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# Economic evaluation of 20,000 M$^3$/Day seawater desalination coupling with floating reactor nuclear power plant

# Economic evaluation of 20,000 M$^3$/Day seawater desalination coupling with floating reactor nuclear power plant

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**Abstract**. The coupling of floating nuclear reactor with different desalination processes was economically evaluated by using a desalination economic evaluation program (DEEP-5) software and a method of levelized annualized production water cost. Three desalination processes, namely, Multi-effect distillation (MED), multi-stage flash (MSF) or reverse osmosis (RO). The capacity of the plant was 20,000m3/day and its energy source was 100MWt nuclear power plant. The analysis indicated that water costs with the RO process have stronger economic competitive comparing to distillation processes, without regard to changes in water quality. The sensitivity analysis results showed that the sensitivity factors affecting the cost of desalinated water are, in order, discount rate, interest rate, Specific Construction Cost and Condensing temperature.

## 1. Introduction

In the North and East of China, several provinces experience moderate to severe water shortages, affecting municipal, industrial, and agriculture needs. The total national shortage in 2030 is forecasted to be nearly 200 billion m$^3$ with more than 25% for domestic needs [1]. Water recycling programs and cross-region water diversion projects have been implemented to mitigation water crisis, but they have not addressed it in its totality. From a technical and economic standpoint, seawater desalination technology can fundamentally solve the problem of water shortage in most areas. Desalination generally involves distillation and membrane processes. Distillation requires electricity and heat, whereas membrane processes employ electricity only. The two majors technical of distillation are multiple effect distillation (MED) and multi-stage flash (MSF) [2]. The major technique of membrane processes is reverse osmosis (RO) [3]. Seawater desalination is an energy-intensive process. Over the long term, desalination with fossil fuels would not be sustainable. Compared to fossil fuels, nuclear energy is suitably cheaper, reliable and efficient. Combined with small nuclear reactor and ship engineering, floating nuclear power plant could provide electricity and steam, also could be coupled with any desalination system. The nuclear sources considered in this study were small pressurized water reactor.

## 2. Coupling of floating nuclear reactors to desalination processes

Typical coupling schemes of the floating nuclear reactors with MED, MSF and RO processes are shown in Fig. 1.
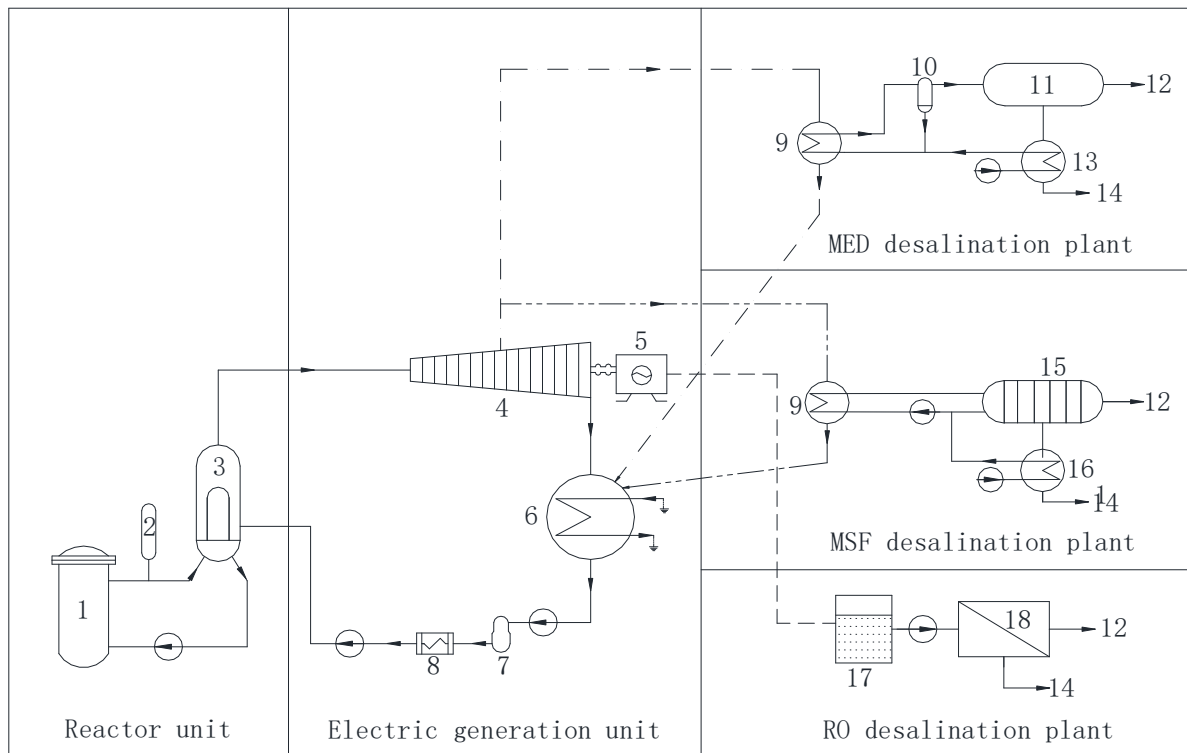
**Figure 1.** Principle of coupling of floating nuclear reactor with MED, MSF and RO desalination plants. 1: Nuclear reactor; 2: Pressuriser; 3: Steam generator; 4: Turbine; 5: Generator; 6: Main condenser; 7: Deaerator; 8: Pre-heater; 9: Seawater heater; 10: Flash tank; 11: MED plant; 12: Brine outfall; 13: MED output condenser; 14: Fresh water; 15 MSF plant; 16: MSF output condenser; 17: Pre-treatment; 18: RO membrane module.

## 3. Theories of DEEP models

To evaluate the nuclear desalination system, IAEA has developed a nuclear desalination system program, which is called as Desalination Economic Evaluation Program (DEEP) [4]. The DEEP software package is a multipart Excel module, calculates and estimates the techno-economics analysis of various desalination systems integrated with alternative energy resources. The desalination plant also comprises any type of these desalination processes: multi-effect distillation (MED), multi-stage flash (MSF), reverse osmosis (RO), and hybrid options.

There are several different criteria to evaluate the economic feasibility of nuclear desalination system. One of the most important method is the levelized water cost (LWC). It involves several parameters, such as the capital costs, operating and maintenance cost, and fuel cost. The formula for LWC is described as follows [5]:

$$\text{LWC} = \frac{\text{Life cycle cost（\$）}}{\text{Lifetime water production（m}^3)} \tag{1}$$

The discounted method is described by dividing the stream of real future costs (*Ct*) and water output (*Wt*) which are divided by the discount factor *(1 + d)^t* in the lifetime. The specific calculation formula is as follows.

$$LWC_{Discount} = \sum_{t=1}^{n} \frac{C_t}{(1+d)^t} \bigg/ \sum_{t=1}^{n} \frac{W_t}{(1+d)^t} \tag{2}$$

The annualized method is described by dividing the annual stream of real costs (*Ct*) and water outputs.

$$LWC_{Annualized} = \frac{\left(\sum_{t=0}^{n}\frac{C_t}{(1+d)^t}\right)\left(\frac{d}{1-(1+d)^{-n}}\right)}{\left(\sum_{t=1}^{n}W_t\right)\Big/n} \qquad (3)$$

Due to constant power in the lifetime duration in floating nuclear power plant, the annual electricity generation, fuel consumption and operating costs are constant. So the annualized method is more appropriate to calculate LWC in this study.

## 4. Calculation hypotheses

A 20,000m³/day desalination plant coupling with floating nuclear power is proposed to be installed in a water-deficient coastal city of china. DEEP-5 software is used for the economic analysis of the project with different desalination processes. All the technology-specific parameters needed for the economic model as well as their default values for each type of desalination are summarized bellows [6].

**Table 1.** Main hypotheses used for water cost calculations

| Model Parameters | units | MED | MSF | RO |
|---|---|---|---|---|
| Power Plant life time | yr | | 40 | |
| Reference thermal power | MWt | | 100 | |
| Reference net efficiency | %. | | 25 | |
| Site specific cooling water temperature | °C | | 25 | |
| Main steam temperature | °C | | 245 | |
| Water Salinity (TDS) | ppm | | 35000 | |
| Discount rate | % | | 5 | |
| Interest | % | | 5 | |
| Lifetime of water plant | yr | | 20 | |
| Water plant operating availability | % | | 90 | |
| Management Salary | $/yr | | 66000 | |
| Labor Salary | $/yr | | 29700 | |
| Base unit cost | $/(m³/d) | 1100 | 1100 | 1100 |
| Specific O&M spare parts cost | $/m³ | 0.01 | 0.01 | 0.03 |
| Specific O&M chemicals cost for pre-treatment and post- treatment | $/m³ | 0.05 | 0.05 | 0.07 |
| Tubing replacement cost(LT-MED) | $/m³ | 0.01 | - | - |
| O&M membrane replacement cost(RO) | $/m³ | - | - | 0.09 |

## 5. Results and discussion

Table 2 summarized the output economic parameters of floating nuclear plant coupling with different desalination processes, including MED, MSF and RO. The economic parameters include the capital costs, energy costs, and operation costs. Table 2 shows that water costs with the RO process are lower than the corresponding costs with the MED and MSF plant. The major different among the three desalination processes is related to the energy cost. The desalination annual costs for MED, MSF, and RO are 0.39, 0.77, and 0.20 $/m3, respectively. Due to the high energy consumption, the MSF process cost is the highest. However, the permeate salinity with the RO process is 199 ppm (only meeting the WHO drinking water standard) whereas MED and MSF produces water with only 25 ppm residual salinity (Can be used for industrial process water). The choice among the three processes is thus dependent on local industrial and potable water requirements.

**Table 2.** The output economic parameters of the desalination plants.

| Parameters | units | MED | MSF | RO |
|---|---|---|---|---|
| Product water TDS | ppm | 25 | 25 | 199 |
| Sp. Annualized capital costs | $/m$^3$ | 0.46 | 0.41 | 0.34 |
| Total energy costs | $/m$^3$ | 0.39 | 0.77 | 0.20 |
| Total operating costs | $/m$^3$ | 0.18 | 0.18 | 0.26 |
| Total water cost | $/m$^3$ | 1.03 | 1.35 | 0.80 |

## 6. Sensitively Analysis

To identify the effect of different variables on the cost of desalination can be evaluated quantitatively by sensitively analysis. The sensitivity factors include discount rate, interested rate, energy plant investment and Condensing temperature. The effects of mentioned above were estimated using DEEP-5 software and presented corresponding results in Table 3~Table 6.

**Table 3.** Effect of discount rate on total water cost

| Discount rate, % | Total water cost($/m$^3$) | | |
| --- | --- | --- | --- |
| | MED | MSF | RO |
| 5 | 1.01 | 1.30 | 0.79 |
| 8 | 1.26 | 1.66 | 0.94 |
| 10 | 1.44 | 1.92 | 1.06 |

**Table 4.** Effect of interest rate on total water cost

| Interest rate, % | Total water cost($/m$^3$) | | |
| --- | --- | --- | --- |
| | MED | MSF | RO |
| 5 | 1.01 | 1.30 | 0.79 |
| 8 | 1.05 | 1.36 | 0.80 |
| 10 | 1.08 | 1.40 | 0.81 |

**Table 5.** Effect of specific construction cost on total water cost

| Specific Construction Cost, % | Total water cost($/m$^3$) | | |
| --- | --- | --- | --- |
| | MED | MSF | RO |
| 3500 | 0.97 | 1.23 | 0.77 |
| 4000 | 1.01 | 1.30 | 0.79 |
| 4500 | 1.04 | 1.37 | 0.81 |

**Table 6.** Effect of condensing temperature on total water cost

| Condensing temperature, °C | Total water cost($/m$^3$) | | |
| --- | --- | --- | --- |
| | MED | MSF | RO |
| 20 | 0.98 | 1.28 | 0.79 |
| 25 | 1.01 | 1.30 | 0.79 |
| 30 | 1.04 | 1.33 | 0.79 |

The results can be drawn from the tables:
- The discount rate has the greatest influence on the water cost, the MSF desalination has the most obvious influence among the three processes. When the discount rate increases to 8% and 10%, the water production cost of MSF desalination increases to 1.66 $/m3and 1.92 $/m3, the water production cost of MED desalination increases to 1.26$/m3 and 1.44$/m3, and the water

production cost of RO desalination increases to 0.94$/m3 and 1.06$/m3, respectively. When the discount rate is 10%, the cost change rate can reach as high as 48%.

- Increased interest rate and changes in project cost have less impact on water costs. Among them, multi-stage flash distillation is the method being affected most, but when the interest rate increases to 10%, the cost of water increases only a few cents.
- The effect of condensing temperature is minimal. In particular, for the reverse osmosis method, the cost of water remains almost unchanged.

## 7. Conclusion

Water cost were obtained with three desalination processes (MED, MSF and RO) coupled with floating nuclear plant by using DEEP-5 software.

Analysis of the results obtained shows that:

- The calculation results show that water costs with the RO process are lower than the corresponding costs with the MED and MSF desalination plant, without regard to changes in water quality. The choice among the three processes is thus dependent on local industrial and potable water requirements.
- Increasing the discount rate from 5% to 8% increases the water cost of MED, MSF and RO 25%, 28%, 19%, while discount rate increase to 10%, the water cost increase to 42%, 48%, 34%. This shows that the discount rate has a significant effect on the total water cost.
- It can be seen from the sensitivity analysis results that the sensitivity factors affecting the cost of desalinated water are, in order, discount rate, interest rate, Specific Construction Cost and Condensing temperature. The Condensing temperature has little effect on the cost of water of RO desalination production.

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