Design of Reverse Osmosis Desalination Plant at Remote Coastal Area

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Abstract. During the long dry season hit most parts of East Java in 2019, there were 566 villages in 180 sub-districts that are categorized as dry areas with critical clean water supply, 236 villages in 93 sub-districts as rare dry areas, and 20 villages in 14 sub-districts experienced limited dryness. In big cities in Indonesia, clean water service coverage has only reached 64.3%, while in rural areas still at 69.4%. This proves that most of the regions in Indonesia still experiencing a clean water crisis. Therefore, alternative clean water processing technology is needed to help supply clean water in these areas. Desalination as one of the technologies is essential for coastal areas that are remote from freshwater resources. In this paper, authors propose a design of photovoltaic reverse osmosis (PVRO) desalination plant at remote coastal area to supply clean water. A 100 m³/day design of PVRO, which is compact and energy efficient including the ultrafiltration method is introduced.

1. Introduction

Indonesian Institute of Sciences (LIPI) [1] predicted the water crisis in Java Island will occur in 2040 due to limited water resources. The proportion area of water crisis will increase from 6.0% in 2000 to 9.6% in 2045 followed by decreasing of quality of water significantly. Water crisis is caused by several factors i.e.: climate change, high population growth, and land use change. Large exploitation of groundwater also makes fast increase in water crisis. In 2019, one reported the water crisis during long dryness season in East Java, which covered 566 villages in 180 sub-districts that are categorized as dry areas with critical clean water supply, 236 villages in 93 sub-districts as rare dry areas, and 20 villages in 14 sub-districts experienced limited dryness [2]. The crisis not only for people in urban areas, which struggle with clean water supply, but also villagers with limited water resources and at remote location such as coastal and small islands.

LIPI suggested that reuse and recycle technology are required to help a sustainability of water supply in Indonesia in the future [1]. Desalination as an alternative clean water processing technology is needed to supply clean water. Reverse osmosis (RO) desalination is feasible economically with the cost of freshwater production related with separation process of dissolved salt and minerals from the source saline water such as sea water or brackish water. Seawater desalination is being applied at 58% of installed capacity, and brackish water desalination reach 23% of installed capacity worldwide [3][4]. Reverse osmosis is becoming a significant technical option of desalination as a sustainable water...
technology with continued advance development to lower the cost of water production and reduce the total energy consumption [5].

Photovoltaic reverse osmosis (PVRO) desalination system is an energy efficient, cost competitive, and modular system that will fit the needs of off-power-grid rural communities such as people at a remote coastal area that face drinking water shortages due to saline water problems [6]. PVRO as one of renewable energy system (RES) - desalination combination systems, has been reviewed comprehensively, which is in term of PV arrays to produce electricity for powering RO system [5]. PVRO was evaluated and recommended as a technology for desalination requiring electrical power in the small size plant (1-50 m$^3$/day) for sea water reverse osmosis (SWRO). As seen in figure 1, PVRO occupies 32% of applied renewable energy powered desalination technologies.

![Figure 1. Distribution of RES-desalination combination technologies [5][7].](image1)

PVRO for sea water or brackish water process in small size capacity plant ranged from 0.4 m$^3$/day to 53 m$^3$/day and power required up to 18 kW have been installed in many places around the world, such in USA, Saudi Arabia, Israel, Oman, Egypt, Australia, including Indonesia, with or without battery system [5][6][8]. In this paper, an outlook design of medium size PVRO 100 m$^3$/day is proposed to accommodate clean water daily consumption in remote coastal communities especially during dryness season.

![Figure 2. PVRO configuration plan [12].](image2)
2. PVRO desalination plant

The design of RO desalination is based on the requirement plan of clean water for rural areas such as remote coastal area, which is covered 1000 inhabitants. According to SNI - 19-6728.1-2002, the standard of water demand in rural areas is 100 L/person/day. Therefore, the required water supply is 100 m³/day or 4.16 m³/hour. RO is designed for desalination of seawater with salinity range of 35000-45000 ppm in the form of total dissolved solids (TDS) to meet permissible limit of salinity of water of 1000 mg/L or less, which refers to WHO and Permenkes RI No. 32/2017 [9][10].

Design of RO followed steps to design RO membrane, which are outlined in DuPont’s Filmtec™ RO membranes technical manual [11]. The results were validated by WAVE software released by DuPont to determine whether there is a failure (design error) in the system. The further step is the analysis of requirement of PV arrays for RO desalination were evaluated using RETScreen® Expert software.

The PVRO configuration is seen in figure 2. The desalination plant is dedicated for remote coastal area especially at the most of south part of Java island, which suffered of clean water every year. A representative location had been chosen, that was the south part village of Sudimoro sub-district in the Pacitan district area. The PVRO system consist of PV cell arrays including charge controller, inverter, MCBs, batteries, pumps, ultrafiltration, RO membranes, and water tanks. A 100 m³/day PVRO system is categorized as a medium size RO plant, which require special attention of efficiency. A conventional PVRO system was recommended for small size plant, however in this study a potential capacity of PVRO using several power schemes will be introduced to provide daily clean water to the communities.

Figure 2 shows the PVRO configuration plan, which introduces possible three combinations of PV configuration i.e.: PV standalone with or without battery and PV-Diesel hybrid to overcome peak power requirement for 100 m³/day continuous water consumption.

3. Results and discussion

3.1. WAVE simulation to design RO membrane

The RO membrane system was designed based on FilmTec™’s steps to design membrane system [11]. Equation (1) is used to calculate the requirement of the number of membrane element ($N_E$) as a formula ratio of the design permeate flow rate ($Q_P$) by a design flux ($f$) and by the cross sectional area of membrane element ($S_E$) (in ft² or m²).

$$N_E = \frac{Q_P}{f \cdot S_E} \quad (1)$$

The membrane type for RO was DuPont FilmTec™ SW30XHR-440. This type was chosen because of the highest rejection rate and the highest active area in the DuPont FilmTec™ membrane range. From the design guidelines, some data are obtained as follows: (i) design of permeate flow rate ($Q_P$): 26,417.2 gpd, (ii) design flux ($f$): 11 gfd, (iii) membrane element ($S_E$) cross-sectional area is 440 ft². Calculation was carried out from the data above and to meet the total required of flow rate design 100 m³/day, hence the number of membrane element ($N_E$) is 5.45, which is equal to 6 membrane elements.

After determining the number of membranes, the next step is to determine the number of seats (housing / pressure vessels) of the required membrane ($N_V$) by dividing the number of membranes needed ($N_E$) by the number of membranes per pressure vessel ($N_{EPV}$) which is stated by the following formula:

$$N_V = \frac{N_E}{N_{EPV}} \quad (2)$$

The number of membranes in each pressure vessel (PV) for standard RO desalination plant and also recommended by DuPont are 6 to 12 membranes arranged in series, but the ones commonly used in the market are 6, 7, 8, and 12. In this study, the PV capacity used was 6 membrane per PV, hence the $N_V$ equals 1.
In the WAVE simulation, the input parameter are the methods, the type of feed water, and the plan of the product water capacity. The type of feed water used for desalination is seawater. The methods used in this system are ultrafiltration (UF) and reverse osmosis (RO) with a capacity of product water is 100 m$^3$/day or 4.17 m$^3$/hour. The next step is to determine the type of reverse osmosis components. The data for simulation include membrane type, amount of PV, number of membranes per PV, recovery rate, and anti-scalant. For the recovery rate, no formula is used to determine it, however, DuPont has determined a range of values for the recovery rate based on the number of membranes in each pressure vessel. In the seawater RO system with a single stage membrane system and 6 membranes in a PV, the range is between 35% and 50%. In this study, the recovery rate is at 45%. The anti-scalant was determined to use Dupont’s Sodium Trimetaphosphat Na$_6$P$_6$O$_18$(100) with concentration of 3 mg/L.

| Stage | Elements | #PV | # Els per PV | Feed | Concentrate | Permeate |
|-------|----------|-----|--------------|------|-------------|---------|
|       |          |     |              | Flow | Press | Flow | Press | Flow | Press |
|       |          |     |              | [m$^3$/h] | [bar] | [m$^3$/h] | [bar] | [m$^3$/h] | [L/MH] | [bar] | [mg/L] |
| 1     | SW30XHR-440 | 1   | 6            | 5.27 | 62.3 | 0.0  | 1.2  | 4.17 | 17.0 | 0.0 | 111.8 |

**Figure 3.** Result of WAVE simulation on 1 PV with capacity 6 membrane.

**Figure 4.** WAVE simulation results on DuPont FilmTec™ SW30XHR-440 membranes.

In this simulation, the selected number of stage is a single stage / single pass, which means that water only passes through the reverse osmosis membrane one time. In addition, the number of Els per PV or the number of membranes in each pressure vessel is 6. The following results of WAVE simulation for DuPont FilmTec™ SW30XHR-440 membrane using one PV with capacity of 6 membranes are seen in figure 3. Total Dissolved Solids (TDS) of product permeate water has a value of 111.8 mg/L. This value meets the requirement by Permenkes RI No. 32/2017, with a maximum level of 1000 mg/L. The pH value is 8.1, which also meets the standard of Permenkes within a range 6.5-8.5. The simulation also had no potential design failures (RO design warnings), so that the membrane could be used. The detail results of simulation for six DuPont FilmTec™ SW30XHR-440 type membranes are shown in figure 4.

3.2. Calculation of Ultrafiltration (UF) Membranes
The RO system uses UF membrane to filter out colloids, viruses, microorganisms, and bacteria. The output of the permeate reverse osmosis membrane was 4.16 m$^3$/hour with a recovery rate of 45%. From above calculation as seen in figure 4, it was obtained that the input flow for reverse osmosis membranes is 9.27 m$^3$/hour. In this system, the position of the ultrafiltration membrane is before the reverse osmosis membrane so that the required output flow from the ultrafiltration membrane shall be at least 9.27 m$^3$/hour. Calculation of UF membrane was using WAVE software based on data of UF membrane type, the number of UF membranes, and the configuration of UF membrane.

![Figure 5. Result of WAVE simulation for UF membrane.](image)

In this RO plant, it was planned to use DuPont UF Module IntegraPac™ IP-77 as a UF membrane. This type is used because the membrane is a package with the flange and other accessories [13]. After determining the type of UF membrane, the next step is to determine the number of membranes and their configurations. When determining the number of membranes and configuration, the WAVE software will display recommendations for the number of membranes in each train. When determining the number of membranes and configuration on the DuPont UF Module IntegraPac™ IP-77, the WAVE software recommends several options for 1 train containing 8, 10, and 12 modules. The results of the simulation of 8 membrane modules per train chosen are shown in the figure 5. From the calculations on figure 5, it is found that the chosen 8 UF membranes has a recovery rate of 69.08%. It can be concluded that if the water flow out of the ultrafiltration membrane is 9.3 m$^3$/hour, then the required input flow is 13.5 m$^3$/hour.

### 3.3. RO components

Refer to PVRO configuration plant in figure 2, all components that are required for RO were listed in table 1. In this research, the electrical power which is required for the RO desalination plant is 35.75 kW. As seen in table 1, the energy required to operate this system is high. This is because there are 3 pumps used in this system. These pumps include a feedwater pump, an ultrafiltration pump, and high-pressure pump that require 750 watts, 5 kW, and 30 kW, respectively. Although it requires high energy, this system does not require replacement of the media used as a filter ( multimedia filter / sand filter / activated carbon / activated zeolite) so it is very suitable to be applied in rural remote areas that really need a compact technology and minimum operation and maintenance aspects. These are necessary for a RO plant to provide longer lifetime.

### 3.4. Photovoltaic system

To provide the electric power of RO desalination plant, PV cell arrays are applied to produce electrical energy from solar irradiation intensity of 4.82-6.07 kWh/m$^2$/day at the area of Pacitan district, East Java. The analysis of PV system was performed by RETScreen® Expert software to calculate the solar irradiation intensity based on certain location including the energy and emission analysis. Based on Energy Sector Management Assistance Program (ESMAP), the PV array is positioned on 12° tilt facing north [14]. The choice of a PV solar panel or module also must consider the efficiency and other several important factors that affect the electric output. Researchers chose monocrystalline silicon (mono-Si) as the solar module for PVRO system, which has high efficiency 14-17%. Based on PVRO design in figure
2, there will be three configurations of electrical wiring and voltage systems are needed on PV system for RO plant, i.e.: 1-phase output for lighting, controller, and feed water pump, and two configurations of 3-phases output for UF pump and HP RO pump during PV-battery and hybrid PV-diesel schemes. The design and requirement of component of PV modules were simulated by RETScreen® Expert, and was followed by calculations of inverter, maximum power point tracking (MPPT), and battery. The results are shown in table 2.

### Table 1. RO components.

| Component                      | Unit | Specification                          |
|--------------------------------|------|----------------------------------------|
| Feedwater Pump (FWP – 01)      | 1    | MC KARLEN SPA 10; 21,6 m³/h; 16 m; 750 W |
| Storage tank (FT – 01 & PT – 01)| 2    | PROFIL TANK TDA 25000 l; 2,9 m × 4,1 m |
| Ultrafiltration pump (UFP – 01)| 1    | GRUNDFOS CRT 16-6A; 16,3 m³/h; 6,481 bar; 5 kW |
| Ultrafiltration membrane (UFM – 01 – 08)| 1 unit (8 membranes) | DuPont IntegraPac IP-77; 9,3 m³/h |
| High pressure RO pump (ROP – 01)| 1    | GRUNDFOS BMPE 10,2 R; 10,2 m³/h; 816 m; 30 kW |
| Reverse osmosis membrane (ROM – 01 – 06)| 1 PV (6 membranes) | DuPont Filmtec SW30XHR-440; 4,17 m³/h |

### Table 2. PV components for 100 m³/h RO plant in amount of number and specification.

|                          | 1 Phase (PV-battery) | 3 Phase (PV-battery) | 3 Phase (PV-diesel) |
|--------------------------|----------------------|----------------------|---------------------|
| Solar Panel              | 20, Suntech STP2655 – 20/Web | 520, Grape Solar GS-S-410-Platinum | 220, Grape Solar GS-S-410-Platinum |
| Inverter                 | 1, Victron Energy Inverter Easy Solar 24/3000/70-50 | 5, Victron Energy Phoenix Inverter 48/5000 | 5, Victron Energy Phoenix Inverter 48/5000 |
| MPPT                     | 1, Victron Energy Smart Solar Charge Controller 150/70 VE.Can | 10, Victron Energy BlueSolar Charge Controller MPPT 150/100 VE. Can | 10, Victron Energy BlueSolar Charge Controller MPPT 150/100 VE. Can |
| Battery                  | 4, Victron Energy Lithium ion-HE | 130, Xantrex Lithium Ion 300AH 24V | 30, Xantrex Lithium Ion 300AH 24V |

3.4.1. Energy management system. The application of PV for RO desalination gives a consequence of a fluctuation of solar irradiation during the day and the requirement of energy substitution at night. To overcome this problem, several schemes of energy will be applied to manage the operation of RO system over the load and capacity of the plant. In this work, an energy management of the PVRO was proposed to opt for powering scheme based on loads and water production capacity. Refer to table 1, the design of PVRO has a maximum water production capacity of 100 m³/day with total required power is 35.75 kW. To calculate the practice power of RO, a safety factor 20% was applied and additional lighting and controller power 4.1 kW was added to the system. As seen in table 2, the PVRO plant will be also supported by a battery system and a diesel generator to provide an optimum electrical powering scheme. The energy management consists of four schemes, i.e.: (i) daytime 6 hours off-grid PV – without battery,
(ii) daytime 10 hours off-grid PV – battery: 6 hrs PV and 4 hours with battery, (iii) 24 hours hybrid PV – diesel: 6 hrs PV and 18 hrs diesel generator, (iv) 24 hours off-grid PV – battery: 6 hrs PV and 18 hrs battery. The arrangements could offer a specific energy consumption of RO desalination plant up to 7.2 kWh/m$^3$, which is excluding the power of feed pump and UF pumps. The results of the energy management in term of power vs load including the capacity of the product water in each scheme of PVRO desalination plant are seen in figure 6.

![Figure 6. Energy management on PVRO desalination plant.](image)

3.5. PVRO layout
The PVRO desalination plant is proposed to provide clean water for rural communities in the remote coastal areas, where experience a power shortage all years and limited water resources and supply. A dedicated PVRO plant was designed to be installed at coastal area which has cliffed, coral, or flat coastlines above seawater high tide level but safe of landslide. The RO plant is a containerized type in a 40 feet box to minimize space. The 100 m$^3$/day PVRO occupies a maximum of 1070.6 m$^2$ (40.4 m × 26.5 m) land area as a total of PV array area for 1-phase and 3-phase off-grid PV-battery schemes. PV array is positioned 12° tilt and cover all systems are located under the panel including containerized RO, batteries, inverters, and MPPTs. Figure 7-10 show the schematic layout picture of the PVRO 100 m$^3$/day desalination plant.

4. Conclusions
A 100 m$^3$/day PVRO seawater desalination plant has been designed to produce clean water for rural communities at remote coastal area. The RO plant has energy consumption of 7.2 kWh/m$^3$, which is provided by a maximum of 520 PV panel system and could manage four energy schemes during daytime and night operations. It is a containerized type of RO plant and equipped with 8 UF membranes and 6 element RO membrane in a unit of pressure vessel. It has recovery rate of 45% and capable to produce permeate flow with TDS of 111.8 mg/L and pH of 8.1, which complies the standard of clean water by WHO and Permenkes RI No. 32/2017. PVRO plant occupies 1070.6 m$^2$ land area and could be installed on a cliffed, coral, or flat coastlines above seawater high tide level.

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