained vapor used for the thermal vapor compression device is extracted from the vapor stream produced in the sixth effect and mixed with the motive steam before it enters the first effect. After successive evaporation occurs in the ten effects, the vapor that comes out of the last effect is sent to a total condenser where it exchanges its heat of condensation with the seawater feed. The produced distillate is then mixed with other distillates generated from other effects, collected, and pumped to the post-treatment facility. The heated seawater feed, after leaving the condenser, is split in a parallel arrangement and preheated between effects before it enters into the effect evaporators.

![Figure 1](image-url) Schematic diagram of the research methodology.

![Figure 2](image-url) Flow sheet of the MED-TVC desalination plant.
Table 1. Existing MED-TVC Desalination Plant’s Specific Information.

| Location                          | West Coast on Red Sea Shores |
|-----------------------------------|------------------------------|
| Capacity                          | 91,200 m³/day                |
| Energy source                     | Crude oil                    |
| Number of effects                 | 10                           |
| Configuration                     | Parallel                     |
| Distillate (kg/h)                 | 376,8000                     |
| Brine (kg/h)                      | 944,2708                     |
| Performance ratio (PR)            | 14.62                        |

Figure 2. Schematic diagram of the existing MED-TVC.

An electrolyte model with metric units was selected in Aspen Plus, with the ELECNRTL property package, to simulate the seawater desalination plant. Each effect in the desalination plant is modeled in Aspen Plus as a combination of a heat exchanger and a simple flash drum, as shown in Figure 3. The vapor generated from each effect is entered into the tube-side of the heat exchanger and condensed to become a distillate. The resultant heat of condensation or the condenser duty is added as a heat stream to the adjacent flash drum. The feed seawater stream is entered into the flash drum, where the generated vapor from flashing exits from the top of the drum, and the rest of the seawater exits as brine from the bottom.

Figure 3. Modules that are used to simulate the MED Effect in Aspen Plus.
The following mathematical expressions represent the model shown in Figure 3. The water feed to each effect \( F_i \) can be calculated from the mass flow rate of the seawater intake \( M_f \) and the total number of effects \( n \), as given in Equation (1):

\[
F_i = \frac{M_f}{n}
\]  

(1)

The mass balance around the effect is calculated as follows:

\[
F_i = V_i + (B_i - B_{i-1})
\]  

(2)

where \( V_i \) is the generated vapor from the effect as a result of seawater being flashed and evaporated on the surface of the tube bundle inside the effect. \( B_i \) denotes the brine flow rate.

The energy balance around the effect is given by Equation (3):

\[
V_{i-1}L_v - (F_iC_{pf}(T_i - T_f) + V_iL_v)
\]  

(3)

where \( (L_v) \) is the latent heat of vaporization inside the effect, and \( (C_{pf}) \) is the heat capacity of the seawater.

The salt balance around the effect can be calculated by Equation (4):

\[
F_iX_{fi} = B_iX_{Bi}
\]  

(4)

where \( X_{fi} \) and \( X_{Bi} \) are the concentration of salt in seawater and brine, respectively.

The heat flow \( (Q_i) \) resulting from the condensation of the vapor inside the tube bundle to the sprayed seawater inside the effect shell is estimated as follows:

\[
Q_i = V_iL_v
\]  

(5)

In the simulation, the temperature of the first effect is assumed to be 70 °C, where the temperature is reduced gradually from the first effect until the last effect at a rate of 3 °C, so that the temperature of the distillate that comes out of the tenth effect is 40 °C. The considered seawater characteristics in the simulation are assumed to be similar to those of Red Sea conditions, as shown in Table 2.

**Table 2.** Approximate Red Sea water specifications.

| Red Sea Water Specifications | 33 °C |
|-----------------------------|-------|
| Chloride (Cl\(^{-}\))       | 22,000 ppm |
| Sodium (Na\(^{+}\))         | 12,032 ppm |
| Total hardness (CaCO\(_3\)) | 8373 ppm |
| Magnesium (Mg\(^{++}\))     | 1570 ppm |
| Calcium (Ca\(^{++}\))       | 738 ppm |
| Potassium (K\(^{+}\))       | 287 ppm |
| Total dissolved solids (TDS)| 45,000 ppm |

The flowsheet was completely built and simulated using Aspen Plus. The results obtained from Aspen Plus agree with the actual data of the MED-TVC desalination plant. Table 3 shows the overall mass and enthalpy balances of the existing MED-TVC desalination plant.

Table 4 shows the simulation results of several streams of the second, sixth, and tenth effects as well as the simulation results of the TVC stream. Table 5 shows a comparison between the actual stream information of the existing MED-TVC plant and the simulation results for the desalination plant.
Table 3. Overall mass and energy balances of the existing MED-TVC desalination plant.

| Input/Output | Seawater | Brine | Distillate |
|--------------|----------|-------|------------|
| Flowrate (ton/h) | 13,200.00 | 9428.25 | 3771.75 |
| Volumetric flowrate (m³/h) | 13,104.07 | 9305.85 | 3794.03 |
| Enthalpy flow (GW) | −56.34 | −39.76 | −16.58 |
| Temperature (°C) | 40.50 | 40.52 | 35.00 |
| Pressure (bar) | 2.3 | 1.6 | 1.0 |

Mass Flows (ton/h):
- H₂O: 12,603.1
- Na⁺: 149.0455
- Cl⁻: 305.9917
- CaCO₃: 109.7203
- Mg²⁺: 19.44825
- Ca²⁺: 9.141919
- K⁺: 3.555191
- Total: 13,200.00

Table 4. Selected streams results obtained from MED-TVC simulation flowsheet.

| Stream | 2nd Effect | 6th Effect |
|--------|------------|------------|
| T (°C) | 58 | 64 |
| P (bar) | 1.50 | 0.24 |
| m (ton/h) | 1740 | 334.85 |

| Stream | 10th Effect | Thermal Vapor Compressor (TVC) |
|--------|-------------|-------------------------------|
| T (°C) | 40.51 | 40.5 |
| P (bar) | 3.4 | 0.07 |
| m (ton/h) | 690.36 | 493.86 |

Table 5. Comparison between the actual design of the exiting MED plant and the simulation results.

| Parameter      | Actual Design | Simulation | %Error |
|----------------|---------------|------------|--------|
| Distillate (ton/h) | 3768 | 3771.753 | 0.10% |
| Brine (ton/h) | 9442.708 | 9428.249 | 0.15% |
| Performance ratio (PR) | 14.62 | 13.86 * | 5.2% |

* The performance ratio (PR) is calculated using the simulation results as in Equation (6).

\[
PR = \frac{\dot{m}_{\text{distillate}}}{\frac{\dot{m}_{\text{motive steam}}(h_{\text{motive steam}} - h_{\text{cooling water}})}{2326 \text{ kJ}}} = \frac{3771.753}{\frac{238.050(2797.16-138.63)}{2326 \text{ kJ}}} = 13.86
\]
4. Water Cost Estimation

The heat required to drive the existing MED-TVC desalination plant was obtained by simulating the desalination plant using Aspen Plus, and it was about 169 MW (th). This amount of heat is utilized as a heat input in DEEP, which was modeled and developed by the IAEA (International Atomic Energy Agency). DEEP was used in this analysis to estimate the desalinated water cost as USD/m\(^3\).

The methodology used in DEEP is based on simplified models of several types of power plants, including fossil and nuclear types, as well as models for desalination plants, including MSF, MED, and RO. Any specific plant can be modelled in DEEP simply by adjusting input data in the program interface. Such data includes power and water plant size, cost, and performance characteristics. The power plant’s economic evaluation model consists of capital costs and operating costs. Capital costs involve the total plant investment costs, including overnight construction costs, contingency factors, and construction time interest. The operating costs include fuel costs, O&M specific costs, and the carbon tax. After annualizing capital costs using a specific discount rate, both capital and operating costs represent the total annual power cost. An important parameter can then be estimated, which is the LCOE (levelized cost of electricity). LCOE is generally used to compare different electricity generating technologies and can be calculated using Equation (7).

\[
\text{LCOE} = \frac{\text{Total Annual Power Cost}}{\text{Annual power Production}} \left( \frac{\$}{\text{yr}} \right) \left( \frac{\text{kWh}}{\text{yr}} \right) \quad (7)
\]

The desalination plant economic evaluation model is very much the same as the power plant economic evaluation model. The only difference is that the capital costs include additional costs related to the backup heat source, while the operating costs include energy costs for heat instead of fuel in the power plant evaluation model. The main output data calculated by DEEP is the level cost of electricity and water. The analysis in this paper considers two types of heat sources. The first one is a nuclear heating reactor dedicated to supplying heat only to the MED-TVC desalination plant. The second one is an oil-fired steam boiler, which is used in the existing MED desalination plants in Saudi Arabia. The same design parameters used in the simulated MED-TVC desalination plant were used in the DEEP model. These parameters are reflected in Table 6.

| Table 6. MED-TVC input parameters in DEEP. |
|--------------------------------------------|
| Temperature of MP Steam from Heat Source (°C) | 230 |
| Temperature of the motive steam (°C) | 201.3 |
| Maximum brine temperature (°C) | 70 |
| SG approach temperature (°C) | 28.6 |
| SG pump head (bar) | 3.5 |
| MED number of effects | 10 |

4.1. Nuclear Heating Reactor

A modified version of the Chinese nuclear heating reactor NHR200-II [16,17] shown in Figure 4 is selected with a power output of 169 MW (th) and coupled with a MED-TVC desalination plant, where the new reactor version is named as NHR170. Table 7 shows the main operating parameters for the two reactors. The NHR-170 has almost the same characteristics as the NHR200-II except that the thermal power output is smaller, and the operating cycle length is higher. Hence, the reactor core design for NHR170 is changed in terms of fuel enrichment, fuel assembly loading pattern, and primary side mass flow rate.
The thermal power output of NHR170, which is 169 MW (th), is selected in DEEP to estimate the cost of the desalinated water. Figure 5 shows a schematic diagram of the NHR170 coupled with the MED-TVC. The reactor is dedicated to producing steam only for the purpose of freshwater production. The primary side of the reactor, namely the RCS (Reactor Coolant System), is considered to be within the RPV (Reactor Pressure Vessel), where an IHX (Intermediate Heat Exchanger) is placed inside the RPV. An IL (Intermediate Loop) is transferring heat from the RCS to the SG to produce the required motive steam to drive the MED-TVC unit. The purpose of the IL is to prevent any leakage of radioactive materials to the desalination plant, and it is better for it to be at a pressure higher than the RCS pressure, so in the case of any tube rupture in IHX, the fluid in the intermediate loop enters on the RCS side. Thus, radioactive materials will be contained within the RCS loop.
The economic parameters for the NHR170 that are used in the DEEP analysis are addressed in Table 8.

![Figure 5. Simplified schematic diagram of suggested NHR170 coupled with the MED-TVC.](image)

**Table 8.** Economic parameters for the nuclear reactor NHR170 and the desalination plant.

| Nuclear Heating Reactor Economic Parameters |  |
|--------------------------------------------|--|
| Construction Duration                      | 40 months             |
| Lifetime                                   | 60 years               |
| Specific Construction Cost (EPC)           | 1100 USD/kW (th)       |
| Specific Fuel Cost                         | 3 USD/MWh              |
| Specific O&M Cost                          | 2 USD/MWh              |
| Discount Rate (WACC)                       | 5%                     |
| Interest During Construction (IDC)         | 5%                     |
| Annual Fuel Escalation                     | 2%                     |
| Tax rate                                  | 20%                    |
| Loan Duration                              | 20 years               |

| Desalination Plant Economic Parameters     |  |
|--------------------------------------------|--|
| Construction Duration                      | 30 months             |
| Lifetime                                   | 30 years               |
| Water Purchase Price                       | 1.9 USD/m³             |

Excluding site-related costs and project contingencies, specific construction costs simply refer to the overnight construction cost, which is the cost of constructing the plant assuming there is no interest incurred during the construction period, as if the project had been completed over one night [18]. It is worth mentioning that the DEEP default value for the specific construction cost for nuclear heating reactors is USD 1300/kW (th). Although the NHR200-I’s specific construction cost is USD 535/kW (th) [19], this cost was estimated at site-specific conditions in China nearly two decades ago, and all associated costs related to capital investment have since increased. Hence, in this analysis, the value of the specific construction cost was reasonably selected to be USD 1100/kW (th). Assumed values for the discount rate and IDC (Interest during Construction) rate are considered acceptable since the water market in Saudi Arabia is centralized. Usually, the Saudi government supports such projects, which contributes to reducing the overall risk of the project. With respect to the tax rate, the maximum income tax for resident companies in Saudi Arabia with full foreign ownership is 20% [20]. Such a project will certainly have joint ownership between local and foreign companies, whereas in this case, the tax rate will be lower than 20%.

By conducting DEEP analysis for NHR170, which is coupled with the MED-TVC, it was found that the cost of producing fresh water is 1.38 USD/m³, with a simple payback
period of 5.8 years. A sensitivity analysis was conducted to analyze the most important factors that strongly impact the water production cost. Notably, the specific construction cost (USD/kW (th)) and the IDC are the most sensitive factors that affect water cost. Figure 6 depicts the cost of water (USD/m³) versus the cost of specific construction (USD/kW (th)), which ranges from USD 500 to USD 1500/kW (th). Also of note, the water cost increases linearly as the construction cost increases. At the lower bound of the range, the water cost is around 1.16 USD/m³ when the construction cost is USD 500/kW (th), and when the construction cost is doubled, the water cost is increased by more than 15%. Figure 7, on the other hand, depicts water cost (USD/m³) versus IDC, where it is varied between 4% and 16%, which resembles the lower and upper limits of IDC in different nuclear projects, including large reactors and SMRs [21]. The water cost is directly proportional to the IDC, where the cost of water will be 40% higher if the IDC is increased to 10%, and nearly double if the IDC is increased further to 16%.

![Figure 6](image6.png)

**Figure 6.** Sensitivity analysis of water cost (USD/m³) versus specific construction cost (USD/kW (th)) of the nuclear heating reactor.

![Figure 7](image7.png)

**Figure 7.** Sensitivity analysis of water cost (USD/m³) versus IDC (%).
4.2. Oil-Fired Steam Boiler

A similar analysis was conducted in DEEP, in which an oil-fired steam boiler was selected with a power output of 169 MW (th) and coupled with MED-TVC to estimate the cost of desalinated water. This analysis aims to mimic the current situation of producing desalinated water from heavy crude oil in Saudi Arabia. In 2018, for electricity generation and seawater desalination, the Saudi domestic price for Arab heavy crude oil was 4.4 U.S. dollars per barrel (USD/bbl) [22], which is the oil price used in this study. The economic parameters for the oil-fired steam boiler that are used in the DEEP analysis are addressed in Table 9.

Table 9. Economic parameters for oil-fired boiler and desalination plant.

| Oil-Fired Steam Boiler Economic Parameters |  |
|------------------------------------------|--|
| Construction Duration                   | 18 months |
| Lifetime                                | 35 years  |
| Specific Construction Cost (EPC)        | 50 USD/kW (th) |
| Specific Fuel Cost                      | 3 USD/MWh  |
| Specific O&M Cost                       | 1 USD/MWh  |
| Discount Rate (WACC)                    | 5%          |
| Interest During Construction (IDC)      | 5%          |
| Annual Fuel Escalation                  | 2%          |
| Tax rate                                | 20%         |
| Loan Duration                           | 20 years   |

| Desalination Plant Economic Parameters  |  |
|-----------------------------------------|--|
| Construction Duration                   | 30 months |
| Lifetime                                | 30 years  |
| Water Purchase Price                    | 1.9 USD/m³ |

The cost analysis for the oil-fired steam boiler coupled with MED-TVC was conducted, and it was determined that the cost of water is 0.95 USD/m³, with a simple payback period of 4.7 years. A sensitivity analysis was performed to investigate the most important factors that strongly impact water cost in this kind of heat source. It is noticed that the specific oil price (USD/MWh) and the carbon tax (USD/ton) are the most sensitive factors that affect the cost of water produced. The specific oil price can be calculated directly from primary oil prices according to the following equation [23].

\[
\text{Specific Oil price} \left( \frac{\$}{\text{MWh}} \right) = \frac{\text{primary fuel price} \left( \frac{\$}{\text{bbl}} \right)}{(\text{Technology Efficiency}) \left( \text{conversion factor of 1.6471} \left( \frac{\text{MWh}}{\text{bbl}} \right) \right)}
\]

The efficiency of boilers operated using crude oil ranges from 89% to 92% [24,25]. Hence, the boiler efficiency in Equation (8) is assumed to be 90% in this analysis.

Table 10 shows specific oil prices for selected crude oil prices, whereas Figure 8 shows the water cost (USD/m³) versus specific oil prices (USD/MWh). It can be seen that the cost of water production is highly affected by the crude oil price. The cost of water is almost doubled when crude oil is purchased for USD 30/bbl. Also, when the oil price is considered to be the same as the global price nowadays, which is around USD 90/bbl, the water cost will be equal to 4.38 USD/m³, which is not affordable for consumers. Having that said, the cost of desalinated water produced by utilizing crude oil in Saudi Arabia is cheap since the country is oil-rich with huge reserves underground.
However, there is a massive amount of value within crude oil, and it is being wasted by just simply burning it for heat generation. It can be processed and refined to produce higher-value products. Consequently, if the government decided to increase domestic oil prices for all consumers, including water producers, the nuclear option would be more competitive just above the USD 15/bbl oil price mark.

On the other hand, considering taxation for GHG emissions is the second factor that affects water prices. Currently, in Saudi Arabia, no carbon tax is imposed on power and water producers nor in other industries, such as oil and gas and petrochemicals. However, to realize the effect of an imposed carbon tax on the cost of water produced with a USD 4.4/bbl oil price, Figure 9 shows the water cost (USD/m$^3$) versus the carbon tax imposed as (USD/ton). It appears that if Saudi Arabia imposed a tax of USD 20/ton of carbon emitted, then the cost of water produced would be very much the same as the nuclear heating reactor option. At present, many carbon pricing initiatives are being considered internationally, and many countries, especially European countries, have already adopted these initiatives and started to implement a carbon tax. For example, in Norway, the current imposed carbon tax is USD 53/ton of CO$_2$ [26].

### Table 10. Specific oil prices (USD/MWh) for selected oil prices (USD/bbl).

| Oil Price (USD/bbl) | Specific Oil Price (USD/MWh) |
|---------------------|-----------------------------|
| 4.4                 | 3                           |
| 10                  | 6.7                         |
| 20                  | 13.5                        |
| 30                  | 20.2                        |
| 40                  | 26                          |
| 50                  | 33.7                        |
| 60                  | 40.5                        |
| 70                  | 47.2                        |

**Figure 8.** Sensitivity analysis of water cost (USD/m$^3$) versus specific oil price (USD/MWh) for oil-fired steam boilers.
5. Carbon Emission Considerations

The carbon emission was calculated using crude oil with a heating value of 47 MJ/kg [27]. The carbon emission of the existing MED-TVC desalination plant was calculated, and it equals 543,235 tons per annum. Figure 10 shows a rough comparison of the estimated GHG emissions when utilizing crude oil, natural gas, or nuclear energy as different energy sources to operate the existing MED-TVC desalination plant. Therefore, since nuclear energy does not generate any direct GHG emissions, the amount of GHG emissions resulting from burning crude oil could be halted by implementing the option of nuclear energy. Increasing the role of nuclear energy within the global energy mix will play a crucial part in meeting the net-zero target set forth by many countries before 2060 or even before 2050.

6. Conclusions

An existing MED-TVC desalination plant located on the western coast of Saudi Arabia was simulated and coupled with a nuclear reactor. Both simulation results and actual data from the existing MED-TVC were compared, and a good agreement was achieved. The required thermal energy for the existing MED-TVC was used as an input value in the
DEEP model to estimate the cost of water using the nuclear heating reactor and the oil-fired boilers. Since there are not many designs of nuclear heating reactors around the world, it is recommended to take serious considerations during the design phase to lower the specific construction cost of the reactor, which in turn will lead to a lower cost of water produced. The analysis showed that MED-TVC desalination using nuclear energy becomes competitive with crude oil only if Saudi Arabia considers increasing domestic oil prices to more than USD 15/bbl or implementing a carbon tax policy of no less than $20/ton of GHG emissions.

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Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| DEEP         | Desalination Economic Evaluation Program |
| GHG          | Greenhouse Gas |
| GOR          | Gain-Output-Ratio |
| Gt           | Giga tons |
| IAEA         | International Atomic Energy Agency |
| IDC          | Interest during Construction |
| IHX          | Intermediate Heat Exchanger |
| IL           | Intermediate Loop |
| kW (th)      | Kilowatt Thermal |
| LCOE         | Levelized Cost of Electricity |
| MED-TVC      | Multi-Effect Distillation-Thermal Vapor Compression |
| MP           | Medium Pressure |
| MSF          | Multi-Stage Flash |
| MW (th)      | Megawatt Thermal |
| NHR          | Nuclear Heating Reactor |
| PR           | Performance Ratio |
| RCS          | Reactor Coolant System |
| RO           | Reverse Osmosis |
| RPV          | Reactor Pressure Vessel |
| SG           | Steam Generator |
| SMRs         | Small Modular Reactors |
| TBT          | Top Brine Temperature |

Nomenclature

| Symbol | Description |
|--------|-------------|
| B      | Brine Mass Flow Rate [ton/h] |
| \( C_{pf} \) | Specific Heat Capacity of Seawater [kJ/kg °C] |
| F      | Feedwater Mass Flow Rate [ton/h] |
| \( h \) | Enthalpy [kJ/kg] |
| \( L_v \) | Latent Heat of Vaporization [kJ/kg] |
| \( M_f \) | Mass Flow Rate of The Seawater Intake [ton/h] |
| \( m \) | Mass Flow Rate [ton/h] |
| n      | Total number of effects |
| P      | Pressure [bar] |
| T      | Temperature [°C] |
| TDS    | Total Dissolved Solids [ppm] |
| Q  | Heat flow [W] |
|----|---------------|
| V  | Vapor Mass Flow Rate [ton/h] |
| X  | Concentration [ppm] |

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