Saline water desalination using solar energy: performance analysis and implementation barriers

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Abstract. Solar water desalination system is one of the alternatives for supplying fresh water. On the other hand, some people are reluctant to use and rely on water produced by the system. Also, there are other barriers to the adoption of this system in Indonesia. This research aimed to conduct a preliminary study on the performance of solar desalination systems and identify factors that hindered its implementation. The methodology applied in this study consist of two approaches. First, the desalination system performance is determined by the quantity of freshwater produced and the quality of feed water, distilled water, and brine compared to Indonesia's water quality standard. Second, the identification of implementation barriers was evaluated in the structural analysis method using MICMAC (the Impact Matrix Cross-Reference Multiplication Applied to a Classification) software. The performance analysis result shows low efficiency based on desalinated water produced, which ranges from 2.59\% up to 9.67\%. The water quality parameters of pH, turbidity, TDS, chloride, Fe, and hardness met the Indonesian water quality standard. The factor of "uncertainty of subsidies," "niche market," "poor solar energy data," and "lack of policy/regulatory framework" were determined as critical barriers which have the most significant influence and highest independence.

1. Introduction
The process of processing seawater into water is ready to be one of the solutions for providing clean water. The process of processing seawater into freshwater is known as the desalination process [1]. The whole desalination process requires energy to remove salt from seawater. If desalination is carried out using conventional technology, it will require burning large amounts of fossil fuels (the production of 1000 m\textsuperscript{3}/day of clean water requires 10,000 tons of oil per year). As the availability of these fuels is decreasing, then other energy sources are needed. One energy source for desalination is using solar power [2]. It is based on solar energy being renewable energy, safe, accessible, and pollution-free. Solar power is a promising solution to save costs. In addition, Indonesia is a country that has abundant solar intensity, which is an average of 4.8 kWh/m\textsuperscript{2}.day [3].

Solar desalination can be divided into direct and indirect technologies. In the direct method, the solar energy collector and desalination component are integral units, for example, a solar still. A general rule of thumb for simple solar stills is that about 1 m\textsuperscript{2} of sunlight collection area must produce 3 - 5 L of
water per day. Thus, a large sunlight collection area is required at a high capital cost. Multi-effect solar stills are used to improve the performance of solar stills [4]. Solar water desalination system is one of the alternatives for supplying fresh water.

On the other hand, some people are reluctant to use and rely on water produced by the system. Also, there are other barriers to the adoption of this system in Indonesia. A transition to renewable energy is a complex process that involves technical [5,6], social, political, and economic factors [7], and environmental [8] aspects. Therefore, this research aimed to conduct a preliminary study on solar desalination systems' performance and identify factors that hindered its implementation.

Several studies that used single solar still have been conducted. Safitri [9] reported that distilled water produced was 0.2 – 0.9 L/m² with an evaporation area of 0.75 m², measurement duration of 4 hours, and collector inclination angle of 30°. Other researchers used the evaporator and condenser under vacuum conditions to treat saline water. Kusumadewi et al. [10, 11] reported that distilled water produced was 4 – 11.6 L/m² with an evaporation area of 0.0576 m², measurement of 8 hours, and collector inclination angle of 30°. This paper reports on the performance of multiple trays tilted still, which is the development of a desalination unit made by Safitri [9]. In this research, a styrofoam layer was used, which functions as a heat insulator to remain in the distillatory box. The distillatory box was covered with glass with a thickness of 5 mm and dimensions of 85 cm × 100 cm with silicon to form a line pattern as the distillate water effluent system. The distillatory box was tilted at an angle of 25°. There are 5 levels with an estuary on the gutter made of a 1.5 inch PVC pipe to drain brine water.

2. Methodology

It was a saline water desalination using solar energy study conducted using experimental work at Environmental Engineering Laboratory, University of Trisakti, Jakarta. A modified MICMAC has been used to analyse enablers and barriers factors in renewable energy studies [8,12]. This study will use free software LIPSOR-EPITA-MICMAC version [13].

2.1. Experimental work

2.1.1. Water distillation system. This distillatory design results from the development of the multiple trays tilted still type distillatory in a previous study [10,11]. In this study, there is an addition of absorbent material in the form of black cloth. The purpose of using a fabric absorber in this design is to increase the absorption surface area, accelerating the evaporation rate. The capillarity effect given by the black cloth as an absorber allows the air in the layer to spread evenly across the surface of the distillation. It is composed of a water input reservoir, where the distillation process occurs, then the distillate water and the resulting brine are accommodated using a container (Figure 1).

The distillatory body is composed of plywood measuring 85cmx100cmx15cm for width, length and height, respectively. It covers with aluminium and black cloth as the heat absorber. The cover of the distillatory is clear glass with a thickness of 5 mm. After the body is completed, it is covered with an insulator in the form of styrofoam measuring 4 cm. Then the distillatory body is placed on an iron frame with a distillatory tilt position of 25°. This distillatory has a distributor pipe. Un-evaporated water (brine) contains high levels of salt. This brine also has a high heat that can heat the input water or feed water. The water outcome of the distillatory is then measured and recorded every 1 hour. So, the efficiency of the distillatory can be analysed and calculated. The distillatory test was carried out from 9.00 WIB to 15.00 WIB in the Pademangan Village area, East Pademangan District, North Jakarta. Water quality testing from the desalination process was conducted at the Trisakti University Environmental Laboratory, West Jakarta, on November 10 - 15, 2020. The ambient air temperature, wind speed and humidity range were 30.6 – 34.2°C, 0.2 – 2.7 m/s, and 51 – 71%Rh, respectively.
Figure 1. Experimental set-up (a) and schematic diagram (b) of the multiple trays tilted still distillator.

2.1.2. The efficiency of the distillation system. This study compares the theoretical efficiency and the actual efficiency of the distillary [14]. The actual efficiency is calculated using equation (1), the ratio of the volume of water leaving and entering the distillary. The theoretical efficiency was calculated by using equations (2), (3) and (4), as follows [15]:

Efficiency:

\[
\eta_t = \frac{\text{Volume out}}{\text{Volume in}} \times 100\% \tag{2.1}
\]

\[
\eta_c = \frac{Q_u}{Q_in} \times 100\% \tag{2.2}
\]

Where \(Q_u\) is the energy supplied by the solar collector (Watt), and \(Q_in\) is the radiation energy in the absorbing plate (Watt).

\[
Q_u = m.C_p.\Delta T + m.h_{fg} \tag{2.3}
\]

Where \(m\) is the mass of distilled water (litre), \(C_p\) equal to 4180 J/kgK [16], \(\Delta T\) is the different temperature between feed water and brine, \(h_{fg}\) is the enthalpy of evaporation of water which equals 22.6 105 J/kg.\(^\circ\)C [16]

\[
Q_in = \alpha.IT_{tot}.A_c \tag{2.4}
\]

Where \(IT\) is solar intensity (W/m\(^2\)), \(A_c\) is an area of the absorbing plate or solar collector (m\(^2\)), \(\alpha\) is absorptivity of the solar collector (0.50)

2.2. Implementation barriers identification

2.2.1. Data collection. Identifying barriers that could hinder the realisation performed through literature review. A literature review is an excellent approach to form a solid foundation and integral part of research [17]. Due to insufficient literature in the context of Indonesia rural sector, this study utilised references from other developing countries.
Table 1. Barrier Factors [8,18,19,20,21,22,23].

| Dimension   | Barrier                        | Description                                                                 |
|-------------|--------------------------------|----------------------------------------------------------------------------|
| Economic    | High Initial Capital Cost (E1) | Cost of installation for the distillation system                           |
|             | Uncertainty of subsidies (E2)  | The subsidies that available from the government to cover the initial installation of the distillation system |
|             | Absence of financing institution (E3) | The companies that are interested to invest                                  |
| Technology  | poor solar energy data (T1)     | Reliable information to design distillation technology may influence Analysis of cost and efficiency. |
|             | Unskilled professionals (T2)    | The distillation system needs a skilled professional in repairing and maintaining the system. |
| Social      | the reluctance of people (S1)   | People perceive that wave energy has a significant dependence on weather conditions. So, it raised doubt on its reliability. |
|             | Niche market (S2)               | There is uncertainty on potential consumers and the availability of information and knowledge about markets. |
| Political   | Lack of Policy/ regulatory framework (P1) | Assurance of solid enforcement of policies, precise regulatory mechanism and legal support |

2.2.2. Impact matrix multiplication applied to classification (MICMAC). MICMAC technique is conducted by mapping variables into a relationship of the influence variables and dependent variables in the matrix [24,25]. The procedures consist of three main steps: classification of the variables, evaluation of the correlation among the variables, and determination of the critical variables. In this study, the classification of the variables is performed to categorise the model under economic, technology, social and political dimensions. Then the Analysis enables the researcher to understand the distribution of the impacts by using the loops and paths [26] using the iteration process. This process simulates the behaviour of the higher-order system. The iteration process is usually completed within 7-8 iterations [27]. There are 8 (eight) variables distributed among sustainability dimensions of the economy, technology, social and policy (Table 2). Table 2 shows the matrix of direct influence. It allows the development of an influence map. Each of these 8 variables was evaluated to develop an 8 x 8 cross-impact matrix called the Matrix of Direct Influence (Table 2).

Table 2. Matrix of direct influence.

| Influence | E1 | E2 | E3 | T1 | T2 | S1 | S2 | P1 |
|-----------|----|----|----|----|----|----|----|----|
| Dependence |    |    |    |    |    |    |    |    |
| E1        | 0  | 0  | 3  | 0  | 0  | 2  | 0  | 0  |
| E2        | 3  | 0  | 3  | 2  | 2  | 3  | 0  | 0  |
| E3        | 1  | 0  | 0  | 0  | 1  | 1  | 0  | 0  |
| T1        | 3  | 2  | 1  | 0  | 1  | 0  | 2  |    |
| T2        | 0  | 0  | 0  | 3  | 0  | 0  | 0  |    |
| S1        | 0  | 0  | 0  | 0  | 0  | 3  | 3  |    |
| S2        | 1  | 1  | 1  | 0  | 3  | 0  | 2  |    |
| P1        | 3  | 3  | 3  | 1  | 1  | 1  | 1  | 0  |
3. Results and discussion

3.1. Saline water desalination performance analysis

3.1.1. Effect of solar radiation on the distilled water volume. The sun's intensity dramatically affects the temperature of the distillate water and the temperature of the glass in the distillator, which appears to increase with the increase in the intensity of the sun (Table 3).

Table 3. Solar radiation intensity, feed water, distilled water, ambient air and glass temperature.

| Parameter                        | Observation day- |
|----------------------------------|------------------|
|                                  | 1    | 2    | 3    | 4    | 5    | 6    |
| Solar radiation intensity (kfc)  | 35.9 | 30.41| 50.02| 50.19| 48.5 | 53.84|
| Feedwater (°C)                  | 45.54| 49.39| 49.19| 37.03| 47.84| 40.76|
| T\text{distilled water} (°C)    | 34.78| 36.53| 37.17| 37.03| 35.62| 35.88|
| T\text{ambient air} (°C)        | 32.07| 32.73| 32.84| 32.67| 33.01| 32.9 |
| Glass (°C)                      | 41.79| 44.99| 43.47| 41.41| 39.8 | 39.5 |

The value of the temperature's distillate water and the glass in the distillator increases with the sun's intensity. It is the plate that absorbs the sun's energy as it receives it at that time and uses it to evaporate the feed water contained in the distillator. Black's Principle states that the heat absorbed is equal to the heat received by the substance and will be proportional to the increase (change) in the temperature of the substance [15].

3.1.2. The efficiency of the distillator. The actual efficiency of the distillator for 6 hours of observation can be seen in Table 3. The actual efficiency of the distillator in this study tends to be low—the lowest efficiency is 2.59%, and the highest is 4.94%. Only a tiny part of the feed water becomes distillate water, and most of it becomes brine (saltwater). It can be caused by the use of solar energy and the evaporation process that is not optimal, the duration of observation is not long, the surface area of the glass in the distillator is not large, and the feed water discharge is too fast.

Table 4. Actual distillatory efficiency.

| Feedwater volume (ml) | Distilled water volume (ml) | Efficiency (%) |
|-----------------------|----------------------------|----------------|
| 11,388.53             | 373                        | 3.28           |
| 13,008.57             | 509                        | 3.91           |
| 14,046.21             | 464.5                      | 3.31           |
| 11,537.98             | 570                        | 4.94           |
| 13,100.33             | 398                        | 3.04           |
| 14,988.41             | 388                        | 2.59           |

Table 5. Energy balance of distillation process (theoretical distillatory efficiency).

| Day | Radiation energy in the absorbing plate (Watt) | The energy supplied by the solar collector (Watt) | Efficiency (%) |
|-----|-----------------------------------------------|-------------------------------------------------|----------------|
| 1   | 14,034.94                                     | 858.63                                          | 6.12           |
| 2   | 12,162.62                                     | 1175.85                                         | 9.67           |
| 3   | 20,006.53                                     | 1071.54                                         | 5.36           |
| 4   | 20,075.23                                     | 1288.2                                          | 6.42           |
| 5   | 19,401.16                                     | 918.46                                          | 4.73           |
| 6   | 21,534.88                                     | 884.26                                          | 4.11           |

Table 4 shows the value of energy balance in the distillation process. It can be seen that for 6 days, only a tiny part of the incoming energy is used for the distillation process. The energy lost during the distillation process is estimated to occur. Due to the heat's conduction and convection processes, either
on the evaporator's walls or the absorbent plate. In addition, the energy that enters the absorbent plate is not all used, but some of the energy is reflected, so it is assumed as energy lost [10].

Table 5 shows that the efficiency of the distillation apparatus has a linear relationship with the amount of energy that enters the evaporator. The calculated efficiency value is the daily efficiency value of the distillation's ability to produce fresh water. Based on the experiment and observation of the distillatory for six days, the highest efficiency value was obtained on the second day with 9.67%, while the lowest efficiency was on the sixth day with a value of 4.11%. Several factors that affect the efficiency value include climatic and weather conditions (sun intensity, irradiation time, ambient temperature, wind resistance, heat transfer rate, and so on) that affect heat or temperature, both in the distillation system and in the environment [10]. Other factors that are also considered influential in the distillation process are the dimensions of the distillation apparatus and the volume of distilled water.

### 3.1.3. Distilled water quality analysis

Brackish water and seawater have different characteristics, so it is necessary to analyze the quality of the distilled water produced from the two types of feed water. The quality of the distilled water produced from artificial brackish water and artificial seawater has met the drinking water quality standards [28] for the parameters of pH, turbidity, electrical conductivity (DHL), total dissolved solids (TDS), salinity, chloride (ion Cl\(^{-}\)), iron (Fe), and total hardness. The distillation process is a physical process where the processing is based on the difference in the boiling point of the liquid so that it can set aside these parameters. The product of the desalination process is generally water with a dissolved salt content of less than 500 mg/L, which can be used for domestic, industrial, and agricultural purposes [28]. This study obtained distillate water with a TDS content of 9 – 83 mg/L for artificial brackish water and 17 – 376 mg/L for artificial seawater. It indicates that the proposed desalination system has met the criteria for a desalination system in general.

**Table 6.** Distilled water quality of feed water from artificial brackish water and seawater.

| Parameter | Unit | Brackish water | Seawater | Water quality standard [28] |
|-----------|------|---------------|----------|-----------------------------|
| pH        | -    | 7.19 - 7.57   | 7.3 - 7.63 | 6.5 - 8.5                   |
| Turbidity | NTU | 1.17 - 2.42   | 22.70 - 66.6 | 5                           |
| DHL       | μS  | 22,710 – 24,100 | 55,400 – 59,300 | -                           |
| TDS       | mg/l | 11,200 – 12,100 | 27,600 -29,700 | 500                          |
| Salinity  | %   | 15            | 33.9 - 38 | 0                            |
| ion Cl\(^{-}\) | mg/l | 760.84 - 1,408.36 | 1991.12 - 1,748.3 | 250                          |
| Fe        | mg/l | 0 - 0.032     | 0 - 0.586 | 0 - 0.055                   |
| Total hardness | mg/l | 72 - 744     | 104 - 291.2 | 0                            |
| Ca hardness | mg/l | 25.6 - 44.8   | 30.4 - 46.4 | 0                            |
| Mg hardness | mg/l | 0 - 480       | 168 - 3672 | 0                            |

The distillation process will produce freshwater that is very high in purity [9]. It can be seen from the shallow salt content in the distillate water resulting from this desalination system. It is evident from the parameters of pH, turbidity, electrical conductivity (DHL), total dissolved solids (TDS), salinity, chloride (Cl\(^{-}\) ions), iron (Fe), and total hardness which is far below the drinking water quality standard. In addition, [12] states that the distillation process produces high-quality water with a TDS (Total Dissolved Solids) value in the range of 1.0 – 50 ppm. From the results of this study, the TDS content in the distillate water was 9 – 83 mg/L for artificial brackish water and 17 – 376 mg/L for artificial seawater.
seawater. IN SOME OBSERVATIONS, the TDS content in this distillate water reached more than 50 ppm but still meets the drinking water quality standards. It can be caused by the condition of the reactor that is not clean so that there is a high TDS content of the feed water in the distillatory and affects the distillate water formed.

3.2. Implementation barriers

The variable of “uncertainty of subsidies”, “niche market”, “poor solar energy data,” and “lack of policy/regulatory framework” are classified as dominant variables in quadrant I (Figure 2). Variables in this quadrant have the most significant influence and the most vital influence among other variables. These variables are categorised within economic (uncertainty subsidies), social (niche market), technology (insufficient solar energy data) and political (lack of policy/regulatory framework) aspects.

These dominant variables have a low dependency and strong influence on other variables. Therefore, priority should be applied to overcome these barriers to implement a solar energy desalination system. The certainty of subsidy for both the investment and maintenance budget is one of the implementation successes. The variable under quadrant II of relay or critical variable is “reluctance of people”. This barrier factor has domino effects throughout all factors in the model.

These factors are considered unstable factors because they have a feedback effect. It means that any action taken to these factors will impact other factors. It might show in the lack of people’s participation in disseminating the system due to a lack of information about the desalination system and its benefit. The people perception and/or acceptance of wave energy cannot be achieved in a short time. The government authorities must conduct frequent campaigns to enhance understanding and knowledge of solar energy desalination systems. There are two (2) dependence variables in quadrant III, which are “high initial cost” and “absence of financing institution”. It indicated that high initial cost and absence of financing institution relatively unimportance factors hinder the adoption of desalination technology. The reason is that the cost of a small scale distillation system is not very expensive. Also, the operational and maintenance of this system is quite simple. Hence the role of financing institutions is not so urgent.

![Figure 2. Barriers variable map of direct influence-dependence (MICMAC).](image-url)
Finally, we can determine the level of dependence and influence among variables in the long term. Figure 3a presents the rank of influence comparison between the existing condition (Direct) and future condition (indirect) among the variables. “Uncertainty of subsidies” (E2) was in rank 1 under the Direct matrix, but in future, it is in rank 2 under the Indirect matrix. It might be due to the "uncertainty of subsidies" (E2) in the future has less influence on other barriers compared to "lack of policy" (P1).

Figure 3b shows factors of high initial cost (E1), absence of financing institution (E3), and the reluctance of people (S1) are consistent in the highest level of dependence variables, both for the direct and indirect time frame. This condition aligns with the fact that these barriers depend on the "uncertainty of subsidy" and "lack of policy" for adopting a solar energy desalination system.

4. Conclusion
The solar water desalination system was designed and tested under actual environmental conditions in Jakarta, Indonesia. The actual efficiency of the distillator in this study tends to be low, with the lowest efficiency being 2.59% and the highest being 4.94%. Only a tiny part of the feed water becomes distillate water, and most of it becomes brine. Based on the experiment and observation of the distillation apparatus for six days, the most significant theoretical efficiency value was obtained on the second day with 9.67%, while the lowest efficiency was on the sixth day with a value of 4.11%. The efficiency of the distillation system has a linear relationship with the amount of energy that enters the evaporator. The calculated efficiency value is the daily efficiency value of the distillator's performance to produce fresh water. Further research should include more experimental set-up variations, such as the fabric colour of the absorber, inclination angle, and feed water discharge.

Eight barrier factors of the implementation of a solar energy water desalination system have been analysed. It shows that “uncertainty of subsidies”, "niche market", "poor solar energy data," and "lack of policy/regulatory framework" are the key barriers. Future studies should be proposed to analyse more variables within the four dimensions to determine an effective strategy for implementing the solar energy desalination system in Indonesia.

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