Modeling and Optimisation of Hybrid Solar Water Desalination System in Indonesia

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Abstract

Clean water demand has significantly increased due to the rise in the global population. Only 2.5% of the total water source on the Earth is freshwater, while the remaining water has high saline content that cannot be consumed directly. Desalinated water is one of the potential solutions to meet the growing demand for freshwater, which is highly energy intensive. This paper analyses the energy, economic and environmental performance of a 5 m^3 PV (photovoltaic) powered reverse osmosis (RO) desalination system. Three scenarios of PV-RO with and without battery storage and diesel generator hybrid systems have been analyzed and investigated for the annual estimate load, net present value, and payback period of the water and electricity production costs. Concurrently, the CO_2 avoidance over the lifetime operation of the designed PV-RO desalination plant is evaluated. In this study, the analysis shows that the PV-RO system without battery 6.3 kW PV panels installed with a 2-days water storage tank system is optimized and economically feasible. The Levelized Cost of Electricity (LCOE), Levelized Cost of Water (LCOW), and Payback Period (PBP) are found to be \$0.154/kWh, \$0.627/$m^{3,}$ and five years, respectively. The CO_2 emissions avoidance by the PV-RO system without a battery was 65,152.5 kg.CO_2eq, while the optimized system could eliminate 111,690 kg.CO_2eq per year.

Keywords: Desalination, Photovoltaic, Reverse osmosis, Solar energy, Hybrid power system.

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Symbols and Abbreviations

Symbols	**Unit**	**Description**
TDS	ppm	Total Dissolved Solids
E_{load}	kWh	Daily energy required
E_{system}	kWh/m^3	The energy required per cubic meter of water production
I_{loss}	kWh	Inverter loss
Au_{loss}	kWh	Auxiliary loss
E_{tot}	kWh	Daily load profile calculated for the system
η_{BOS}	%	Balance of system efficiency
E_p	kWh	The energy produced by a panel
A	m^2	Solar panel area
H	kWh/m^2/day	Average solar radiation
PV_{req}	-	Number of panels required
η_p	%	Efficiency of panel
F_0	L/hr/kW	Fuel curve intercept coefficient
F_1	L/hr/kW	Fuel curve slope
Y_{gen}	kW	Rated capacity of the generator
P_{gen}	kW	The electrical output of the generator
DoD	%	Battery depth of discharge
η_b	%	Efficiency of battery
CF	$	Annual Cash Flow
MARR	%	Minimum Attractive Rate of Return
LCOE	$/kWh	Levelized Cost of Electricity
LCOW	$/m^3	Levelized Cost of Water
PBP	year	Payback Period
IRR	%	Internal Rate of Return
NPV	$	Net Present Value
CAPEX	$	Capital Expenditures
OPEX	$	Operating Expenditures
COD	-	The chemical oxygen demand
BOD	-	The biochemical oxygen demand
MED	-	Multiple-effect distillation
MSF	-	Multi-stage flash
RO	-	Reverse osmosis

1. Introduction

Water and energy are the essences of modern human needs. The development of any nation is highly dependent on the availability of clean water and energy. The energy is needed to produce and supply the water, so the energy demand is accelerated with the increasing demand for clean water. Like many countries, clean water scarcity is also a severe problem in Indonesia. Only 47.71% of the total population in Indonesia has proper access to clean water sources [1]. About 70% of water usage is used for agricultural purposes, with 9% for industry and 11% for domestic activities [2]. However, fossil-based energy generation, which is still the main energy source for water production and supply, has sparked global warming and climate changes. Therefore, producing clean water from the renewable energy assisted desalination process can address the water shortage challenges and reduce climate changes. There are 16,876 desalination plants operated globally, with 85% using the RO system, 270 plants under construction, and 3,825 offline plants [3]. The combination of a desalination system and renewable energy is not new and has already been implemented worldwide. Most of these renewable energy based desalination plants are driven by solar energy. Note that the solar water desalination separates salt from saline water to obtain clean water using solar energy as the power source. **Figure 1** shows the percentage of the global renewable energy based desalination plant. The solar-powered plant occupies nearly half of the total, followed by wind and geothermal.

The desalination technology can be differentiated into two types; thermal technologies such as multiple-effect distillation (MED) or multi-stage flash (MSF) and membrane processes, including reverse osmosis (RO). Thermal processes generally come with a higher capital cost and are noticeably energy intensive. On the other hand, RO technology has a lower capital cost but higher maintenance spending and is unsuitable for high salinity or poor water quality. The RO process is also easy to upgrade and requires around 25% less area than the MED. The membrane plays the most vital role in the RO process without heating or phase change. The RO membranes have a dense barrier layer which is selective for not allowing large molecules or ions through its pores but allows solvent to pass through the thick layer freely. High pressure is required for conducting the RO process, usually 2-17 bar (30-250 psi) for brackish water and 40-70 bar (600-1000 psi) for seawater [4]. Generally, the RO process consumes about 3.5 kWh/m^3 of energy for brackish water (Kaya et al., 2019) and approximately 6.99 kWh/m^3 for seawater [5]. The variation of solar energy outputs of heat or electricity lead to further considerations in designing a desalination system. In Indonesia, the combination of solar photovoltaics and reverse osmosis (PV-RO) has a high potential to be implemented. The primary energy requirement in RO is for pressurizing the feed water.

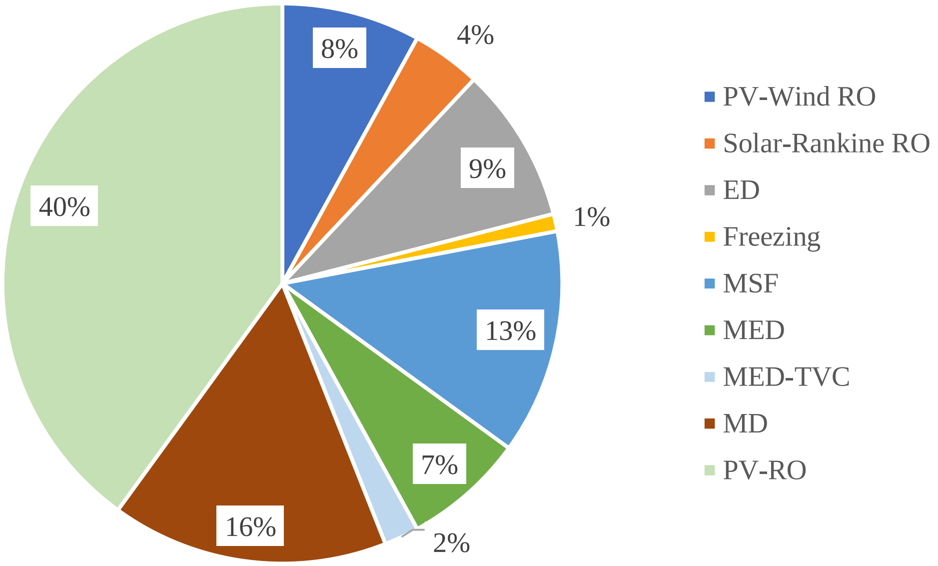

Figure 1. Desalination technologies are powered by solar energy [6]

PV technology is ideal for powering RO units, particularly in remote areas where the electricity grid is inaccessible [7]. It can either be used as a standalone or hybrid system with another energy source such as batteries, wind, and diesel engines. As a renewable source for desalination, the wind turbine has been used since the early 1980s [8]. Compared to the hybrid Diesel-PV-RO system in which the energy generation is executed by PV and transfers to diesel if the energy generated does not meet daily requirements, the PV-RO standalone system has a high capital cost but lower operating cost than the hybrid Diesel-PV-RO system. A buffer tank is usually installed to increase the productivity of the PV-RO system. This tank is used as the storage system for permeation in the range of 28% to 36% based on the pressure applied [9]. Another approach to increase productivity is by developing high capacity dual-stage plant. A study showed that a dual-stage plant with a capacity of above 5 m^3 could have a high recovery rate of 65%. In comparison, a desalination plant with a capacity below 5

m^3 was not economically feasible as increasing capacity will reduce the production costs [10]. On the other hand, the efficiency of PV systems has increased during the past decade through different methods, including solar tracking addition, tilt angle adjustment, autonomous cleaning systems, and cooling/preheating [11].

In terms of an economic view, the RO desalination process requires a relatively high capital cost, preventing its large-scale commercialization. The RO vessels consumed nearly one-third of the total cost, followed by seawater pre-treatment and electrical systems by 18.6% and 17.8%, respectively [12]. Thus, the initial stages of a desalination project need to be suitably forecasted for financial feasibility. This forecast includes the financing, permitting, operation and maintenance costs, and the environmental and social related expenses. Much of the cost component depends on the plant capacity, power generation, location, environmental conditions, feed water quality, and projected life span. The increase in feedwater's salt content would likely increase the operating costs as it requires more treatment and technologies. Generally, seawater as the feedwater to a desalination plant will probably cost five times more than brackish water as feedwater for a given size of the plant and water production. Also, more than half of the total costs of the desalination system are for thermal or electrical energy requirements to power pumps and other equipment. Thus, the PV-RO desalination plant offers exciting and affordable technology to provide clean water to the community. Also, PV-RO offers a competitive price at a lower capacity, unlike other technologies, which require large water treatment capacities to lower the cost per unit of clean water produced. Thus, leveraging financial measures for the distillation method has efficiently reduced freshwater costs.

Moreover, the environmental impact of a PV-RO desalination system would be low. Brine discharge from the desalination process is considered a significant environmental impact because it carries almost all the liquid waste. As a result, this waste affects most aquatic life, which is mainly credited to chemical components [13]. The impact of the temperature and pH of the brine is minimal as the temperature of the brine approaches the water input temperature with a maximum difference of about

2 °C in an RO system [14, 15]. In addition, renewable energy sources can reduce the possible greenhouse gas (GHG) emissions compared to that fossil energy sources.

The following specific problems have been identified in the present research work to address the opportunities and challenges of the PV-RO system in Indonesia:

- Clean water production in Indonesia is not sufficient for sustainable supply.
- A desalination system requires high energy, so finances are the primary issue.
- There is a low level of research based on technology enhancement and economic and environmental assessment of solar desalination for water production.

The overall objective of this study is to explore the potential of RO desalination with solar PV systems in Indonesia by evaluating the energy, economic and environmental impacts of the integrated renewable energy system. The proposed study investigates the performance of reverse osmosis desalination with solar energy generation by simulating different power generation scenarios. The scenarios utilize an integrated design concept for optimizing energy performance, costs, and environmental impact. The anticipated cost of production and maintenance is low since cheaper material could be used and result in significant CO_2 emission reduction to the environment.

2. Methodology

2.1 Site description and input parameters

The studied PV-RO system is assumed to be installed on Parang Island, part of Karimunjawa islands, Indonesia (5^{o}49.2'S, 110^{o}27.5'E). This selection is based on several factors: the lack of fresh water in some areas, high solar irradiance throughout the year, and lack of awareness of the health impacts of consuming brackish water from the inhabitants. Karimunjawa Islands is one of the exotic islands located in the Java Sea, specifically about 120 km north of Semarang, Java Island. The Parang island's population is approximately 10,000 inhabitants, primarily working as fishermen.

The island's topography is an undulating lowland with an altitude ranging from 0–506 meters above sea level with a total area of 71.2 km^2. The maximum daily water requirement was estimated based on consumption of 3.3 liters per day per person. Therefore, the daily water capacity for the PV-RO system is 5 m^3 per day. The total dissolved solids (TDS) assumption used in the current study is 32,000 mg/L [16].

2.2 The PV-RO Plant Design

A simplified flowsheet for the RO plant is shown in **Figure 2**. Pretreated brackish water flows to the pump with a pressure between 15 to 40 bars to be desalinated further. Permeate leaving the desalination system should have a level of TDS lower than 500 ppm to meet the drinking water criteria [17], and the reject is discharged into the discharge. Filmtec BW 2.5-inch membranes are used in the desalination process. Post-treatment includes the disinfection and mineralization process whereby the unused liquid goes to saltwater waste treatment and disposal.

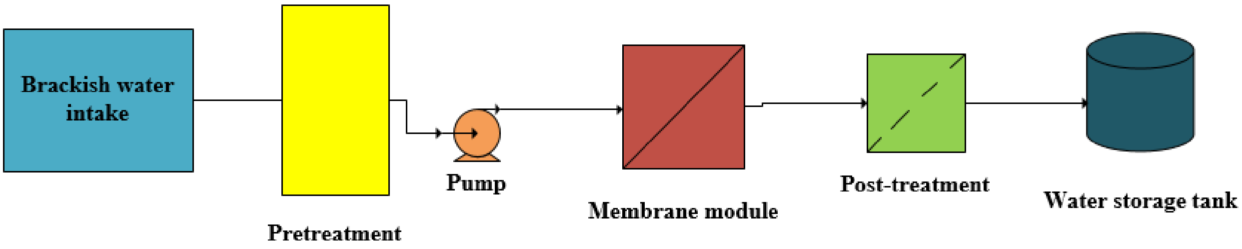

Figure 2. Process flow of RO desalination plant

This research defined three different power sources configuration to provide electricity to the desalination unit. A 5 m3 storage tank will be installed in each scenario to store produced water. The specific energy consumption of the PV-RO system studied in this work was considered to be 3.5 kWh/m^3/day [18]. The project lifetime for the PV-RO desalination plant is 20 years.

2.2.1 Batteryless PV-RO System

The first scenario of the PV-RO system is installing a standalone PV system to power the desalination without battery storage. Because of this arrangement, the plant will only produce freshwater during sunshine hours daily. The details of this scenario are shown in **Figure 3**. This primary combination is designed with a larger capacity of the PV system to produce more clean water to be stored in 5 m^3 water tanks with an additional tank to store the excess water from the system. These two tanks are installed to back up the RO system when PV is offline. This design is the best option for RO plants driven by solar power without batteries, as proposed by Kumarasamy, Narasimhan [9]. Their experimental results showed that the optimized daily production of PV-RO without a storage tank is 0.6417 m^3/day, while the optimized result for PV-RO with a storage tank is 0.8682 m^3/day to store two days of water production.

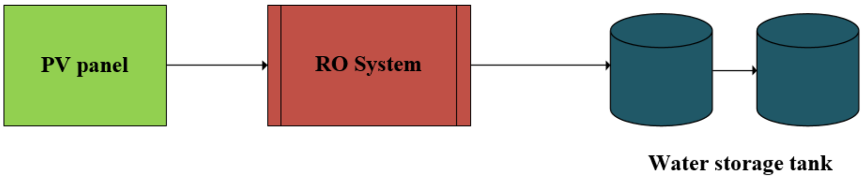

Figure 3. Process flow of batteryless PV-RO system

2.2.2 PV-RO System with Battery Storage

The second scenario of the PV-RO desalination system is configured with battery installation as an energy storage system powered by solar PV. The excess energy produced from the PV plant will be stored in the battery storage system to be used later when the solar energy is unavailable to power the RO plant. The process flow of the PV-RO system with battery storage is shown in **Figure 4**. Unlike the previous configuration, this system only uses one water tank to store the water. The battery's addition means the PV-RO works longer to meet the clean water needs.

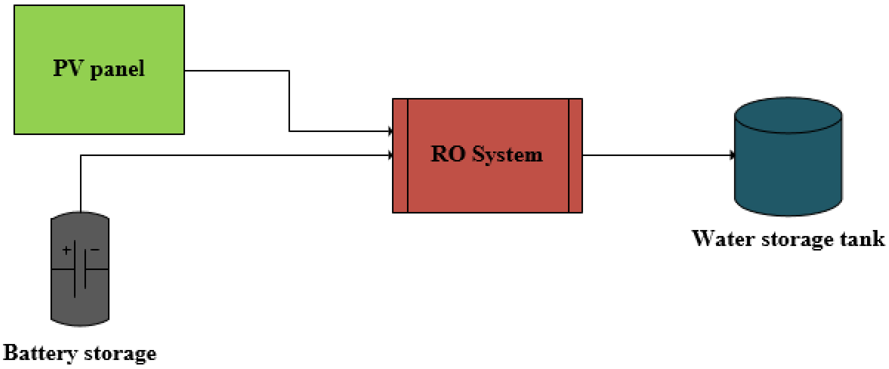

Figure 4. Process flow of PV-RO system with battery storage

2.2.3 Hybrid Diesel-PV-RO System

In the third scenario, simulation is performed for a hybrid system of PV-diesel generation to power the RO desalination plant. This plant also does not use an additional battery storage system; only one tank is used. The energy required by the PV-RO system is supplemented with the power from the diesel generator when the PV array's electrical production is insufficient. The diesel generators also act as power backup at night time and on cloudy days to power up the RO system. **Figure 5** shows the process flow of the hybrid diesel-PV-RO system. Gökçek (2018) considered this design to integrate hybrid power involving wind, solar photovoltaic, diesel, and battery for small-scale RO desalination applications.

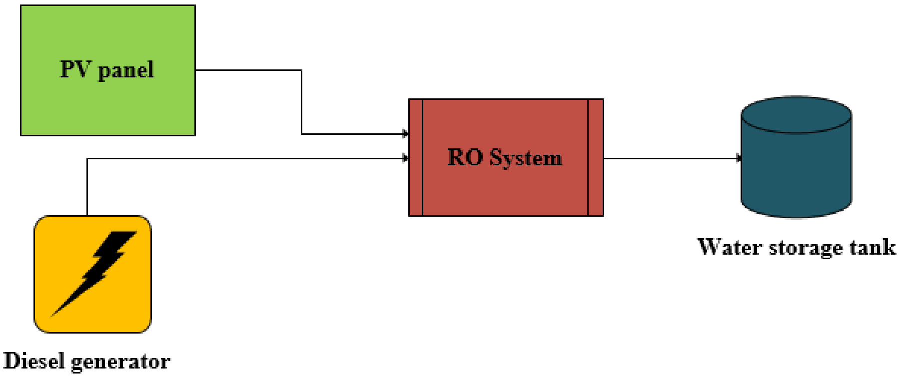

Figure 5. Process flow of hybrid diesel/PV-RO desalination system

2.3 Energy analysis

The power generation capacity from PV modules to power RO system is based on the following assumptions:

- The energy requirement for the system is 3.5 kWh/m^3.
- Inverter loss is 10% of the total daily energy requirement.
- Auxiliary load is 10% of the total energy and inverter loss.

2.3.1 PV system sizing

The daily energy required from the PV RO system plant with system losses is given in Equation (1).

$$E_{load} = (E_{system} \times V) + I_{loss} + Au_{loss} \tag{1}$$

Where E_{system} is the energy required per cubic meter of water production (kWh/m^3), V is the total volume of daily water production from the RO system (m^3), I_{loss} is inverter loss from the system (kWh), and Au_{loss} is auxiliary loss from the system (kWh). Furthermore, the calculation of total energy load, the electrical energy generation as an output of a photovoltaic system, can be calculated using Equation (2).

$$E_{tot} = {E_{load}}/{\eta_{BOS}} \tag{2}$$

Where E_{load} is the daily load profile calculated for the system (kWh) and η_{BOS} is the balance of system efficiency (%). Thus, the energy produced by a panel is given in Equation 3 as below:

$$E_p = A \times \eta_p \times H \tag{3}$$

Where A is the solar panel area (m^2) and η_p is the panel's efficiency (%), while H is the average solar radiation (kWh/m^2/day) on tilted panels where shadings are not included. The ambient temperature is assumed unchanged, so this study does not consider its effect on the PV. The number of required PV panels can be calculated using Equation (4).

$$PV_{req} = {E_{tot}}/{E_p} \tag{4}$$

Where PV_{req} is the number of panels required, E_{tot} is total daily energy required (kWh), and E_p is energy produced by the panel (kWh).

2.3.2 Diesel generator model

Hybrid power systems that combine PV systems and diesel generators are essential to ensure energy supply continuity and increase the reliability of the energy production system. Diesel generators are used in this study to back up the power of the PV arrays due to their intermittent nature. The diesel works when the output power from the renewable power unit does not meet the load demand. The following Equation (5) is to define the generator capacity.

$$E_{gen} = E_{req} \times A \tag{5}$$

Where E_{req} is the energy required (kWh), and A is the backup period for the generator design (%). Moreover, Equation (6) gives the generator's fuel consumption in L/hr as a function of its electrical output.

$$F = F_0 \times Y_{gen} + F_1 \times P_{gen} \tag{6}$$

Where F_0 is the intercept coefficient of the fuel curve (L/hr/kW), F_1 is the fuel curve slope (L/hr/kW), Y_{gen} is the generator's rated capacity (kW) and P_{gen} is the electrical output of the generator (kW). The values for $F_0 = 0.246\, L/kWh$ and $F_1 = 0.08145\, L/kWh$ [19]. The diesel fuel price is considered flat at \$0.85/L, and there is no penalty for CO_2 emission.

2.3.3 Battery sizing

As the storage system of the PV-RO system due to sunshine intermittency, battery systems are installed for energy storage and backup. The excess energy generated by PV in the peak time is used to charge the battery until it is fully charged. However, the hybrid system uses the battery to supply power within its allowable limit. Battery storage capacity is calculated in detail using Equation (7).

$$E_{battery} = {}^{E_{load} \times n}\!/_{DoD \times \eta_b \times V} \tag{7}$$

Where E_{load} is the daily load energy profile for the system (kWh), η_b is the number of autonomy days, DoD is the battery depth of discharge (%), and η is the battery efficiency (%). Ganora et al. [20] found that PV-RO battery design is considered oversizing around 5-10% higher to significantly improve the plant system, providing energy to the battery system.

2.3.4 Inverter sizing

An inverter converts the DC from PV cells to AC delivered to the RO plant. The array-to-inverter ratio is needed to determine the sizing of the inverter, which can be measured with the DC rating of the PV array divided by the maximum AC output of the inverter. The installation of the inverter generally has a ratio between 1.15 to 1.25 according to the array-to-inverter ratio. The manufacturers usually limit the ratio to 1.55 for safety and economic purposes. The more excellent output rating of the inverter should be selected for safety reasons. The inverter also should be 20-30% or more significant for safety measurements. The inverter would be more efficient if running slightly higher than the overall capacity.

2.4 Economic Analysis

Economic analysis is critical in proposing an optimal renewable generation system scenario. The economic evaluation is based on the net present value (NPV) method, which uses the difference between the current value of all costs over the life of the system and the present value of all benefits over the project's useful life.

The value of the specific capital cost of the system in this study is assumed to be \$ 1400/ (m^3/d) with the costs percentage breakdown of the RO system components capital costs listed in **Table 1**, as derived from Papapetrou, Cipollina [21]. The operating costs include membrane replacement, cost of equipment maintenance, chemicals for pre-treatment and post-treatment, insurance and labor, and energy cost [22]. The system capacity influences the cost of the RO desalination system.

Table 1. Estimation of capital cost breakdown components [21]

Capital cost components	Value (\$/(m^3/d))
RO modules (membrane elements and pressure vessels)	250
Other types of equipment (pumps, pre-treatment, and post-treatment include filtration and chemicals, power electronics, etc.)	450
Brackish water intake	100
Site preparation, installation, and infrastructure	400
Other costs (engineering, insurance, shipping and legal costs)	140
Total	**1,400**

Financial benefits are an essential aspect to be evaluated in this study whereby calculating a project's internal rate of return (IRR) and the project's return during a specific period can be determined. The

IRR is also used to evaluate the project's feasibility and compare scenarios. The IRR for 20 years of project lifetime can be computed through Equation (8) from [23].

$$NPV = \sum_{n=1}^{20} {CF}/{(1+r)^n} \tag{8}$$

Where CF is annual cash flow (\$), n is the number of years, NPV is the net present value (\$), and r is the internal rate of return (%). NPV will be set at zero to determine the value of IRR. The discounted rate and minimum attractive rate of return (MARR) are assumed to be 10%, with no inflation and depreciation considered. The calculation of cumulative cash flow is used to understand the annual economic performance at the end of the project period.

Furthermore, the profit from the first year is subtracted over capital cost to calculate the cumulative cash flow, which gives the cumulative cash flow of the first year. The result is then added to the second year's cash flow gain to get the cumulative cash flow for each year and is repeated until the last year of the project. The final results show the closing cash flow after the project ends. Accordingly, the payback period and the cumulative cash flow results can be computed using Equation (9) for the discounted payback period calculation.

$$PBP = A + {B}/{C} \tag{9}$$

Where A is the year with a negative discounted cumulative cash flow (year), B is the cumulative discounted cash flow in the year before recovery (\$), and C is the discounted cumulative cash flow in the year after recovery (\$).

Next, the Levelised Cost of Energy (LCOE) is defined as a value to assess the energy cost over the lifetime of the project. This LCOE calculates the present value of the total price per unit of electricity generated throughout the project life. Additionally, LCOE allows the comparison of different energy resources. It can be alternatively said that LCOE is the minimum price at which the electricity generated by the project is required to be sold over the total lifetime production costs. The following Equation (10) is used to calculate the LCOE.

$$LCOE = {C_{ann,tot}}/{E_{gen}} \quad (10)$$

Where $C_{ann,tot}$ is the total of the costs annualized for the power system source ($/year) and E_{ser} is the total electricity generated per year (kWh/year).

Furthermore, the Levelised Cost of Water (LCOW) needs to be considered. The LCOW defines the cost per unit volume of water produced by a water treatment process. Lower values represent a more efficient method as the value measures efficiency. The LCOW can be computed by using the following Equation (11).

$$LCOW = {CAPEX + OPEX}/{W_{tot}} \quad (11)$$

Where $CAPEX$ define capital expenditure ($), $OPEX$ as operating and maintenance expenditure ($) and W_{tot} is the total water production (m^3).

2.5 Environmental Analysis

Environmental analysis is vital in proposing a power generation project to monitor pollutants and other chemicals in the atmosphere, water, and other parameters. This section will calculate and tabulate the CO2 emission for each scenario. For solar PV plant, the avoidance emission could be computed from Equation (12).

$$CO_2\,PV = E \times e_{elec} \times t \quad (12)$$

Where E is the estimated annual energy generation (kWh), e_{elec} is the generic emission factor of electricity for CO_2 (kg/kWh), and t is the project lifetime (years). The generic emission factor of CO_2 is 0.6 kg/kWh CO_2, which the Indonesian Ministry of Energy and Mineral Resources provides. On the other hand, for hybrid diesel and PV energy generation, CO_2 emission reduction can be obtained by multiplying avoidance emissions from PV and emissions produced from the diesel generator. The formula for calculating diesel emission can be seen in Equation (13).

$$CO_2\,diesel = E \times e_{diesel} \times t \quad (13)$$

Where E is the estimated annual energy generation (kWh), e_{diesel} is the CO_2 emission factor of diesel fuel (kg/kWh), and t is the project lifetime (years). The CO_2 emission factor of diesel fuel is 0.267 kg/kWh [24].

3. Results and Discussion

The basic assumption for this study is the PV-RO system has a maximum total water capacity of 5 m^3 per day with a daily energy requirement of 3.5 kWh/ m^3. Then, the theoretical daily energy requirement for the system is found to be 21.25 kWh/day, including inverter losses and auxiliary loads. The total daily energy requirements for the PV-RO unit involving the auxiliaries are computed and summarized in Table 2.

Table 2. The energy needs of the system

Type of load	Maximum power energy needs	
Energy requirement	3.5	kWh/m^3
Total water capacity	5	m^3/ day
RO daily requirement	17.5	kWh/day
RO load, including inverter losses (10%)	19.25	kWh
Auxiliary loads	2	kWh
Total energy	21.25	kWh

The PV system sizing calculation must consider the solar irradiation, sunshine hours, and site temperature. The solar irradiation and clearness index radiation are illustrated in **Figure 6**. The clearness index represents a measurement of the clearness of the atmosphere in which the solar radiation factor is transmitted through the atmosphere to reach the Earth's surface. **Figure 6** shows an increasing pattern from January to September, then decreasing in the remaining month. The monthly radiation in the Karimunjawa islands ranges from 4.03 kWh/m^2 to 6.59 kWh/m^2, with the highest radiation in September and the lowest in December. The average annual radiation is 5.23 kWh/m^2. Meanwhile, the clearness index shows a range between 0.382 to 0.645. The index goes the highest value in September, while December is the lowest. The average peak of sunshine hours and daily temperature are shown in **Figure 7** and **Figure 8**, respectively.

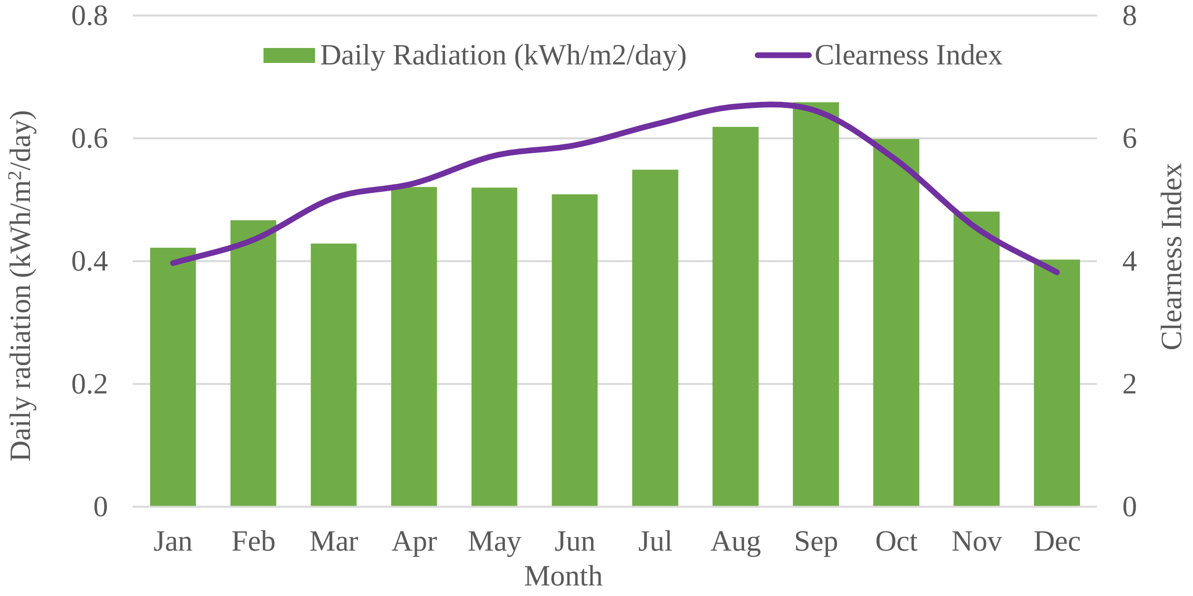

Figure 6. Monthly radiation and clearness index profile

Five sunshine hours are used as the optimum and annual average peak to optimize the design of the PV-RO system. **Figure 7** depicts the average monthly sunshine hours within the range of 4.5 to 6.5 hours as the highest throughout the year. Likewise, **Figure 8** represents the average temperature for every month, ranging from 27.08 to 28.26 °C. The highest temperature is in June, and the lowest one is in August. The temperature is relatively stable throughout the year, with an average of 27.61 °C in the Karimunjawa islands.

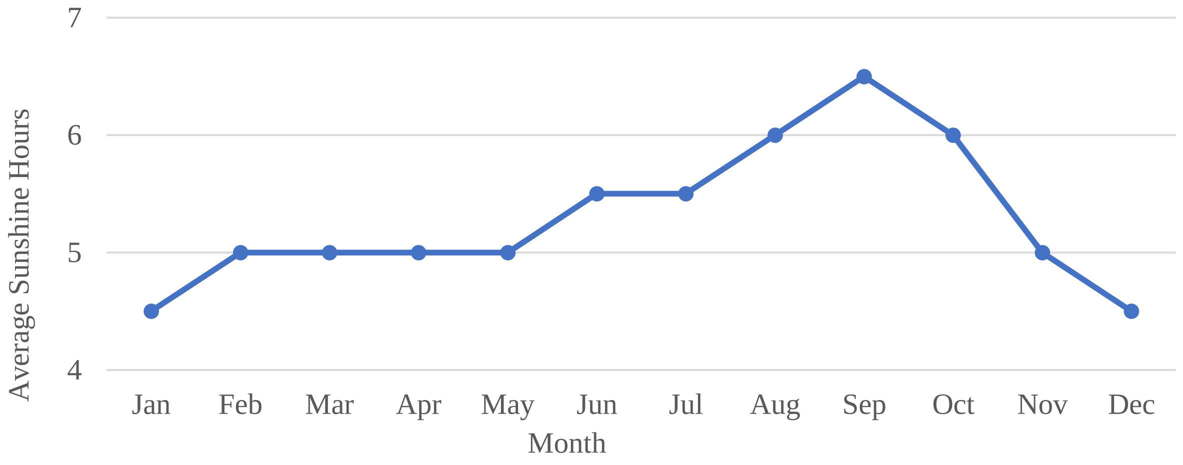

Figure 7. Monthly average sunshine hours

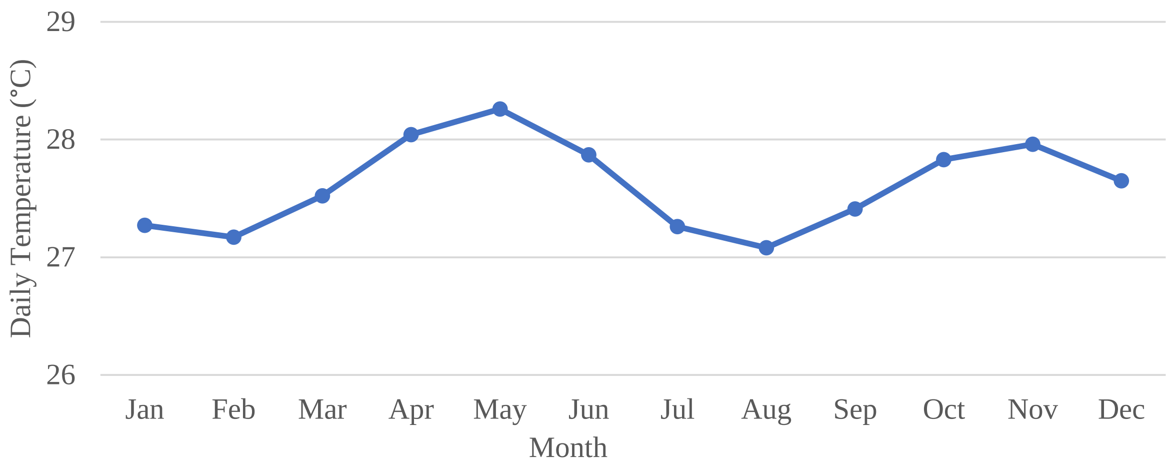

Figure 8. Monthly average daily temperature

3.1 Batteryless PV-RO System

In this scenario, energy generation is entirely driven by a PV system, so the energy consumption obtained from the designed RO plant is used to develop the PV requirement. The PV system is designed to have enough energy to supply the operation of the RO plant. The required PV panels are estimated based on the energy required to operate pressure pumps in the RO plant.

The capacity of the PV modules is designed so that all the water demand is produced during sunshine for about 8 hours, as this scenario did not have any backup system. Thus, the PV plant is designed to have a 20% bigger size than the typical daily energy requirement. The optimal size for the PV array is 6.3 kW, obtained from the calculation in Equation 2. Polycrystalline solar panels of LONGi LR6-72HV-350M from LONGi Solar are selected for this system, with the power rating of each module being 350 W. The power output of the PV array is a function of the average solar irradiation and the sunshine hours in Parang Island as 5 hours.

Further, a grid-tied inverter is required to connect the PV panel's DC output to the grid's AC power. Thus, a bi-directional inverter is connected between battery and load for DC/AC conversion and battery charging when there is low power from PV. Adding this inverter requires several string inverters for the PV string array. The advantages of the string inverter are reducing the combiner box and easier troubleshooting and system monitoring. In case of inverter failure, only a tiny part of the production will be lost. The inverter model of Schneider Conext XW+ 8548 E has been chosen in this study with optimal efficiency of 96%. The technical parameters for PV, converter, and battery considered in this RO design are shown in **Table 3**.

Table 3. Technical parameters for Scenario 1

PV		Converter	
Factors	**Value**	**Factors**	**Value**
Model	LONGi LR6-72HV-350M	Model	Schneider Conext XW+ 8548 E
Maximum power	350 W	Lifetime	15 years
Dimensions (L*W*H)	1956×991×45 mm	Efficiency	96%
Module efficiency	18.1%	Output power	7000 W
Derating factor	90%	Input DC voltage range	40 to 64 V (43 V nominal)
Lifetime	25 years	Maximum input DC current	180 A

The calculated energy generation from the PV system can be seen in **Figure 9**. The designed PV system has a 20% bigger size than the daily energy load to ensure enough electricity to power the RO system. **Figure 9** shows that the PV output ranges between 5.09 kW to 8.32 kW, with the lowest month in December and the highest in September. This scenario does not install a battery or diesel system. The additional tank is installed to store the overproduction of water and used during uncertain weather later.

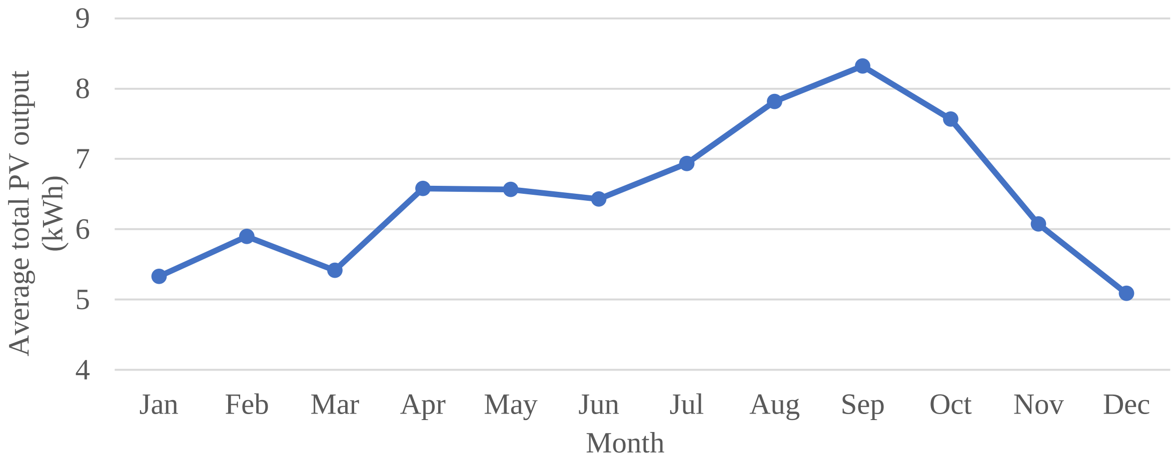

Figure 9. Energy generation from PV system for Scenario 1

This study presents the economic analysis for three different scenarios compared to the standalone diesel-powered RO system. From an economic point of view, using an RO plant and PV system together could reduce desalinated water costs. **Table 4** represents the financial data for the power system considered.

Table 4. Economic parameters for Scenario 1

No	System component	Unit	Price
1.	**RO plant**		
	Capital cost	$	7,500.00
	Operation and maintenance	$/year	350
	Projected lifetime	year	20
2.	**PV unit**		
	Capital cost	$/unit	350.00
	Operation and maintenance	$/year	10.00
3.	**Converter**		
	Capital cost	$/unit	1,500.00
	Replacement cost	$/unit	1,300.00
	Operation and maintenance	$/year	10

A cash flow diagram visually represents income and expenses over some project lifetimes is required to analyze the economic impact further. The details of the cash flow diagram of Scenario 1 are given as detailed in **Figure 10**, where the downwards arrow defines the cost associated with the project or negative cash flow and upwards arrow C for the positive cash flow. In **Figure 10**, the capital cost is symbolized by C, while C1 is the O&M cost during the project lifetime, which shows the same value, and C2 is the replacement of equipment costs. The first and second replacements will be in the years 5 and 10 for auxiliaries, where replacement in year 15 is for auxiliaries and converter. There is R for revenue or profit the project will obtain annually on the positive cash flow side. Thus, under Scenario 1, using the discounted rate of 10%, each component cost is broken down in Table 5 shows three cost components: the RO system, the PV panel, and the converter. More than 80% of the total costs associated with the RO system include auxiliaries, while the other 20% are from PV panel and converter costs. Scenario 1 resulted in a total NPV of $ 21,143.1.

Table 5.

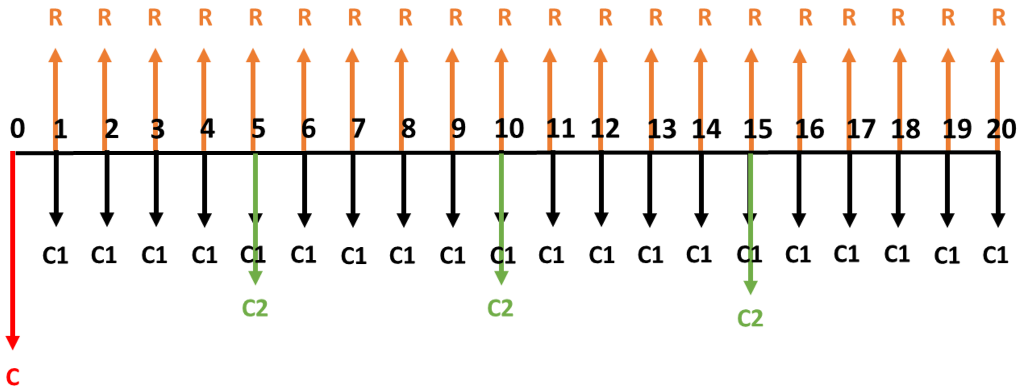

Figure 10. Cash flow diagram of Scenario 1

Table 5 shows three cost components: the RO system, the PV panel, and the converter. More than 80% of the total costs associated with the RO system include auxiliaries, while the other 20% are from PV panel and converter costs. Scenario 1 resulted in a total NPV of $ 21,143.1.

Table 5. Net present value of each component for Scenario 1

Component	Capital	Replacement	O&M	Total
RO system	$ 7,500.00	934.35	2,979.90	11,414.25
PV panel	$ 6,300.00		1,532.52	7,832.52
Converter	$ 1,500.00	311.22	85.14	1,896.36
			Total NPV	**21,143.1**

Further, the details of economic performance for Scenario 1 are given in **Table 6** to depicts the annual cash flow of the project involving capital cost, operation and maintenance (O&M) cost, replacement cost, annual savings, and annual profit. The capital cost is $ 24,900.00, with a yearly O&M cost of $ 690.00. There are two replacement costs: auxiliary replacement accounted for every five years and converter replacement in year 15. With the amount of energy generation from PV, the annual saving was $ 2326.88 per year from diesel savings. Meanwhile, yearly profit was taken from drinking water sold to the inhabitants.

Table 6. Annual economic performance of Scenario 1 in USD ($)

Year	Capital cost	O&M	Replacement cost	Annual saving	Annual profit	Cash flow	Cumulative cash flow
0	15,300.00					15,300.00	-15,300.00
1		540.00		2,326.88	1,775.65	3,562.53	-11,737.48
2		540.00		2,326.88	1,775.65	3,562.53	-8,174.95
3		540.00		2,326.88	1,775.65	3,562.53	-4,612.43
4		540.00		2,326.88	1,775.65	3,562.53	-1,049.90
5		**540.00**	**750.00**	**2,326.88**	**1,775.65**	**2,812.53**	**1,762.63**
6		540.00		2,326.88	1,775.65	3,562.53	5,325.15
7		540.00		2,326.88	1,775.65	3,562.53	8,887.68
8		540.00		2,326.88	1,775.65	3,562.53	12,450.20
9		540.00		2,326.88	1,775.65	3,562.53	16,012.73
10		540.00	750.00	2,326.88	1,775.65	2,812.53	18,825.25
11		540.00		2,326.88	1,775.65	3,562.53	22,387.78
12		540.00		2,326.88	1,775.65	3,562.53	25,950.30
13		540.00		2,326.88	1,775.65	3,562.53	29,512.83
14		540.00		2,326.88	1,775.65	3,562.53	33,075.35
15		540.00	2,050.00	2,326.88	1,775.65	1,512.53	34,587.88
16		540.00		2,326.88	1,775.65	3,562.53	38,150.40
17		540.00		2,326.88	1,775.65	3,562.53	41,712.93
18		540.00		2,326.88	1,775.65	3,562.53	45,275.45
19		540.00		2,326.88	1,775.65	3,562.53	48,837.98
20		540.00		2,326.88	1,775.65	3,562.53	52,400.50

After calculating cumulative cash flow, the simple payback period and discounted payback period are given in year 6 of the project lifetime. Hence, to determine the system's energy and water cost, LCOE for Scenario 1 is $ 0.154/kWh, with the LCOW of $ 0.627/m^3. This result is slightly lower than the study by Subedi [25] for the solar-powered RO desalination system analysis. He presented a design to produce 12 m^3 of water per day, and the water desalination cost from the PV-RO plant was estimated to be around $0.67/$m^3$.

Furthermore, for the environmental aspect, it is essential to switch fossil fuels with renewable energy resources to decrease the carbon footprint and greenhouse gas emissions. The use of solar energy as a source of electricity in an RO plant consequently saves fossil fuel. This study examined the operational emissions of the hybrid power system and did not compute associated emissions with the production of the equipment used. Since the study only measures emissions generated by diesel generators in the hybrid power generation, Scenario 1 considered not emitting any pollutants because renewable sources power 100% of the operation.

However, this scenario's annual CO_2 emission reduction can be computed with the 111,690 kg CO_2 equivalent and 20 years project lifetime based on the Indonesian electricity emission factor or about six metric tons per annum. This figure is lower than the finding by Subedi [25], which estimated to save approximately ten metric tons of CO_2 per annum. This difference in results is mainly due to the different sizing systems. Subedi [25] analyzed a PV-RO system with a capacity of 12 m^3, while the present study calculated it for a capacity of 5 m^3. In contrast, this result is consistent with the previous statement that the sizing system will affect the overall analysis, resulting in economic and environmental benefits.

3.2 PV-RO System with Battery Storage

This second scenario has an energy configuration of a PV system as the primary energy generation source and battery storage as a backup system when sunshine is unavailable during certain times. The total energy required for Scenario 2 was found to be 5.25 kW on the PV array. This project selects Polycrystalline solar panels of LONGi LR6-72HV-350M from LONGi Solar with an efficiency of up to 18.1%. As the storage system, battery type selection will affect the designed system lifetime depending on the number of operation cycles. The battery type considered is a 12 V lead-acid battery of Discover 12VRE-3000TF for this PV-RO system design because of its reasonable cost. To convert DC to AC load, the inverter model of Schneider Conext XW+ 7048 E has been chosen in this study with output rated AC power 6000 W with optimal efficiency of 96%. To sum up, the technical parameters for PV, converter, and battery considered in this RO design are shown in **Table 7**, while the renewable generation can be seen in **Figure 11**.

Table 7. Technical parameters for Scenario 2

PV		**Battery**	
Factors	**Value**	**Factors**	**Value**
Model	LONGi LR6-72HV-350M	Model	Discover 12VRE-3000TF
Maximum power	350 W	Nominal voltage	12 V
Dimensions (L*W*H)	1956×991×45 mm	Nominal capacity	3.11 kWh
Module efficiency	18.1%	Maximum capacity	220 Ah
Derating factor	90%	Capacity ratio	0.563
Lifetime	25 years	Maximum charge current	43 A
Converter			
Factors		**Value**	
Model		Schneider Conext XW+ 7048 E	
Lifetime		15 years	
Efficiency		96%	

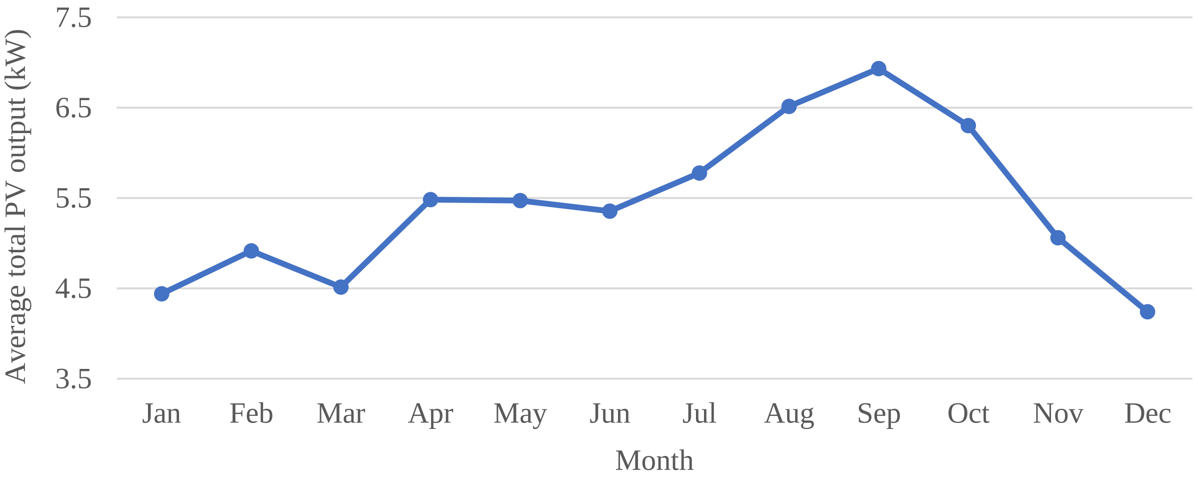

Figure 11. Energy generation from PV system for Scenario 2

As shown in **Figure 11**, the energy output from the PV system started from 4.24 kWh in December and increased slightly until September, delivering the highest energy generation of 6.93 kWh. The remaining month shows a decreasing pattern up to the lowest energy produced in December of 4.24 kWh due to the daily solar radiation throughout the year. Ganora, Hospido [20] stated that this energy created is enough for energy storage options for PV-RO desalination. They found that the average energy requirement for PV-RO with batteries is approximately 3.3 kWh/m^3. This comparison shows that the proposed system required reasonably higher energy. However, a similar finding is reported by Karimanzira [26] in the research of wind-powered RO desalination plants that a system that uses energy storage and optimization requires at least a specific Energy of 6.34 KWh/m^3. In addition, using an RO plant and PV system together reduces desalinated water costs. This study presents the economic analysis for three different scenarios compared to RO powered by a diesel generator. **Table 8** represents the financial data for the power system considered, while the system cash flow diagram is detailed in **Figure 12** to provide more detail on the annual cost.

Table 8. Economic performance of Scenario 2

No	System component	Unit	Price
1.	**RO plant**		
	Capital cost	$	7,000.00
	Operation and maintenance	$/year	350
	Projected lifetime	year	20
2.	**PV unit**		
	Capital cost	$/unit	350.00
	Operation and maintenance	$/year	10.00
3.	**Batteries**		
	Capital cost	$/unit	300.00
	Operation and maintenance cost	$/unit/year	5.00
	Replacement cost	$/unit	300.00
4.	**Converter**		
	Capital cost	$/unit	1400.00

No	System component	Unit	Price
	Replacement cost	$/kW	1300.00
	Operation and maintenance	$/year	10

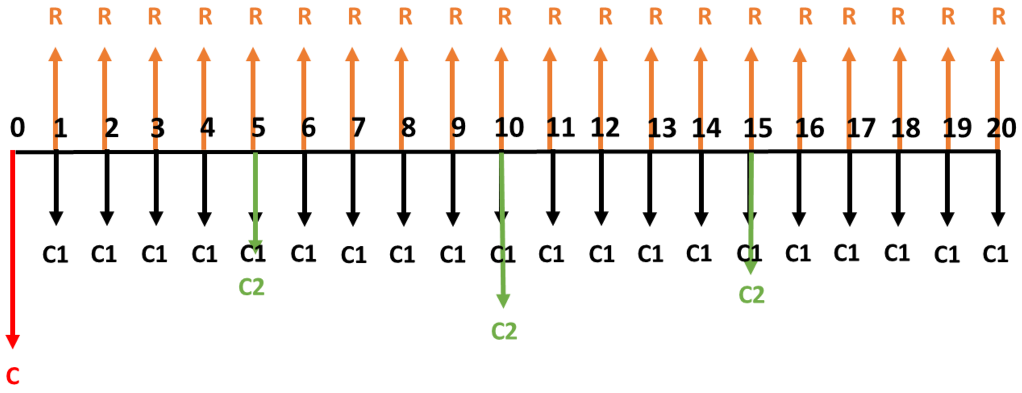

Figure 12. Cash flow diagram of Scenario 2.

The diagram presents opposite arrows that define a negative value or cost for the downside arrow and a positive value or revenue for the upside arrow. A negative value represents all costs during useful project life, including capital cost (C) at the beginning year, annual O&M costs (C1), and replacement which takes place in the years 5, 10, and 15 (C2). This project has the same revenue or profit (R), shown by an upwards arrow. Hence, each component cost can be breakdown using a discounted rate of 10% in **Table 9**.

Table 9. Net present value of each component for Scenario 2.

Component	Capital	Replacement	O&M	Total
RO system	7,000.00	872.06	2,979.90	10,851.96
PV panel	5,250.00		1,277.10	6,527.10
Battery	3,720.00	2,309.75	510.84	6,346.08
Converter	1,400.00	1,300.00	85.14	2,785.14
			Total NPV	**26,510.28**

As shown in **Table 9**, there are four components: costs of RO system, PV panel, battery, and converter. Each part consists of capital, replacement, and operation and maintenance costs, and all expenses are considered to net present value. The highest cost was found for the RO system at $

10,851.96, while the PV panel and battery costs slightly differ between $ 6,527.10 and $ 6,346.08, respectively. The converter was the least cost that was accounted for $ 2,785.14. In total, the net present value for Scenario 2 was $ 26,510.28. This cost agrees with the study by Ganora, Hospido [20] that a PV-RO desalination plant equipped with batteries and reservoir storage has about 1.2 times higher investment costs. Accordingly, the details of economic performance for Scenario 2 are given in **Table 10**. It can be seen that the payback period for Scenario 2 will be around six years. However, the IRR shall also be computed as a guideline for proceeding with a project or investment. IRR for this scenario is 15.92%, LCOE is $ 0.174/kWh, and LCOW of $ 0.686/m^3.

Table 10. Annual economic performance for Scenario 2 in USD ($).

Year	Cost	O&M	Replacement cost	Annual saving	Annual profit	Cash flow	Cumulative cash flow
0	17,250.00					17,250.00	17,250.00
1		570.00		2,326.88	1,668.63	3,425.50	13,824.50
2		570.00		2,326.88	1,668.63	3,425.50	10,399.00
3		570.00		2,326.88	1,668.63	3,425.50	-6,973.50
4		570.00		2,326.88	1,668.63	3,425.50	-3,548.00
5		570.00	700.00	2,326.88	1,668.63	2,725.50	-822.50
6		**570.00**		**2,326.88**	**1,668.63**	**3,425.50**	**2,603.00**
7		570.00		2,326.88	1,668.63	3,425.50	6,028.50
8		570.00		2,326.88	1,668.63	3,425.50	9,454.00
9		570.00		2,326.88	1,668.63	3,425.50	12,879.50
10		570.00	4,300.00	2,326.88	1,668.63	-874.50	12,005.00
11		570.00		2,326.88	1,668.63	3,425.50	15,430.50
12		570.00		2,326.88	1,668.63	3,425.50	18,856.00
13		570.00		2,326.88	1,668.63	3,425.50	22,281.50
14		570.00		2,326.88	1,668.63	3,425.50	25,707.00
15		570.00	2,000.00	2,326.88	1,668.63	1,425.50	27,132.50
16		570.00		2,326.88	1,668.63	3,425.50	30,558.00
17		570.00		2,326.88	1,668.63	3,425.50	33,983.50

Year	Cost	O&M	Replacement cost	Annual saving	Annual profit	Cash flow	Cumulative cash flow
18		570.00		2,326.88	1,668.63	3,425.50	37,409.00
19		570.00		2,326.88	1,668.63	3,425.50	40,834.50
20		570.00		2,326.88	1,668.63	3,425.50	44,260.00

From the environmental view, this scenario does not produce any emissions during operation time because it has fully solar-driven energy generation. However, CO_2 emission reduction can be computed from the electricity emission factor of using fossil fuels. This PV-RO configuration avoided 93,075 kg CO_2 equivalent emission to the atmosphere.

3.3 Hybrid Diesel-PV-RO System

The last scenario is the hybrid diesel-PV-RO plant with a daily capacity of 5 m^3/day. The PV model is LONGi LR6-72HV-350M, with 12 panels with a total capacity of 4.2 kW, while the diesel generator power output is 5 kW with total fuel consumption of 963.6 L/year. The diesel generator of Generac GP5000 is used to back up the PV array system. The Schneider Conext SW4048 is also used in this configuration with a capacity of 4000 W and an efficiency of 94%. The technical parameters for PV, converter, and battery considered in this RO design are shown in **Table 11**, while the annual energy generation is estimated in **Figure 13**.

Table 11. Technical parameters for Scenario 3.

PV		**Diesel Generator**	
Factors	Value	Factors	Value
Model	LONGi LR6-72HV-350M	Model	Generac GP5000
Maximum power	350 W	Lifetime	10 years
Open circuit voltage (Voc/V)	46.9	AC rated output	5000 W
Short circuit current (Isc/A)	9.68	**Converter**	
Dimensions (L*W*H)	1956×991×45 mm	Factors	Value

PV		**Diesel Generator**	
Factors	Value	Factors	Value
Module efficiency	18.1%	Model	Schneider Conext SW4048
Derating factor	90%	Lifetime	15 years
Lifetime	25 years	Efficiency	95%

Less solar irradiance in September and October results in high consumption from the diesel generator. **Figure 13** illustrates the energy output of the PV system by monthly average data. The total energy lies within the range of 3.39 to 5.54 kW. However, the average total generator output shown in **Figure 14** is between 0.20 kW to 1.86 kW. The highest production lies in December while the lowest is in September, opposite the solar PV output. This result agrees with the study by Gökçek [27] for RO powered by hybrid wind, solar photovoltaic, diesel, and battery. In this study, water production capacity was 24 m^3/day with an energy requirement of 4.38 kWh/m^3. This energy consumption is still relatively high even with the advantages of reliable operation. This system can be optimized further by changing the design and setting the maintenance and production schedule proposed by Al-Obaidi, Rasn [17], which achieves a low energy consumption of as low as 3,755 kWh/m3.

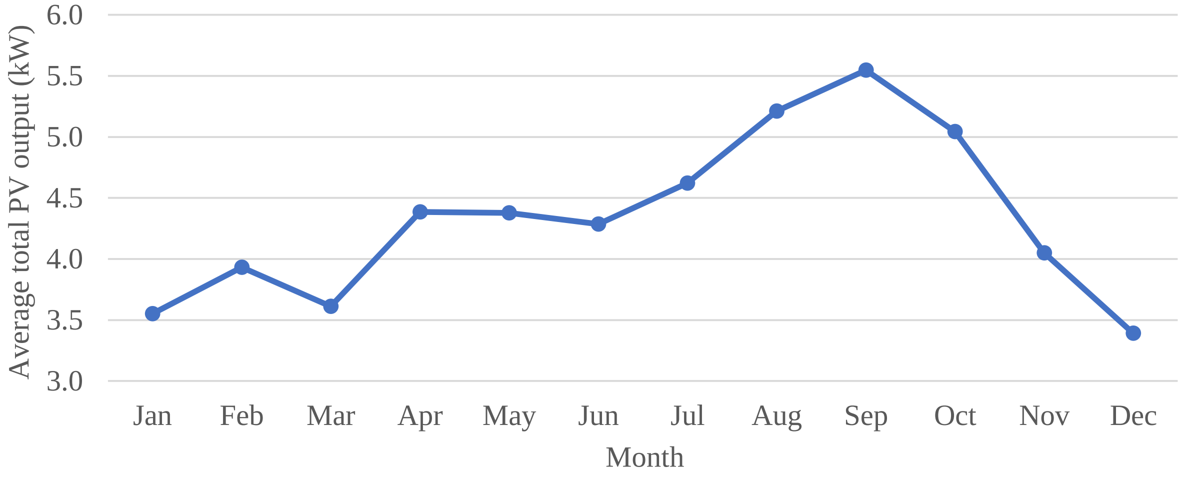

Figure 13. Energy generation from PV system for Scenario 3

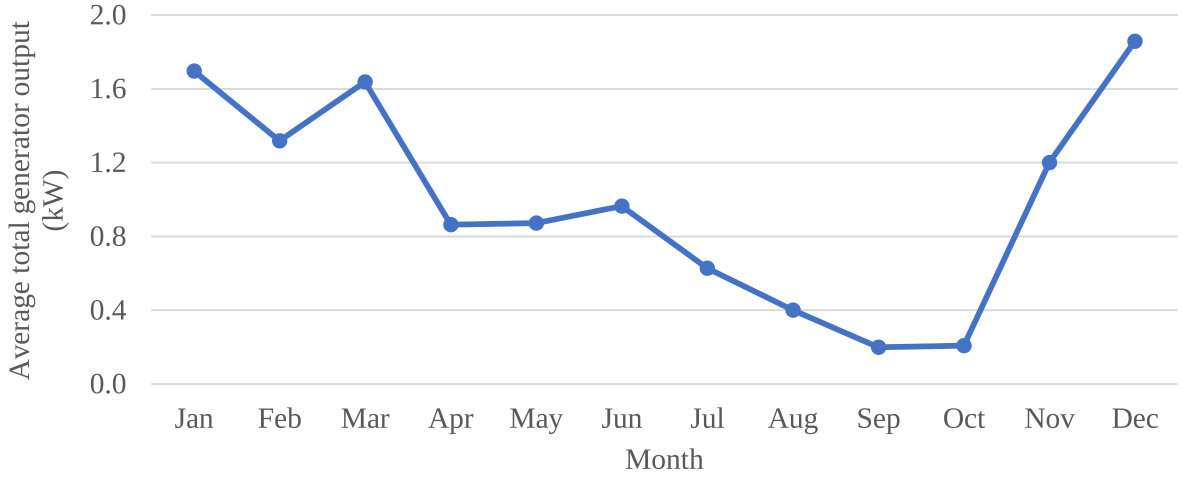

Figure 14. Energy generation from diesel generator for Scenario 3

The details of each cost associated are needed to analyze the economic impact of Scenario 3. **Table 12** gives details of financial data for the power system considered, while the cash flow diagram of Scenario 3 is detailed in **Figure 15**.

Table 12. Economic parameters for Scenario 3.

No	System component	Unit	Price
1.	**RO plant**		
	Capital cost	$	7,000.00
	Operation and maintenance	$/year	350
	Projected lifetime	year	20
2.	**PV unit**		
	Capital cost	$/unit	350.00
	Operation and maintenance	$/year	10.00
3.	**Diesel generator**		
	Capital cost	$/unit	1,200.00
	Replacement cost	$/unit	1,200.00
	Operation and maintenance	$/hour	0.030
	Diesel fuel price	$/L	0.85
4.	**Converter**		
	Capital cost	$/unit	1,200.00

No	System component	Unit	Price
	Replacement cost	$/unit	1,200.00
	Operation and maintenance	$/year	10

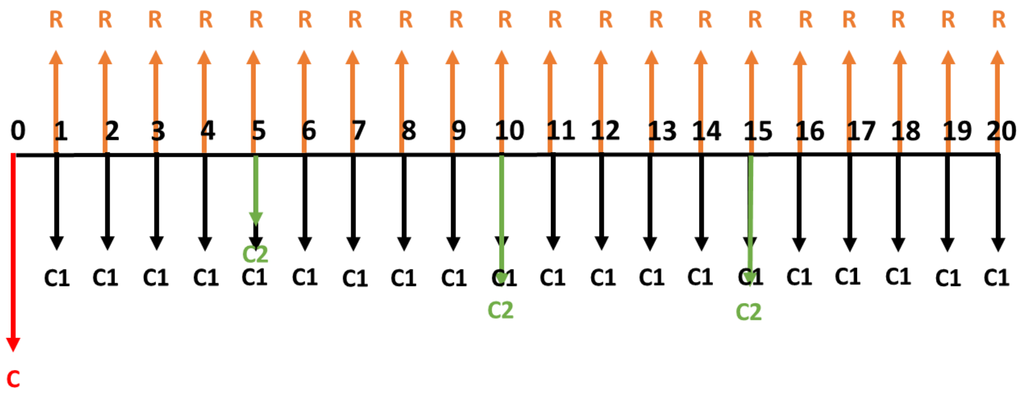

Figure 15. Cash flow diagram of Scenario 3.

As shown in **Figure 15**, cash out consists of capital, annual operating, and replacement costs for auxiliaries every five years, and converter and generator replacement. Cash in is expected to be a constant revenue throughout the project lifetime. Correspondingly, using a discounted rate of 10%, each component cost is broken down in **Table 13**. PV panel and converter costs accounted for 15% of the total NPV for Scenario 3 of $ 26,377.99. It can be seen in **Table 13** that the highest cost is contributed by the RO system of $ 10,851.96, followed by a generator.

Table 13. Net present value of each component for Scenario 3

Component	Capital	Replacement	O&M	Total
RO system	7,000.00	872.06	2,979.90	**10,851.96**
PV panel	4,200.00	-	1,021.68	**5,221.68**
Generator	1,200.00	-	6,619.21	**7,819.21**
Converter	1,200.00	1,200.00	85.14	**2,485.14**
			Total NPV	**26,377.99**

The diesel generator has a low capital cost, but a significant fuel cost increases the total generator cost by up to $ 7,819.21. Further, the details of economic performance for Scenario 3 are given in

Table 14. The discounted payback period was found in year 7 of the project, while IRR for this scenario was found to be 13.42%. Therefore, Scenario 3 generates a value of \$ 0.165/kWh for LCOE and \$ 1.036/m^3 for LCOW. This result is way lower than the previous study by Gökçek [27] that the PV-wind-diesel hybrid system had a reasonable electricity cost with a value of \$0.308/kWh.

Table 14. Annual economic performance of Scenario 3

Year	Cost	O&M	Replacement cost	Annual saving	Annual profit	Cash flow	Cumulative cash flow
0	13,600.00					13,600.00	-13,600.00
1		-1,353.81		2,326.88	1,028.99	2,002.06	-11,597.95
2		-1,353.81		2,326.88	1,028.99	2,002.06	-9,595.89
3		-1,353.81		2,326.88	1,028.99	2,002.06	-7,593.84
4		-1,353.81		2,326.88	1,028.99	2,002.06	-5,591.78
5		-1,353.81	700.00	2,326.88	1,028.99	1,302.06	-4,289.73
6		-1,353.81		2,326.88	1,028.99	2,002.06	-2,287.67
7		-1,353.81		2,326.88	1,028.99	2,002.06	-285.61
8		**-1,353.81**		**2,326.88**	**1,028.99**	**2,002.06**	**1,716.44**
9		-1,353.81		2,326.88	1,028.99	2,002.06	3,718.50
10		-1,353.81	1,900.00	2,326.88	1,028.99	102.06	3,820.55
11		-1,353.81		2,326.88	1,028.99	2,002.06	5,822.61
12		-1,353.81		2,326.88	1,028.99	2,002.06	7,824.66
13		-1,353.81		2,326.88	1,028.99	2,002.06	9,826.72
14		-1,353.81		2,326.88	1,028.99	2,002.06	11,828.77
15		-1,353.81	1,900.00	2,326.88	1,028.99	102.06	11,930.83
16		-1,353.81		2,326.88	1,028.99	2,002.06	13,932.88
17		-1,353.81		2,326.88	1,028.99	2,002.06	15,934.94
18		-1,353.81		2,326.88	1,028.99	2,002.06	17,936.99
19		-1,353.81		2,326.88	1,028.99	2,002.06	19,939.05
20		-1,353.81		2,326.88	1,028.99	2,002.06	21,941.10

The diesel generator is a hybrid power system to power the RO plant if solar sources are unavailable in this scenario. However, the diesel generator operation will emit CO_2, CO, SO_2, NO_x, unburned hydrocarbons, and particulate matter. This study has examined the CO_2 emission produced by the generator as the operational emissions of the hybrid power system but did not compute associated emissions with the production of the equipment used. With the assistance of PV generation, this system can save 65,152 kg.CO_2eq of carbon dioxide emission to the atmosphere. Nevertheless, power generation usage also emits such amount of carbon dioxide. With a diesel emission factor of 0.267 kg/kWh, the average total energy requirement of 6.375 kWh/day may produce 12,425 kg.CO_2eq. Total emission reduction is the subtraction number of avoidance electricity and diesel emission. Thus, carbon dioxide emission of 52,727 kg.CO_2eq can be avoided using this configuration system.

3.4 Comparison Between Scenarios

The primary energy generation for three different scenarios comes from the PV system. The average monthly output is compared in **Figure 16**. As illustrated in **Figure 16**, three scenarios have a similar pattern. Each configuration system requires the same amount of energy to run the desalination system in the condition of having the same solar exposure.

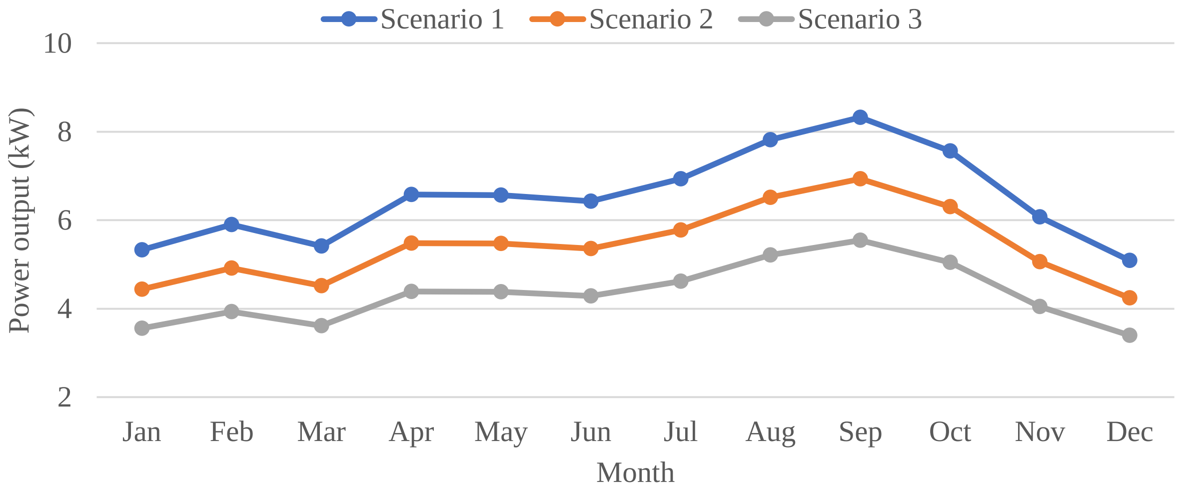

Figure 16. Comparative energy performance among scenarios

However, the first two scenarios have 100% renewable penetration, while Scenario 3 has a hybrid system with a diesel generator. Scenario 1 has a 6.3 kW PV array, the highest among the three. As a result, it produces substantial power throughout the year. Following Scenario 2, which has a 5.25 kW PV array and energy ranges from 4.24 to 6.93 kW. The least amount of energy produced from PV is from Scenario 3 in a 3.5 kW PV configuration, in which a diesel generator assists in creating enough power.

After determining the economic performance for each scenario, an NPV comparison is presented in **Figure 17** to analyze the economic impact of each project. According to the results, Scenario 3 has the lowest capital cost at $ 13,600.00. However, in the case of diesel generator assisted, the fuel price significantly affects the economy, which generates the highest O&M costs among scenarios of up to $ 11,526.34. In Scenario 2, the PV coupled with the battery storage system has the most increased capital cost of $ 17,250.00 due to battery installation. Likewise, the replacement cost was also highest at $ 4,407.30 as the batteries that contribute considerable cost need to be replaced in the middle of the project lifetime.

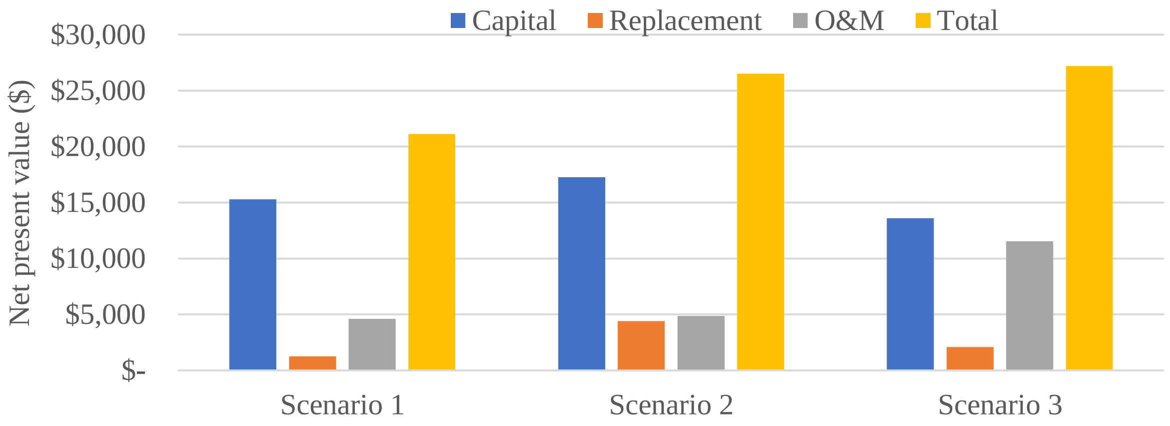

Figure 17. Comparative net present value among scenarios

On the other hand, the batteryless configuration PV-RO system in Scenario 1 yields the lowest replacement cost and O&M of $ 1,245.57 and $ 4,597.56, respectively. Therefore, from all the different costs associated with each scenario, Scenario 3 has the highest total NPV of $ 27,198.40, followed by Scenario 2, which generated $ 26,510.28, and Scenario 1 became the least at only $

21,143.13. Concurrently, the economic performance of each design can be compared in which the comparison of results are shown in **Table 15** and **Figure 18**.

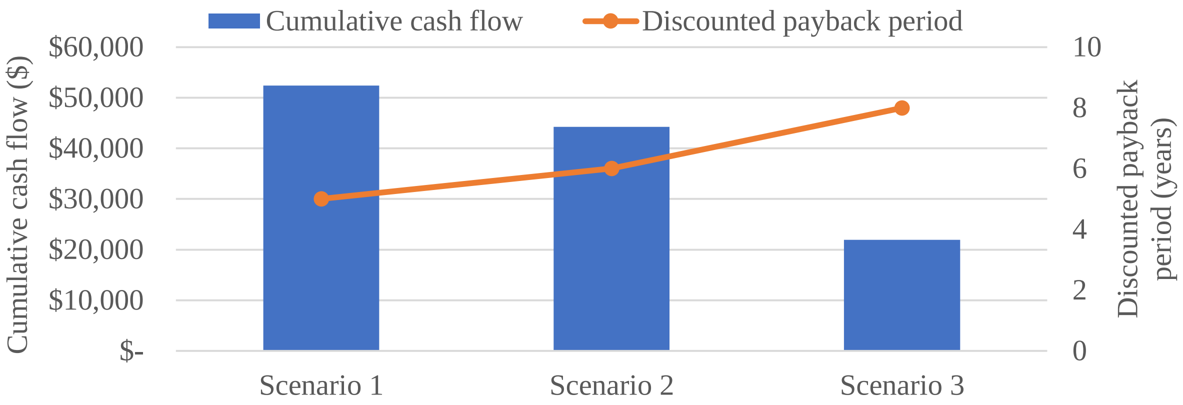

Figure 18. Comparison of cumulative cash flow and payback period among scenarios

From **Figure 18**, the cumulative cash flow is a reverse function of discounted payback period. The Batteryless PV-RO system scenario has the highest cumulative cash flow of $ 52,400.50 and yields the least payback period in five years. On the other side, the diesel-assisted PV-RO plant produced only $ 21,941.10 and had a longer discounted payback period of up to 8 years. This calculation shows that installing a storage system is beneficial for the PV-RO plant.

Apart from cumulative cash flow and discounted payback period, the IRR of various configuration system scenarios also needs to be examined to evaluate investment feasibility. The higher IRR computed in a project indicates more significant net cash flows can be generated, making the project more profitable and feasible to proceed with. As shown in **Table 15**, it can be interpreted that lower IRR yielded as a result of either high capital or operating expenditure. The scenario when the PV-RO system did not install with the battery system gave the highest IRR.

Table 15. Comparison of internal rate of return value among scenarios

Project Scenario	IRR
Scenario 1	21.83%
Scenario 2	15.92%
Scenario 3	12.00%

Figure 19 is used to compare the Levelized cost of electricity and water. Those values range from the scenario projection of the cost of solar electricity generation tariffs by 2030 of \$ 0.06 to \$ 0.22/kWh [28]. **Figure 19** shows the LCOE values for all scenarios considered. As seen in **Figure 19**, each scenario slightly differs from the others. The lowest LCOE of \$ 0.154/kWh is as Scenario 1 value, while the highest LCOE value of \$ 0.174/kWh from Scenario 2 is due to the high cost of batteries. This comparison is a 2% increment compared to a batteryless PV-RO plant.

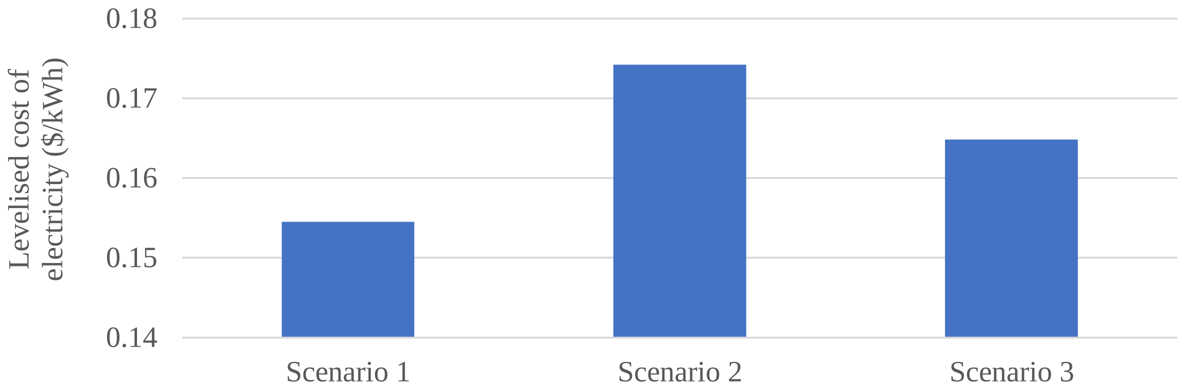

Figure 19. Comparison of LCOE among scenarios

Figure 20 depicts the LCOW for the RO system powered by the power systems with the different configurations considered. It can be seen that the PV-RO system without a battery backup system has the lowest LCOW of \$ 0.627/m^3, called Scenario 1. The other scenarios have a slightly higher value of \$ 0.686/ m^3 and \$ 1.036/ m^3, respectively, for Scenario 2 and Scenario 3. The higher LCOW means the higher cost to produce the amount of water. The price of the produced water or LCOW was then \$ 0.627/m^3, which is low enough to compete with RO powered by fossil fuels, which range between \$ 1 – 2.2/m^3 [18].

This study's results show that a non-battery PV-RO desalination system is more feasible than a battery and diesel-assisted system. The least NPV indicates this conclusion among the three scenarios and the highest cumulative cash flow and IRR value with the shortest payback period. The lowest value of LCOE and LCOW shows the low cost of generating energy, following a higher profit range from the water sell price.

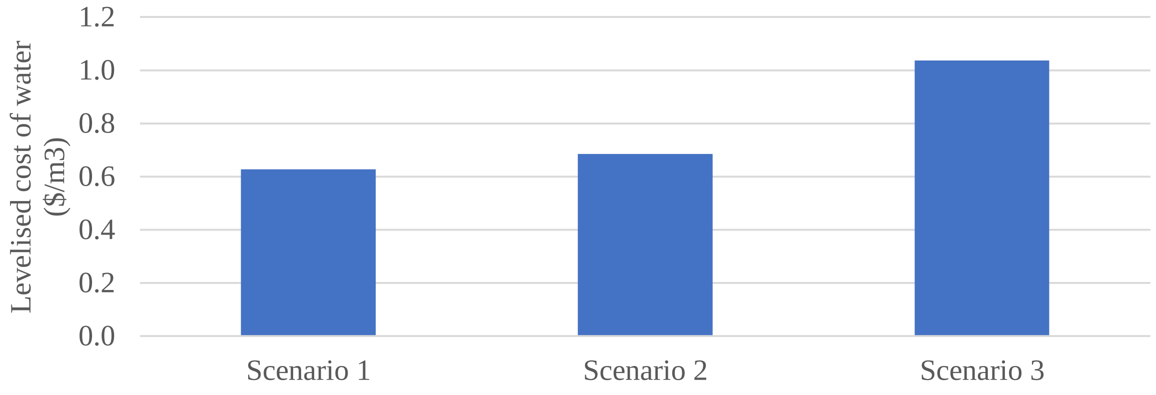

Figure 20. Comparison of LCOW among scenarios

Figure 21 shows the CO_2 emission avoidance from project scenarios after multiplying the energy generation with the respective emission factor. **Figure 21** also reveals a noticeable difference in a PV-RO system's optimal CO_2 emission reduction compared to a diesel-assisted PV-RO system. As can be seen from **Figure 21**, the CO_2 emission has been reduced up to 45,000 kg.CO_2eq. from Scenario 1 to Scenario 3.

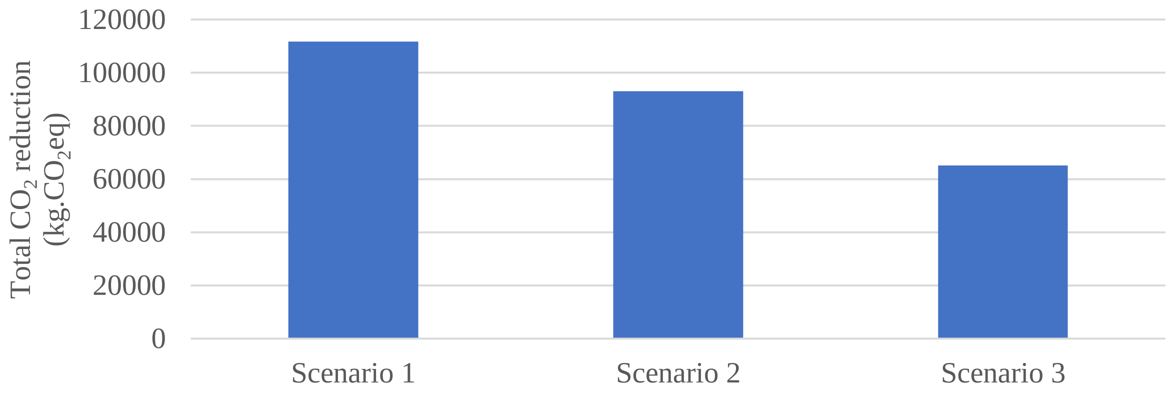

Figure 21. Comparison of CO_2 emission reduction among scenarios

PV-RO system without a battery backup system produces the highest amount of energy generation along with the project so that it can save a considerable amount of CO_2 emission of 111,690 kg.CO_2eq, while the presence of diesel generation that emits CO_2 has the lowest CO_2 reduction of 65,152.5 kg.CO_2eq. It can be seen that the integrated renewable energy systems prevent the overproduction of CO_2 emissions and thus reduce overreliance on conventional fossil fuel power generation. This result is in accordance with the government's policy to reduce dependence on fossil fuels while increasing the energy mix in renewable energy for power generation.

4. Conclusion

The Karimunjawa Islands in Indonesia are expected to experience water challenges in the future. Water desalination technologies are proposed to solve this problem. Subsequently, RO desalination, which has emerged as a leading and low-cost process, is recommended. However, the desalination process is energy-intensive and requires significant energy to operate the system. On the other hand, the PV technology that converts solar energy to electricity is a prospective power source for the desalination system. The abundant solar potential is proposed to provide this RO desalination plant power.

This study has systematically analyzed several PV-RO desalination systems with a 5 m^3/day capacity for daily use on Parang Islands. Three different scenarios are studied: batteryless, battery, and diesel generator assisted. The analysis results show that the batteryless PV-RO system (scenario 1) is the most optimized and economically feasible among other strategies. Scenario 1 comprises 6.3 kW PV panels installed with a 2-day water storage tank during prolonged periods with less sunshine. The LCOE of scenario 1 was found to be \$ 0.154/kWh, with the LCOW calculated to be \$ 0.627/m^3. The NPV and payback period of the optimized system was \$ 21,143.13 and 5 years, respectively. The analysis indicated the PV-RO system is economically feasible for the site.

Harnessing renewable resources for power generation decreases fossil fuel consumption and avoids harmful emissions. For this reason, the diesel-assisted PV-RO system (scenario 3) is the less preferable option because of its high pollutant emissions. The CO_2 emissions avoidance by this system was 65,152.5 kg.CO_2eq, while the optimized system could eliminate 111,690 kg.CO_2eq per year. Thus, it was found that using a diesel generator could increase the annual CO_2 emissions by 50%.

Acknowledgments

The authors would like to acknowledge the Japan International Cooperation Agency for AUN/SEED-Net on Collaboration Education Program UM CEP 1901, Japan ASEAN Collaborative Education Program (JACEP), and UM Power Energy Dedicated Advanced Centre (UMPEDAC), the University of Malaya to carry out this research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Author contributions

Athaya Fairuz: Conceptualization, Methodology, Data curation and Writing- Original draft preparation. **M.F. Umam**: Formal analysis, Writing- Original draft preparation. **M. Hasanuzzaman**: Conceptualization, Writing- Reviewing and Editing, Funding acquisition, and Supervision. **NA. Rahim**: Writing- Reviewing and Editing, Funding acquisition, and Supervision. **IM Mujtaba**: Conceptualization, Writing- Reviewing and Editing.

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