

Article

Experimental Evaluation of the Power Output and Efficiency of a Small Solar-Boosted OTEC Power Plant

Reemal D. Prasad , Muzammil Ali and Mohammed Rafiuddin Ahmed * 

Division of Mechanical Engineering, The University of the South Pacific, Laucala Campus, Suva, Fiji;
reemal.prasad@usp.ac.fj (R.D.P.); muzammilali369@rocketmail.com (M.A.)

* Correspondence: ahmed_r@usp.ac.fj; Tel.: +679-3232042

Abstract: Ocean thermal energy is an emerging energy source that holds great promise, especially for tropical countries. Ocean thermal energy conversion (OTEC) efficiency can be improved by raising the temperature difference between the hot water and the cold water. In the work reported here, a laboratory-scale closed-cycle OTEC system was constructed and tested for power output and efficiency. A solar heating system heated the water up to 70 °C. Experiments were conducted at cold water inlet temperatures of 5 °C, 8 °C, and 11 °C. The mass flow rate of the hot water was varied, while that of the cold water was kept constant. Increasing the hot water inlet temperature from 30 °C to 70 °C while keeping the cold water inlet temperature constant at 5 °C at the highest mass flow rate of hot water increased the power output from 32.07 W to 66.68 W (107.9% increase) and the thermal efficiency from 1.96% to 4.37% (123% increase). The pressure drop across the turbine was higher for a larger temperature difference between the hot water and cold water, indicating a higher transfer of energy to the working fluid. Increasing the mass flow rate of the hot water for the increasing temperature difference between the hot water and cold water increased the power output and efficiency due to the increase in the energy transfer from the hot water to the working fluid. Experimental works on solar-boosted OTEC systems are very rare, and this work should pave the way for practical implementation.

Keywords: ocean thermal energy conversion (OTEC); closed-cycle OTEC; solar-boosted OTEC; thermal efficiency



Academic Editor: Kian Jon Chua

Received: 12 December 2024

Revised: 23 December 2024

Accepted: 26 December 2024

Published: 31 December 2024

Citation: Prasad, R.D.; Ali, M.; Ahmed, M.R. Experimental Evaluation of the Power Output and Efficiency of a Small Solar-Boosted OTEC Power Plant. *Energies* **2025**, *18*, 127. <https://doi.org/10.3390/en18010127>

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

To deal with the harmful effects of climate change, leaders of 196 countries signed the Paris Agreement in an international treaty at the COP 21 in 2015 [1]. The aim of this agreement was to combat the climate crisis by reducing greenhouse gas emissions to limit the global temperature rise to 2 °C for this century and to limit the increase to 1.5 °C in the near future [2]. The Emissions Gap Report of 2022, however, indicates that the current policies in place to achieve the Paris Agreement are not sufficient, as the global temperature rise is predicted to be around 2.8 °C by the end of the century [3]. As per the report, one of the urgent actions required to close this gap is the expansion of the renewable energy sector as soon as possible [3] to considerably reduce greenhouse gas emissions.

Renewable energy is an alternative to traditional energy sources such as coal and oil. Renewable energy is energy produced from naturally available resources such as the sun and the wind. Renewable energy sources, mainly wind, solar, hydro, biomass, geothermal, and ocean, are now contributing significantly to the electricity generation of many countries [4]. The amount of solar energy released from the sun on a daily basis is

sufficient to meet the energy demand of the earth for an year [5]. The oceans covers around 70% of the earth's surface, capturing an extensive amount of the solar energy released on a daily basis [6].

Some of the existing technologies which can be used to extract this energy from the ocean include wave, tidal, salinity gradient and ocean thermal energy conversion (OTEC) systems. OTEC power plants have the largest potential compared to other ocean energy extraction technologies; an estimated 44,000 TWh of steady-state power can be extracted per year using OTEC [7]. The total available resource for OTEC systems are estimated to be around 30 TW [7].

An OTEC power plant is essentially a heat engine which operates on the Rankine cycle utilizing the thermal temperature difference between the warm surface seawater and cold deep seawater. OTEC power plants can be land-based or mounted on top of a barge which can be a floating type or moored to the seabed [8]. The OTEC systems can work on an open cycle, a closed cycle, or a hybrid cycle. An open-cycle OTEC system uses seawater as the working fluid, whereas a closed-cycle system uses a refrigerant. A closed-cycle OTEC power plant vaporizes a low-boiling-point working fluid in the evaporator by utilizing the warm surface seawater. The vaporized high-pressure working fluid is then used to drive a turbine. The pressure and temperature drop across the turbine produce mechanical work which is used to drive a generator for generating electricity. The working fluid then flows to the condenser where deep cold seawater is used to condense the working fluid. The working fluid is then pressurized and made to flow back to the evaporator using a pump and the cycle is repeated.

An OTEC plant requires a minimum temperature difference of 20 °C between the two sources to be considered viable [9]. The hot water for the system is supplied from the ocean surface, which has a temperature range of 26–28 °C, whereas the cold water is drawn from depths of around 1000 m, where the temperature of the water is of the order of 4–5 °C [10]. A temperature difference of 20 °C between the warm and the cold waters gives a Carnot cycle efficiency of about 6.7% [11]. The theoretical thermal efficiency of an OTEC plant is, however, in a range of 3–5% for a temperature difference of 15–25 °C [12]. Numerous research works have shown that the most critical parameter which affects the thermal efficiency of an OTEC plant is the temperature gradient between the warm and the cold deep seawater; the greater the temperature difference, the greater the thermal efficiency.

In a boosted OTEC system, external energy sources are used to enhance the operating temperature difference of the plant [13]. Researchers have started to employ supplementary heat sources such as waste energy from industries, solar energy, and geothermal energy to improve the performance of OTEC plants [14]. In the present work, a solar water-heating system employing evacuated tubes is used to heat the water before it enters the evaporator and transfers heat to the working fluid. The increased temperature difference is expected to enhance the performance of the OTEC power plant. The temperature difference between the hot inlet water and cold inlet water was varied over a wide range and at different mass flow rates of the hot and cold water to study their effect on the power output and efficiency of the closed-cycle OTEC plant. Considering the high solar insolation available in the tropical region, this work would be extremely beneficial in gauging the usefulness of OTEC and making investment decisions.

In terms of review of OTEC systems, Liu et al. [15] carried out a review of closed-cycle OTEC systems considering the effect of a number of parameters on cycle efficiency. Some of the parameters reported to positively affect the OTEC cycle efficiency were the utilization of other energy sources to enhance the temperature difference in the cycle, reducing the heat loss during the phase changing process in the heat exchanger by using a non-azeotropic

mixture as a working fluid, and using an ejector to increase the pressure difference across the turbine and through heat recovery. Abbas et al. [11] also carried out a review on the enhancement of OTEC systems and reported similar findings. They stated that the steam turbine can be optimized to improve the efficiency of the system, the operating temperature difference of the system can be enhanced by the use of external heat sources, non-azeotropic working fluid can be used to reduce heat losses in the evaporator, the turbine pressure difference can be increased by increasing the turbine inlet pressure, the turbine back pressure can be reduced, and an ejector can be used to reduce the turbine outlet pressure, which will improve the turbine pressure drop. In another review, Zhang et al. [16] identified mechanical issues incurred by an OTEC system during the design and operation period. The three major mechanical issues identified were the need for a low-pressure and -temperature steam turbine to be designed specifically for OTEC plants to improve the efficiency of the system, the consideration of the effect of hydrodynamics on the cold water pipe, and the overall seakeeping performance of the system. Langer et al. [17] conducted a review on the progress of economics in OTEC systems and identified seven knowledge gaps and provided recommendations to minimize these gaps for future research. They also suggested that the problems were mainly due to a lack of long-term operational data and experience in OTEC technologies.

With respect to site-based studies, Zereshkian and Mansoury [5] investigated the feasibility of OTEC plants for supplying electricity to offshore oil and gas fields located in the Caspian Sea in Iran, where the vertical water temperature difference is low because of shallow depths. Out of all the locations studied, the optimum temperature of 20 °C was available only in the southern Caspian basin during the months of July, August, and September. The eastern part of this basin has a depth of 200 m and was identified as the best location for an OTEC plant, providing an optimal temperature difference greater than 20 °C for 62 days in a year. Langer et al. [18], in their study, presented a model which can be used to upscale small OTEC systems to meet local electricity demands. They reported that, by 2050, an OTEC system with up to 45 GW capacity can be installed in Indonesia, catering for 22% of the national demand. It was also reported that upscaling the OTEC should only be done for regions with high electricity demand in order for the system to be feasible. OTEC must grow by 28% per year, a value comparable to wind and solar power, in order to contribute to energy transition globally. Arias-Gaviria et al. [19] studied the potential of deep ocean water for five cities in the Caribbean and determined that the available deep ocean water potential per city is around 50 m³/s, enough to fully meet a city's air-conditioning requirement together with 60% of a city's electricity requirement. Osorio et al. [20] proposed an ocean thermal energy Eco Park for the Colombian island of San Andrés. They proposed a four-stage process for the consolidation of their idea, which included an OTEC and a seawater air-conditioning system. The first stage of preliminary study was already completed in the study. The next two stages included the feasibility and completion of the final design. The final process included the utilization of discharge deep ocean water for other industries. Souza et al. [21] investigated the idea of an ocean thermal energy park to be located in Brazilian Blue Amazon, which covers 1.89 million km², showing the potential for nearly 376 OTEC plants. They also stated that the park would remove 60.16 GW of ocean heat and 8.13 kg/s of CO₂ under maximum operational conditions.

Researchers have also evaluated the effect of changing the working fluid on the performance of an OTEC system. Chen et al. [22] reported results from theoretical and experimental studies on an OTEC system operating on the Rankine cycle. Out of the several working fluids studied, R717 was reported to be the most suitable refrigerant for an OTEC system. The thermal efficiency from the experiments increased from 1.659% to 1.954% when the turbine inlet pressure was raised from 1.3 MPa to 1.5 MPa. The theoretical cycle thermal

efficiency, however, was reported to be 3.851% at a turbine inlet pressure of 1.44 MPa. It was also reported that the theoretical results were higher than the experimental results due to factors such as assumed thermal efficiencies for theoretical calculations. Wang et al. [23] carried out a multi-objective optimization for the levelized cost of electricity (LCOE) and exergy efficiency for an OTEC model working on different working fluids. The six working fluids, i.e., R717, R601, R152a, R600a, R134a, and R227ea, produced Pareto solutions of USD 0.34/kWh, USD 0.52/kWh, USD 0.52/kWh, USD 0.55/kWh, USD 0.57/kWh, and USD 0.67/kWh for LCOE. It was also reported that LCOE and exergy efficiency are conflicting parameters and could not be simultaneously optimized. Yang and Yeh [24] investigated the effect of R717 on the performance of an OTEC system by using it as a pure working fluid and blending it with R32 and R1234YF at different mass fraction ratios. The R717/R32 blend with a mass fraction ratio of 0.21/0.79 improved the maximum net power output by 18.9% and the R717/R1234YF blend with a mass fraction ratio of 0.41/0.59 improved the maximum power output (net) by 12.23% compared to the pure R717 working fluid.

Several researchers have also focused on hybridizing OTEC systems. Ishaq and Dincer [25] carried out a comparative study for hydrogen production systems utilizing OTEC, wind, and solar energy. The energy efficiencies for the OTEC-, solar-, and wind-based systems were reported to be 5.61%, 32.7%, and 33.51%, respectively. Hasan and Dincer [26] investigated a novel tri-generation OTEC system in which an organic Rankine cycle was used to produce electricity. The electricity was then used to power a multi-stage ammonia synthesis system and the discharge seawater from the condenser was used to provide district cooling. The maximum cooling capacity for this cooling system was reported to be 64.4 MW. Yilmaz [27] evaluated a novel hybrid OTEC system combined with a wind turbine designed to meet the energy requirements for a petrol station in Antalya, Turkey. The energy efficiency for the hybrid system was reported to be 12.27% compared to 4.49% for the OTEC system. Khanmohammadi et al. [28], in their study, presented two hybrid OTEC systems. The first hybrid system was a solar-OTEC system (S-OTEC) which utilized flat plate collectors, whereas, in the second design, the S-OTEC system was combined with a thermoelectric generator (S-OTEC/TEG). Idrus et al. [29] developed a thermodynamic model to investigate an OTEC system combined with a geothermal waste energy superheater installed between the evaporator and the turbine. The study reported that, as the working fluid's superheat was increased, the thermal efficiency of the system also increased. An interesting observation reported was that, when the quality of the vapor at the exit of the evaporator was 0.5, the efficiency of the cycle was 4.61%, but when the quality of the vapor was increased to 1.0, the cycle efficiency reduced to 4.53%. Another observation made was that, as the superheat of the working fluid increased, the required mass flow rate of the working fluid was significantly reduced. The maximum power output of the proposed plant was reported to be 32.593 MW with 27.49 MW of geothermal waste energy input. Aydin et al. [30] carried out a numerical design point analysis on a 100 kW OTEC system by either preheating the surface seawater before it entered the evaporator or by superheating the working fluid after it exited the evaporator. Both cases increased the net power output by 20–25%. For the case of superheating, the thermal efficiency was reported to improve by 60% compared to the OTEC cycle, indicating that superheating the working fluid was a better approach. Khosravi et al. [31] proposed a hybrid OTEC/PV concept with a hydrogen-based system for energy storage. The proposed system was tested with a number of working fluids for optimal maximum specific power. R717 was reported to provide the maximum specific power of 0.3622 kW/m². The cost of electricity was improved to USD 0.168/kWh compared to USD 0.28/kWh for previously proposed OTEC systems. Malik et al. [32] carried out multi objective optimization on a concept including a

solar-assisted OTEC system, PEM electrolyzer, and a thermoelectric generator to produce electricity and hydrogen. The study reported that the exergy efficiency, net power output, and sustainability of the system improved when a thermoelectric generator was employed. The production rate of hydrogen was also reported to be directly proportional to the power output of the proposed system. Yilmaz et al. [33] carried out a thermodynamic study on an OTEC-based multigeneration plant integrated with a hydrogen generation and liquefaction system. Ahmadi et al. [34] developed a program using MATLAB software to simulate an OTEC system coupled with a PEM electrolyzer. The electric power produced from the turbine was used to power the PEM electrolyzer for hydrogen production. The integrated OTEC system was estimated to have an energy efficiency of 3.6%. Semmari et al. [35] proposed the concept of utilizing a CAPILI engine in an OTEC cycle. The CAPILI engine uses an inert gas as a liquid piston between two cylinders, which are connected to the evaporator and the condenser along with a suitable working fluid. The most suitable working fluid for the CAPILI cycle was reported to be R-134a refrigerant. The efficiency of the CAPILI cycle was 3.82% while operating at a pressure difference of 190 kPa. Hu et al. [36] proposed the concept of integrating a compression-assisted ammonia–water absorption refrigeration cycle to an OTEC system. Kim et al. [37], in their study, utilized effluent from a nuclear power plant to evaporate the working fluid instead of the warm ocean surface water. They concluded that the thermal efficiency of the OTEC plant improved by 2% when using the effluent. Bombarda et al. [38] studied the effect of three-level organic Rankine cycle modules in series and solar hybridizing on the OTEC plant. They determined that the three-level cycle results in an approximately 30% improvement in the performance of the system, and solar hybridization boosts the energy production of the OTEC system by almost three times during daytime operation.

Wu et al. [39] investigated the dual-pressure organic Rankine cycle by introducing a secondary evaporator and turbine in the OTEC system. They determined that a dual-pressure organic Rankine cycle improves the thermal efficiency by 1.24% and net power output by 1.38% compared to a single-pressure organic Rankine cycle. They also stated that an increase in warm water inlet temperature and the diameter ratio of the turbine wheel positively affect the net power output, whereas an increase in cold water inlet temperature and the mass flow rate of the working fluid negatively affect the power output (net) of their proposed system. OTEC systems are now being seriously considered as base-load power plants, as they can provide power round the clock. In view of the changing rain patterns, the utility companies of many countries are considering moving to OTEC as their base power plant. As the thermal efficiency of the OTEC plant operating between the surface seawater and cold deep seawater is normally of the order of 20–25 °C, ways should be found to improve the thermal efficiency. Solar-boosted OTEC plants are proposed and studied only theoretically [29,33,35]. However, no detailed experimental works have been reported on systematically increasing the hot water inlet temperature over a wide range. The present work addressed this lack of experimental results and also proposed options of heating the surface water to temperatures from 30 °C to 70 °C to achieve higher efficiencies and power outputs.

2. Materials and Methods

An evacuated-tube solar water-heating system supplied by Jiangsu Micoe Solar Energy Co., Ltd., Jiangsu, China, as shown in Figure 1, was used to supply hot water to the evaporator of the OTEC plant.



Figure 1. A photograph of the evacuated-tube solar water-heating system.

An evacuated tube consists of a small-diameter glass tube concentrically suspended inside of a large-diameter glass tube with one end of the glass sealed off. The details of an evacuated tube can be seen in [40]. The outer surface of the vacuum tube is coated with excellent light-absorbing and minimal light reflection material such as titanium nitride oxide or aluminum nitrate to maximize solar radiation absorption. The air between the two concentric glasses is evacuated, creating a layer of vacuum which acts as a thermal insulation eliminating convective and conductive heat losses. A number of evacuated tubes can be connected to a header tank to form a solar collector. One or more solar collectors can be connected in parallel along with a tank and a circulation pump to form a heating system where the number of evacuated tubes and the size of the tank are dependent on the hot water demand.

Figure 2 depicts the layout of the evacuated tubes and the header manifold. As mentioned earlier, many tubes can be connected to a header tank to form a solar collector; in this case, a total of 200 tubes were provided on both sides of the header tank. The heated water rises up the tubes, is discharged to the header tank, and, finally, is collected in the tank, as shown in Figure 1.

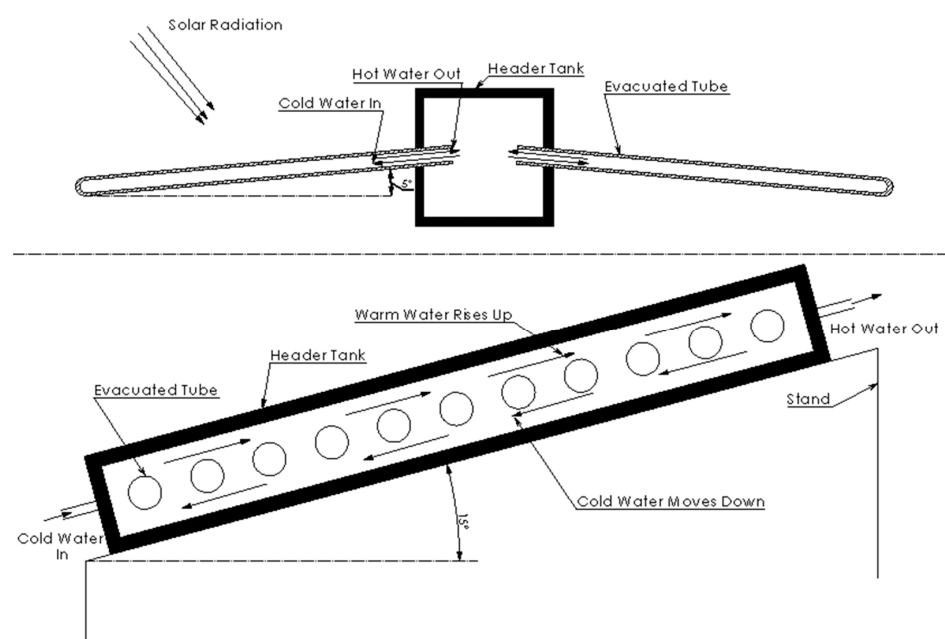


Figure 2. Layout of the evacuated tubes and the header manifold.

A schematic diagram of the solar-boasted OTEC power plant is presented in Figure 3. Solar radiation from the sun comes into contact with the evacuated tubes as early as 6 a.m. The radiation from the sun passes the outer transparent glass of the evacuated tube and heats up the water inside of the inner tube. As the water in the evacuated tube heats up, due to the small inclination angle of the evacuated tube, the thermosyphon effect causes the warm water in the evacuated tube to move into the header manifold, and cold water inside of the header manifold moves into the evacuated tube. As the temperature of the water in the header manifold increases by a pre-set degree, the water circulation pump turns on, pumping the warm water from the evacuated tube into the water tank. As the warm water is transferred to the tank, the water at a lower temperature, which is at the bottom of the tank, is transferred to the evacuated tubes. This cycle continues as long as sufficient solar insolation is available to provide heating. As the cycle continues, the water temperature in the tank reaches temperatures of 60–80 °C. Once the required water temperature is reached, a secondary pump can be used to transfer the water to the evaporator of the OTEC system.

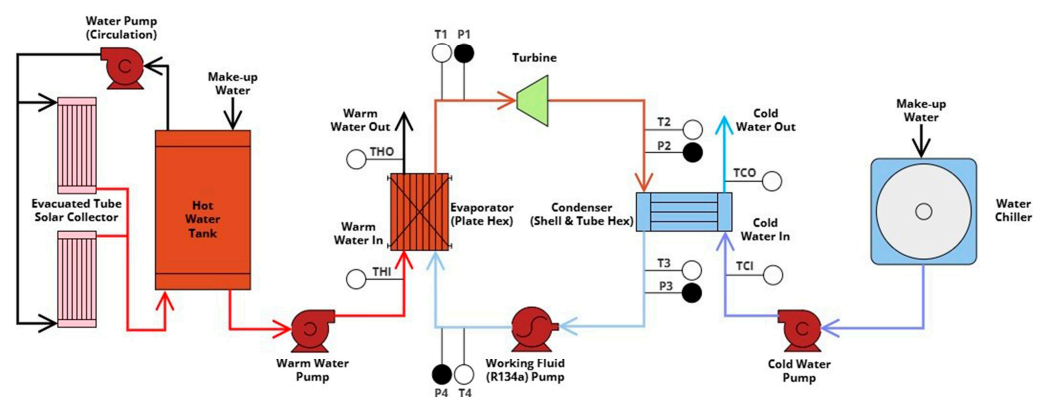


Figure 3. Schematic diagram of the solar-boasted OTEC system.

Figure 4 shows the T-s diagram of the cycle on which the closed OTEC system operates. Process 1–2 is the work-producing process in the turbine, during which isentropic expansion of the working fluid takes place; process 2–3 is condensation in the condenser; process 3–4 is isentropic pressure rise in the pump; and process 4–1 is the constant pressure heat addition (absorption) in the evaporator.

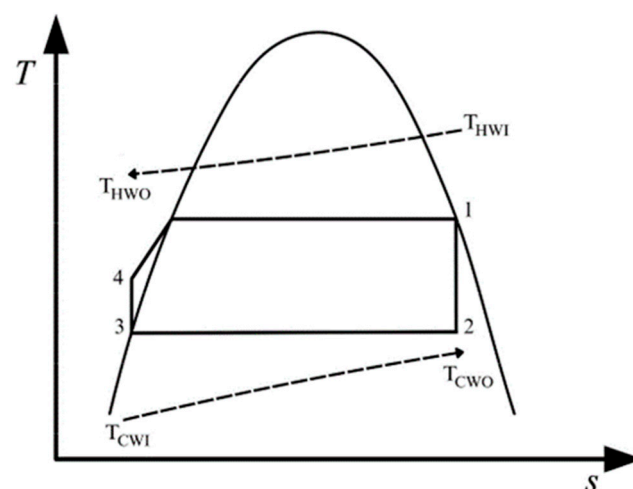


Figure 4. T-s diagram of the closed OTEC cycle.

Table 1 shows the specifications of the evacuated-tube solar heating system used for experimentation in the present work. Each evacuated tube has a length of 1800 mm, an outer tube diameter of 58 mm, and an inner tube diameter of 47 mm. The storage tank has a volume of 1140 liters. The system is also provided with backup heaters that can heat the water up to 100 °C.

Table 1. Specification of the evacuated-tube solar water heater.

Component	Parameter	Specification	Unit
Evacuated Tube	Outer Tube Diameter	58	mm
	Inner Tube Diameter	47	mm
	Glass Thickness	1.6	mm
	Length	1800	mm
	Material	Borosilicate Glass 3.3	-
	Volume	3.12	L
	Weight	2.2	kg
	Vacuum Pressure	0.005	Pa
	Absorption	92	%
	Number of tubes	200	-
Manifold	Header Tank Length	2000	mm
	Header Tank Width	160	mm
	Header Tank Height	160	mm
	Header Tank Volume	51	L
	Tubes per Header Tank	50	-
	Material	Aluminum Alloy	-
Insulation	Material	Glass wool, Aluminum Foil, Polyurethane	-
Storage Tank	Volume	1140	L
Backup Heaters	Power	18,000	W
	Temperature Range	0–100	°C
	Length	220	mm
Circulation Pump	Maximum Flow Rate	60	L/min
	Total Head	4	m
System	Total Volume	1968	L

The components of the small closed-cycle OTEC power plant were procured and then connected with suitable piping in the Fluid Mechanics lab of The University of the South Pacific. The setup consisted of a condenser, evaporator, turbine, working fluid pump, reserve tank, and refrigerant flowmeter. The evaporator used in this work was a plate heat exchanger, supplied by Tianjin Botai Heat-exchanger Equipment Co., Ltd., Tianjin, China. R-134a was employed as the working fluid in the present work. Figure 5 shows the experimental setup for the OTEC plant. The hot water supply was sourced from the solar heater tank, which allowed a large temperature difference to be investigated for the performance of the OTEC plant. The pipe carrying the hot water from the solar heater tank to the OTEC setup was insulated to ensure that the water temperature did not drop as it reached the evaporator unit of the setup.

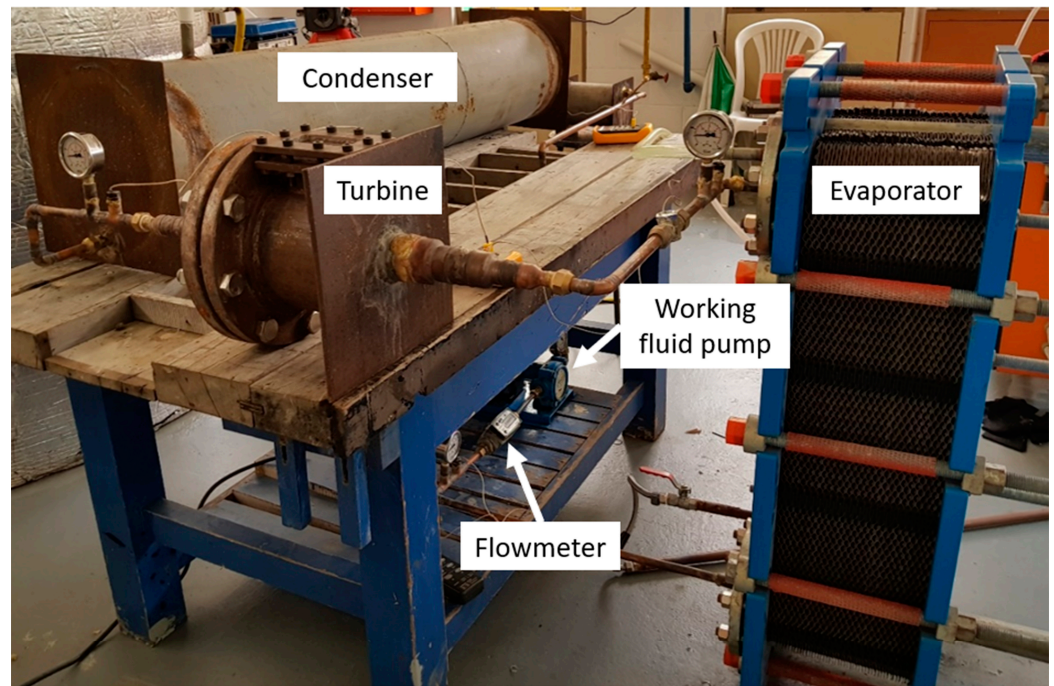


Figure 5. A photograph of the small OTEC power plant setup.

A turbine housing was designed, taking into consideration the high operating pressure of an OTEC plant. Figure 6 given below shows the fabricated turbine housing. An 11-bladed axial flow turbine was installed inside of the turbine housing. Additional pictures of the setup and the components are provided in the supplementary material.

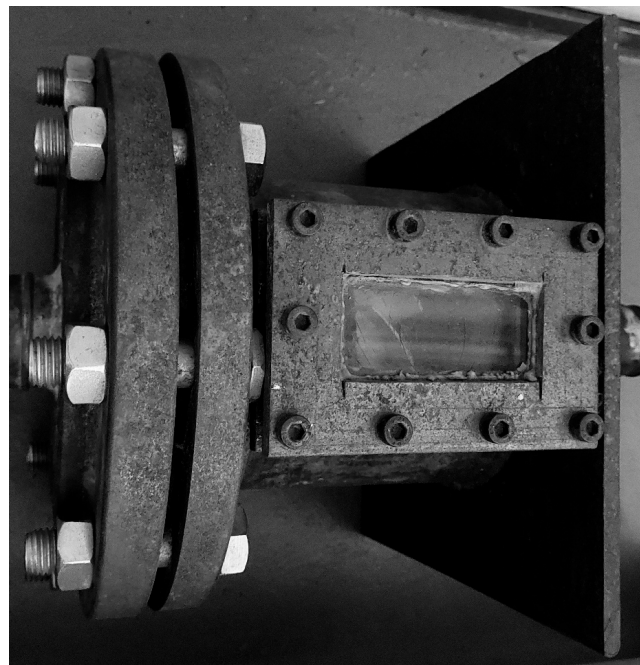


Figure 6. A photograph of the turbine housing.

A shell-and-tube-type heat exchanger, as shown in Figure 7, was designed and fabricated to be used as a condenser for the present setup. Baffles were added along the tube bundles to ensure that effective heat transfer took place between R-134a and the cold water. The temperature of the cold water at the inlet and at the outlet was lower than that of

the surrounding temperature; this may have caused some heat gain in the condenser and reduced the rate of heat transfer.



Figure 7. A closer view of the shell-and-tube heat exchanger that was used as a condenser.

An LP22E refrigerant pump (part of the setup in Figure 5), manufactured by National Refrigeration Products, PA, USA, was used to circulate the refrigerant within the system. A voltage regulator was used to regulate the supply voltage to the pump to control the flow rate of the refrigerant. An industrial-grade Alfa Laval type single-pass-plate heat exchanger served as the evaporator in the system. A GPI commercial-grade flowmeter, manufactured by GPI Flow Meters, NJ, USA, was also installed after the refrigerant pump to measure the refrigerant flow rate. A water chiller, supplied by Iceman Fiji Pvt. Ltd., Suva Fiji, was used to supply cold water to the condenser. Specifications for all the components are provided in Table 2.

The specifications of the measuring instruments used during the experimentation are provided in Table 3. K-Type thermocouple and Wika pressure gauges, manufactured by Wika Alexander Wiegand SE & Co. KG, Klingenberg, Germany, were installed before and after each of the major components. A center 305 datalogger thermometer, manufactured by Center Technology Corporation, Taipei, Taiwan, R.O.C., was used to log all the temperature readings during the experiments. The pressure readings were directly obtained from the pressure gauges. The GPI low-flow aluminum flowmeter recorded the refrigerant flow rate.

Table 2. Specifications of the major components of the OTEC plant.

Component	Parameter	Specification	Unit
Refrigerant pump	Power rating	372.8	W
	Mass flow rate capacity	0.15	kg/s
Evaporator	Heat transfer area	10.08	m ²
	Relative fluid direction	Countercurrent	-
	No. of plates	47	-
	No. of effective plates	45	-
	Plate thickness	0.5	mm
	Plate material	Titanium	-
	Design pressure	7	bar
	Design temperature	130	°C
Condenser	Heat transfer area	3.01	m ²
	Relative fluid direction	Countercurrent	-
	No. of tubes	20	-
	Tube material	Copper	
	Tube diameter	30	mm
	Tube length	1.6	m
	Shell material	Mild Steel	-
	Shell diameter	0.3	m
	Shell length	1.8	m
	Design pressure	1500	kPa
	Design temperature	N/A	-
Hot and cold water supply pumps	Power rating	750	W
	Maximum flow rate	60	L/min
	Maximum suction head	8	m
	Maximum discharge head	50	m

Table 3. Specifications of the measuring instruments used in the present work.

Instrument	Range	Resolution	Accuracy
K-Type thermocouple	−50–250 °C	0.1 °C	±1 °C
Wika Pressure gauge (Model: EN837-1)	0–4000 kPa	1 kPa	±1% of reading
GPI commercial grade flowmeter (Model: A109A025LM)	1–11 L/min	0.01 L/min	±1% of reading
Center 305 Datalogger Thermometer	−200–1370 °C	0.1 °C	±0.3% + 1 °C

The performance of the OTEC system was experimentally tested first by varying the hot water inlet temperature from 30 °C to 70 °C while keeping the cold water inlet temperature and mass flow rate fixed at 5 °C and 0.25 kg/s, respectively. The mass flow rate of the hot water was varied from 0.1 kg/s to 0.25 kg/s for each of the hot

water temperatures. The cold water inlet temperature was then increased to 8 °C and the experimentation was repeated. Finally, the cold water inlet temperature was raised to 11 °C and the experimentation was once again repeated. The temperature and pressure readings after the evaporator, turbine, condenser, and the working fluid pump were recorded. The cold and hot water mass flow rates and their inlet and outlet temperatures were also recorded. The mass flow rate of the refrigerant was kept constant at 0.0084 kg/s.

An Engineering Equation Solver (EES) program, previously used in [41], was used to obtain the enthalpy values of the refrigerant at each point of the cycle for further analysis. The refrigerant properties including the pressure and temperature at each stage of the cycle were fed into the EES program to obtain the enthalpy values. The enthalpy values were then used to calculate some of the output parameters. The rate of heat input to the working fluid was obtained from the mass flow rate and the change in enthalpy; the error in the estimation of the rate of heat input was obtained from the resolution and accuracies of the flow meter and the enthalpies. The absolute maximum error in the estimation of the heat addition rate was estimated to be $\pm 2.15\%$. The error in the estimation of the power output was estimated to be $\pm 2.4\%$. The thermal efficiency is the ratio of the power output and the rate of heat input; the maximum error was estimated to be $\pm 1.8\%$.

3. Results

The evacuated-tube solar water-heating system used in this study was initially tested from June 2020 to January 2021. Figure 8 given below shows the temperature of the water in the evacuated tubes and the storage tank from 6.00 a.m. to 12.00 a.m. on a sunny day. The water temperature in the evacuated tubes increases as soon as solar radiation contacts the evacuated tubes. When the water temperature in the evacuated tube increases by a preset value, e.g., 5 °C, the circulation pump automatically turns on, pumping hot water from the evacuated tubes to the storage tank and supplying new water from the tank to the evacuated tubes. The rate of temperature rise of the water in the storage tank is relatively low in the morning due to the large volume of water. The water temperature in the evacuated tubes and the storage tank increases with increasing solar insolation and reaches a maximum at 4.00 p.m. The maximum temperature of the water, as seen in Figure 8, is 83 °C in the evacuated tubes and 81 °C in the storage tank. At 5.00 p.m., the temperature of the water in the evacuated tubes starts dropping because of the absence of solar radiation. The circulation pump is turned off at this instance. The hot water available in the storage tank at this time can be utilized in the OTEC plant. There is a slight reduction in the temperature of the water in the storage tank after 5.00 p.m. due to convective and radiative losses. After 5.00 p.m., i.e., in the absence of solar insolation, the temperature of the water in the evacuated tubes significantly reduces due to convective and radiative losses. Similar trends were seen for days on which solar insolation was minimal. The temperature of the water in the evacuated tubes and the storage tank increases until 4.00 p.m. and then the water temperature in the storage tank slightly reduces, while the temperature of the water in the evacuated tubes rapidly falls.

The effect of different average daily solar insolutions on the water temperature in the storage tank was also observed from 6.00 a.m. to 12.00 a.m., as shown in Figure 9. The solar insolation for the duration during which direct sunlight mostly fell on the system was averaged and used in this analysis. The average solar insolation for which water temperatures were recorded varied from 32 W/m² to 367 W/m². The highest water temperature of 82 °C, which was available for supply to the OTEC plant, was recorded at an average daily solar insolation of 367 W/m². On a day which had relatively low solar radiation, i.e., the weather during the day was gloomy and cloudy, the daily average solar insolation was 32 W/m². Despite the low average daily solar insolation of 32 W/m², the

maximum water temperature in the storage tank available for use in the OTEC plant was 68 °C.

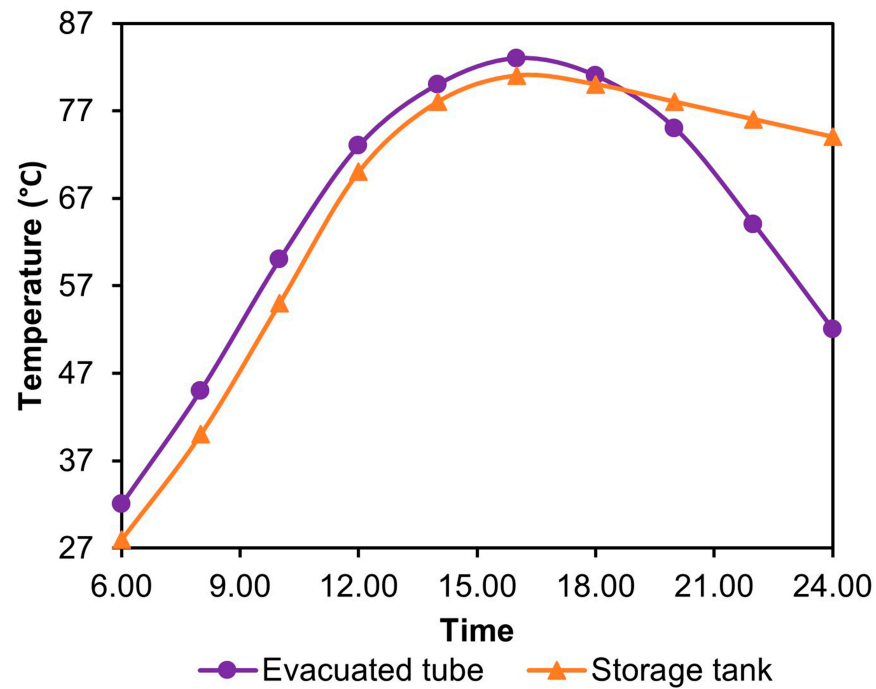


Figure 8. Variation of water temperature in the evacuated tubes and the storage tank over a day.

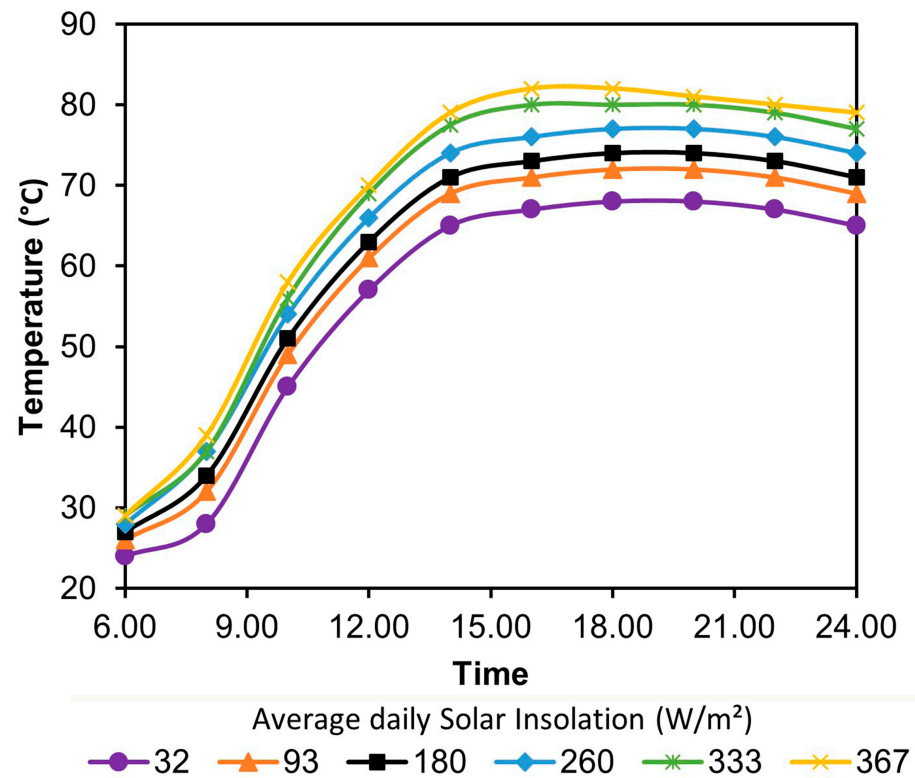


Figure 9. Variation of water temperature in the storage tank from 6.00 a.m. to 12.00 a.m. at different daily averaged solar insulations.

Figure 10 shows the thermal efficiency of the OTEC plant and the power output against the hot water flow rates. For all the hot water inlet temperatures, i.e., 30 °C to 70 °C, the thermal efficiency and the power output increase as the mass flow rate of the hot water

increases. The highest hot water inlet temperature that was used in the present work was 70 °C; this was due to the loss of energy from the pipe carrying the hot water from the solar system to the OTEC setup. As the mass flow rate of the hot water increases, more heat energy is added by the hot water to the working fluid. This increased heat transfer improves the turbine performance, hence, enhancing the thermal efficiency and the power output. As seen in Figure 10A, when the mass flow rate of the hot water is 0.1 kg/s and the hot water and cold water inlet temperatures are 30 °C and 5 °C, respectively, the thermal efficiency and power output are 1.39% and 22.78 W, respectively. The thermal efficiency and power output increase to 1.96% and 32.07 W when the mass flow rate of the hot water is increased to 0.25 kg/s, keeping the inlet temperatures constant for both the hot and the cold water. Faizal et al. [41] presented similar results on the effect of the mass flow rate of hot water on thermal efficiency and power. As the temperature of the hot water inlet rises, the thermal efficiency and the power output of the system increase. However, it should be noted that the increase in power output and efficiency is higher when the hot water inlet temperature increases from 30 °C to 40 °C compared to when it increases from 60 °C to 70 °C. This could be due to some loss of energy to the surroundings when the hot water inlet temperature is 70 °C, as the temperature difference between the water and the surroundings increases in this case.

The effect of cold water inlet temperature on the thermal efficiency of the OTEC cycle and the power output are presented in Figure 11. The thermal efficiency of the OTEC cycle and power output are generally dependent on the operating temperature difference of the system, i.e., the temperature difference between the hot water and the cold water inlet temperatures. Increasing the cold water inlet temperature reduces the operating temperature difference of the system, hence, directly reducing the thermal efficiency and the power output. As the cold water inlet temperature is increased, the condensation temperature also increases. An increase in the condensation temperature causes the enthalpy at the turbine outlet to also increase, which directly reduces the thermal efficiency and the power output. As can be seen from Figure 11B, when the hot water inlet temperature is kept constant at 40 °C, the mass flow rate is kept constant at 0.25 kg/s and the cold water inlet temperature is 5 °C, the thermal efficiency is 2.57%, and the power output is 41.35 W. However, when the cold water inlet temperature is increased to 8 °C, the thermal efficiency reduces to 2.46% and the power reduces to 39.66 W. The thermal efficiency and the power output further decrease to 2.40% and 38.82 W when the cold water inlet temperature is increased to 11 °C. Yang and Yeh [42] presented similar trends on the effect that condensation temperature has on the power output of the system. Ahmadi et al. [34], in their study, also concluded that an increase in the condensation temperature reduces the net power output of the system. Chen et al. [22] also showed a similar trend on the effect that condensation temperature has on the thermal efficiency. At a fixed turbine inlet pressure of 0.85 MPa, when they increased the condensation temperature by three degrees from 6 °C to 9 °C, the thermal efficiency of the cycle decreased from 3.5% to 2.8%. Yuan et al. [43], in their study, also stated that a lower cooling source temperature was beneficial to the performance of the cycle.

The effect of varying the hot water inlet temperature on the thermal efficiency and the power output are presented in Figure 12. Idrus et al. [29], in their study, suggested that the most effective way to improve the thermal efficiency of the Rankine cycle is by increasing the inlet temperature of the hot water. Increasing the inlet temperature of hot water increases the operating temperature difference of the system, which causes the enthalpy drop across the turbine to increase, which has a positive effect on the power output and the thermal efficiency of the system. Gao et al. [44] increased the temperature at the solar collector outlet from 54 °C to 72 °C to superheat the working fluid and found that

the thermal efficiency increased in the range of 2.02–3.26%. As can be seen in Figure 12A, when the cold water inlet temperature is kept constant at 5 °C and the hot water mass flow rate is kept constant at 0.25 kg/s, the thermal efficiency and power output significantly improve as the hot water inlet temperature is raised from 30 °C to 70 °C. When the hot water inlet temperature is 30 °C, the thermal efficiency is 1.96% and the power output is 32.07 W. However, when the hot water inlet temperature is increased to 70 °C, keeping other parameters constant, the thermal efficiency and the power increase to 4.37% and 66.68 W, respectively.

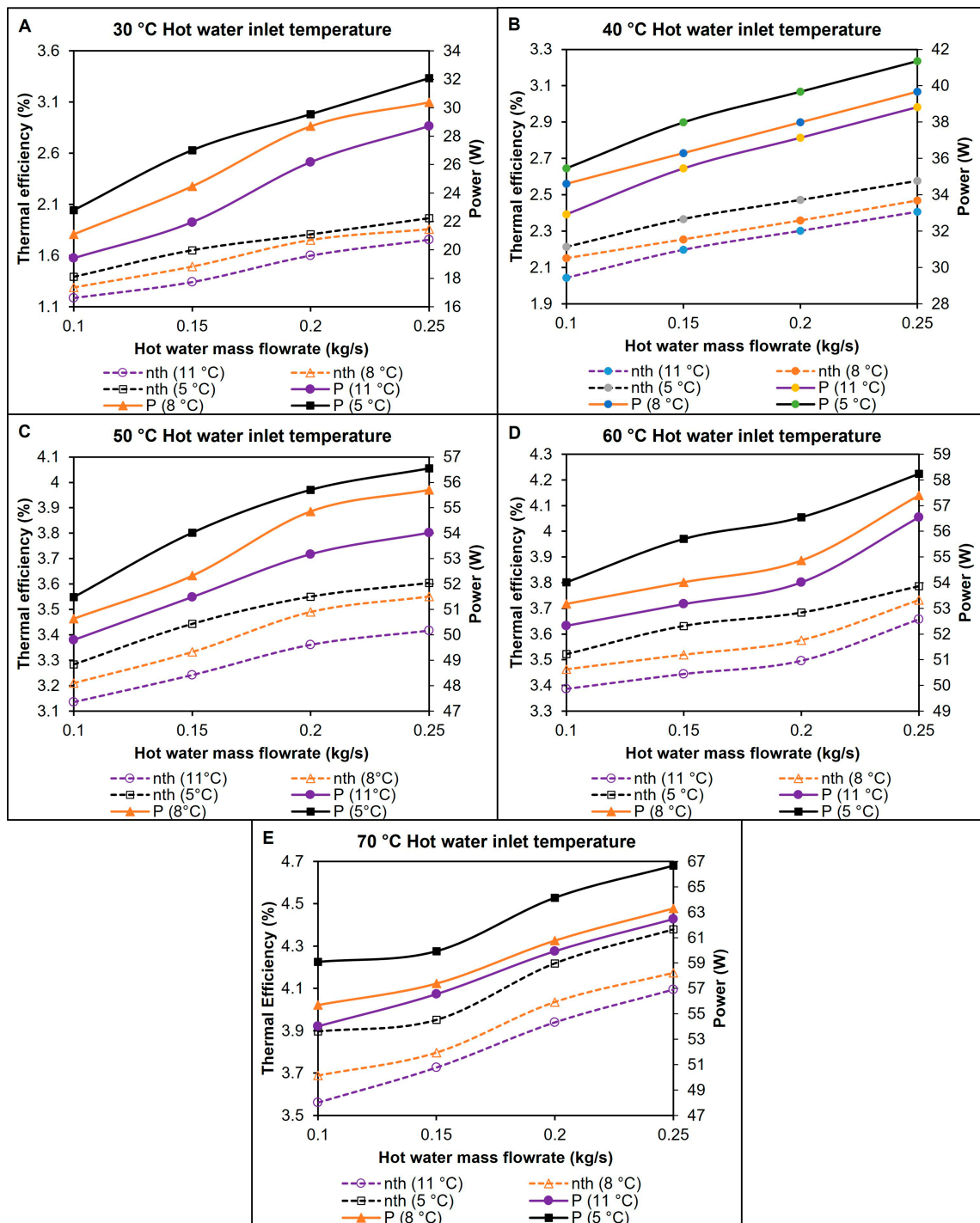


Figure 10. Thermal efficiency of the system and power output against the hot water flow rates at hot water inlet temperatures of 30 °C (A) to 70 °C (E).

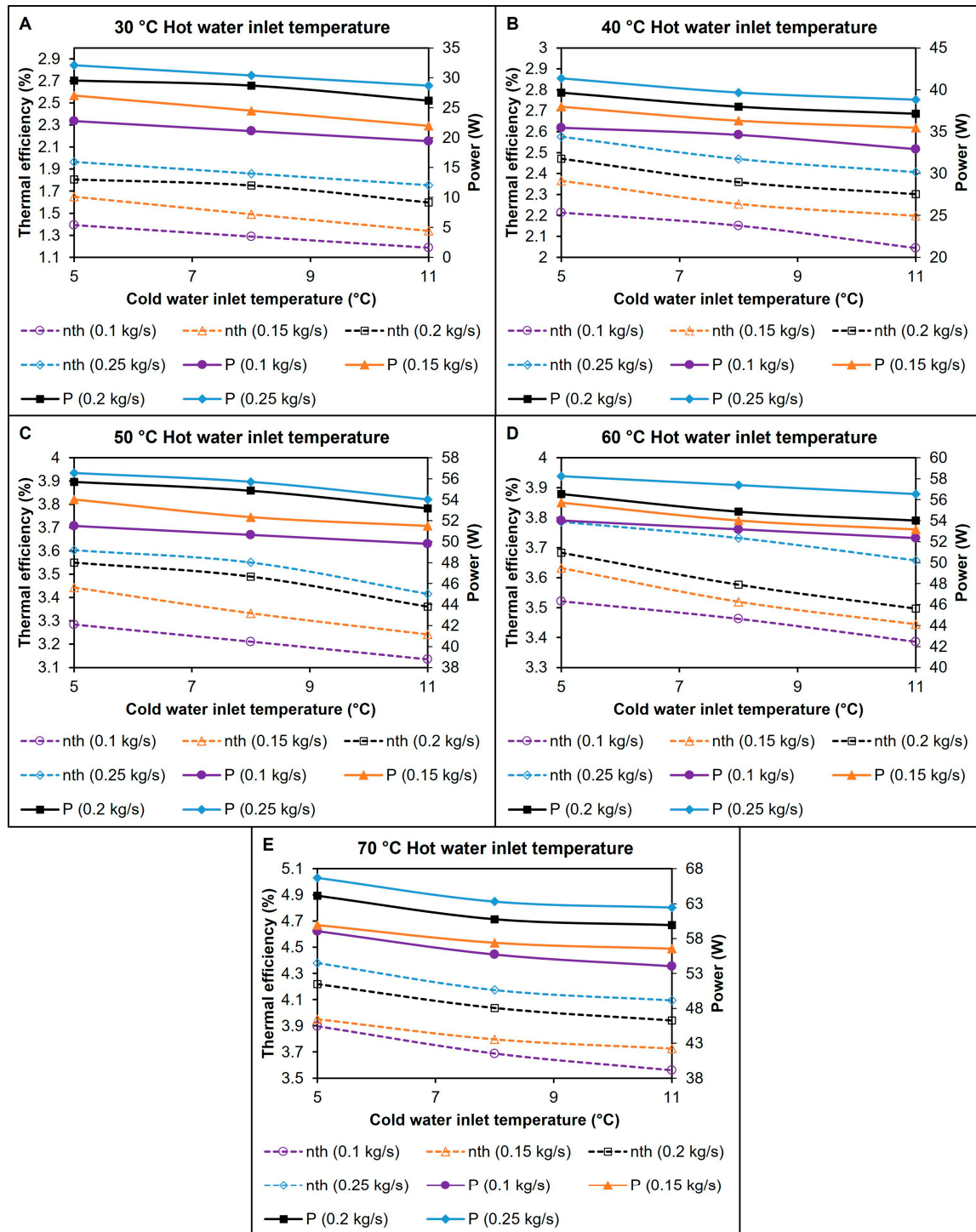


Figure 11. Variation of the thermal efficiency and the power output with the cold water inlet temperature at different hot water flow rates at hot water inlet temperatures of 30 °C (A) to 70 °C (E).

Figure 13 shows the effect of operating temperature difference on the turbine inlet pressure for different cold water inlet temperatures. The turbine inlet pressure increased as the operating temperature difference of the system was increased. When the operating temperature difference of the system was 19 °C, the turbine inlet pressure was 570 kPa; however, when the operating temperature difference was increased to 65 °C, the turbine inlet pressure increased to 1140 kPa. Faizal et al. [41] presented similar results on the effect that the system operating temperature difference has on the turbine inlet pressure.

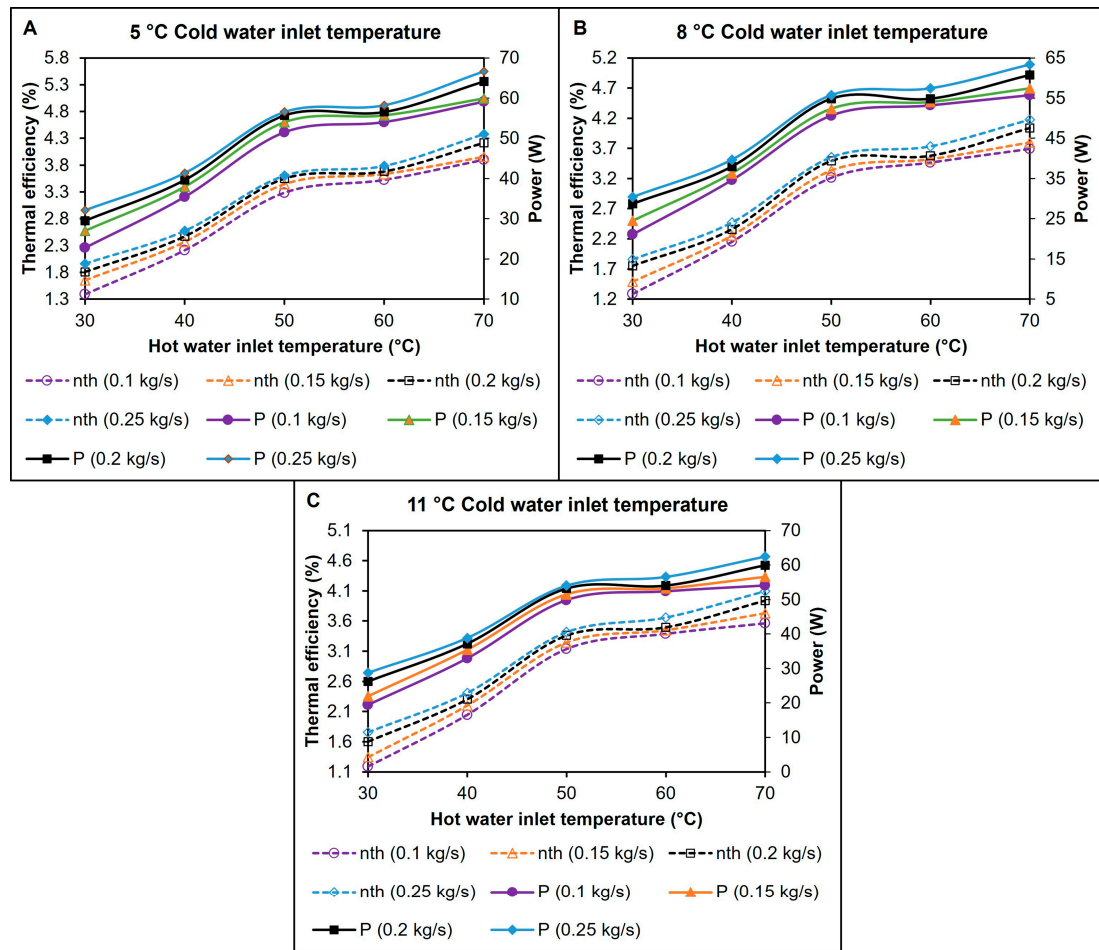


Figure 12. Thermal efficiency of the system and power output against the hot water inlet temperature at cold water inlet temperatures of 5 °C (A) to 7 °C (C).

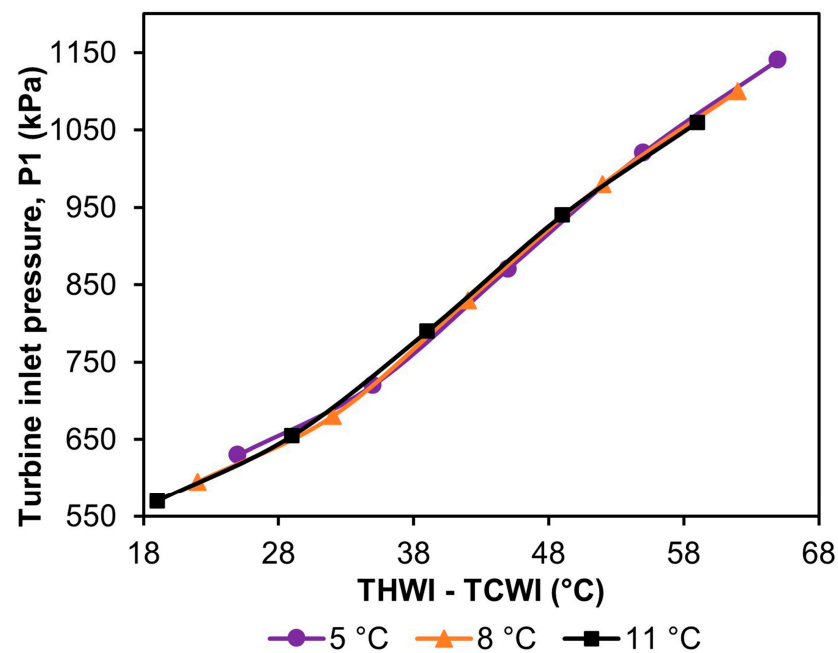


Figure 13. Turbine inlet pressure against the operating temperature difference for different cold water inlet temperatures.

The effect of operating temperature difference on the pressure drop across the turbine is depicted in Figure 14. For a 5 °C cold water inlet temperature and a 30 °C hot water inlet temperature, the operating temperature difference was 25 °C. At this operating temperature difference, the pressure drop across the turbine was 80 kPa. However, at the same cold water inlet temperature, when the operating temperature difference was increased to 65 °C by increasing the inlet temperature of the hot water to 70 °C, the turbine pressure drop increased to 255 kPa.

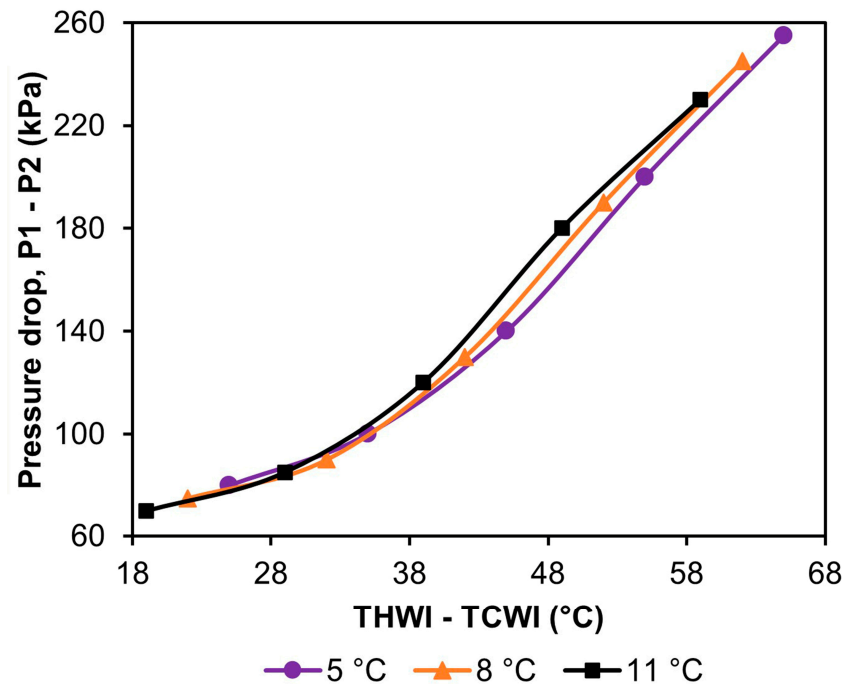


Figure 14. Pressure drop across the turbine against the operating temperature difference for different cold water inlet temperatures.

For all the operating temperature differences that were experimented, the turbine inlet pressure and the pressure drop across the turbine are presented in Figure 15. It can be seen from the figure that the turbine inlet pressure and pressure drop increase linearly as the operating temperature difference is enhanced. At the minimum operating temperature difference of 19 °C, the turbine inlet pressure and the pressure drop across the turbine were recorded to be 570 kPa and 70 kPa, respectively. However, when the cycle operating temperature difference was increased to 65 °C, the turbine inlet pressure and the pressure drop across the turbine increased to 1140 kPa and 255 kPa, respectively. Faizal et al. [41] presented similar trends on the effect of operating temperature difference on the turbine inlet pressure and the pressure drop across the turbine.

According to Yang and Yeh [42], greater warm water temperatures and lower cold water temperatures enhance the efficiency and power output of an OTEC system. Figure 16 shows the effect of operating temperature difference on the thermal efficiency of the system. The results presented in Figure 16 are also for all the possible operating temperature differences that were experimented. Increasing the operating temperature difference of the system significantly improves the thermal efficiency of the OTEC cycle. Increasing the operating temperature difference results in a greater pressure drop across the turbine, as seen in Figure 15 given above. An increase in the pressure drop across the turbine has a positive effect on the thermal efficiency of the OTEC cycle. When the hot water mass flow rate was kept constant at 0.25 kg/s and the operating temperature difference of the system was increased from 19 °C to 65 °C, the thermal efficiency of the OTEC cycle improved from

1.75% to 4.37%. Yuan et al. [43], in their study, showed that a higher operating temperature difference will lead to improved thermal efficiency. Faizal et al. [41] also showed a similar relationship between the thermal efficiency and increasing temperature difference. Yamada et al. [45] also studied the effect of solar-boosting an OTEC system on the net thermal efficiency of the OTEC system. They stated that the net thermal efficiency of an OTEC system operating during daytime is around 2.3%. They also reported that solar-boosting the OTEC system by 20 K and 40 K improves the net thermal efficiency to 6.3% and 9.5%, respectively. Aydin et al. [30] also reported that solar-superheating the OTEC system improves the net thermal efficiency by about 60%. Nguyen and Lee [46] also found, in their study, that the annual average efficiency increases from 2–4% to 6.23% when solar thermal energy was employed as a secondary heating system in an OTEC cycle. Setiawan et al. [47] also showed that increasing the operating temperature difference of the OTEC cycle by increasing the warm water inlet temperature from 26 °C to 33.5 °C increases the thermal efficiency from 7.1% to 9.54%.

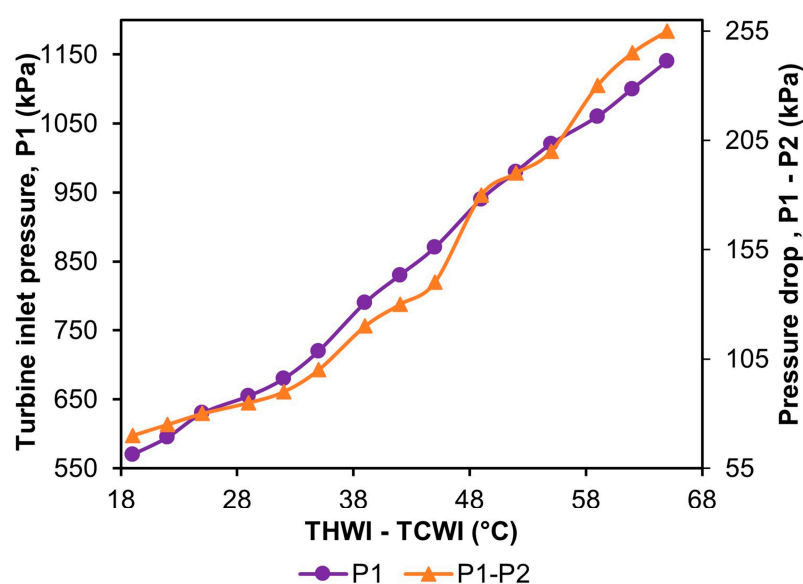


Figure 15. Turbine inlet pressure and turbine pressure drop against the operating temperature difference.

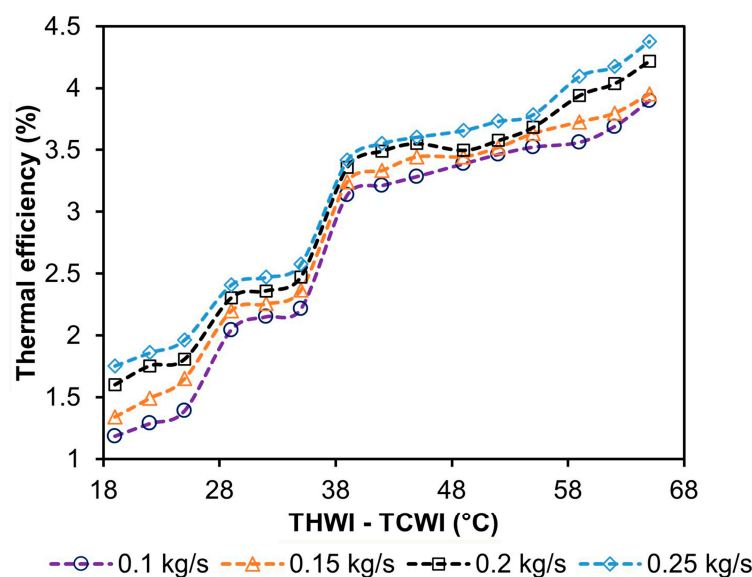


Figure 16. Effect of operating temperature difference on the thermal efficiency at different mass flow rates of the warm water.

Figure 17 depicts the effect of the operating temperature difference of the system on the power output. The power output also linearly increases as the operating temperature difference is increased. When the hot water mass flow rate was kept constant at 0.25 kg/s and the operating temperature difference of the system was increased from 19 °C to 65 °C, the power output increased from 28.69 W to 66.68 W. Numerous researchers have also shown similar trends between power output and operating temperature difference [30,31,42,44,47–49].

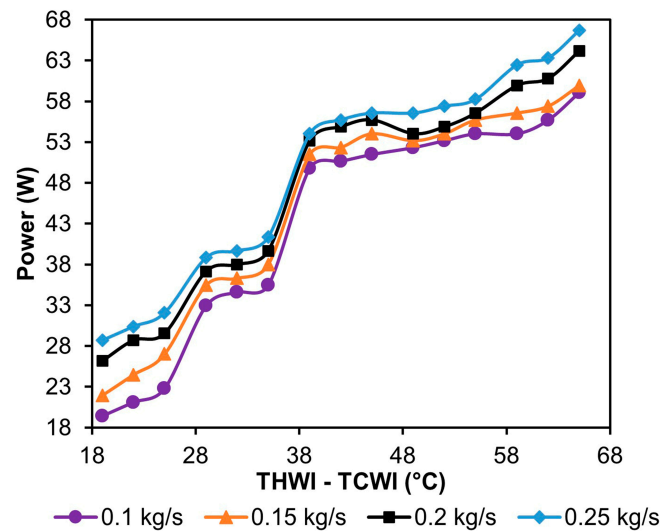


Figure 17. Effect of operating temperature difference on the power output at different mass flow rates of the warm water.

The effect of the pressure drop across the turbine on the thermal efficiency and the power output was investigated by plotting the two output parameters against the pressure drop. It can be seen from Figure 18 that the thermal efficiency and power output show an increasing trend with a rising pressure drop across the turbine. Abbas et al. [11], in their review, concluded that increasing the turbine inlet pressure and reducing the turbine back pressure improves the pressure drop across the turbine, which results in the improvement of the thermal efficiency of the system and the power output.

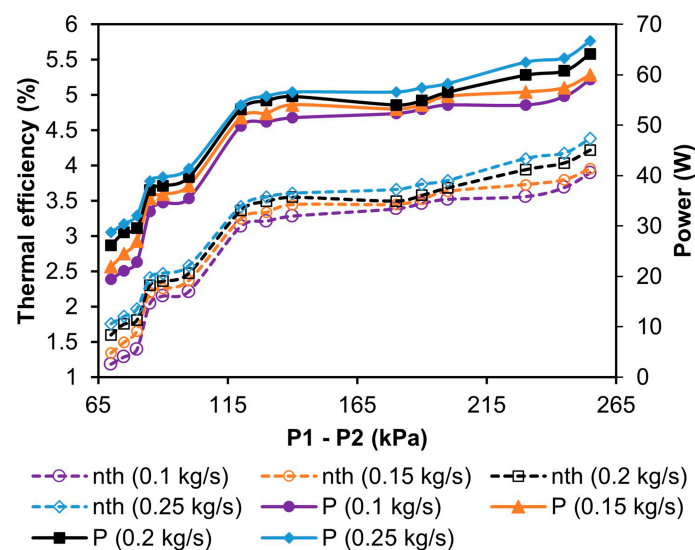


Figure 18. Variation of the thermal efficiency and the power output against the pressure drop across the turbine.

Figure 19 shows the effect of the turbine pressure inlet on the thermal efficiency of the OTEC cycle and the power output. It can be seen that both the thermal efficiency of the OTEC cycle and the power output increase as the turbine inlet pressure increases. For the highest hot water flow rate, i.e., 0.25 kg/s, the thermal efficiency of the OTEC cycle and the power output were 1.75% and 28.69 W, respectively, for the turbine inlet pressure of 570 kPa. However, when the turbine inlet pressure was increased to 1140 kPa, the thermal efficiency of the OTEC cycle increased to 4.37% and the power output increased to 66.68 W. Similar trends were seen for all the hot water flow rates.

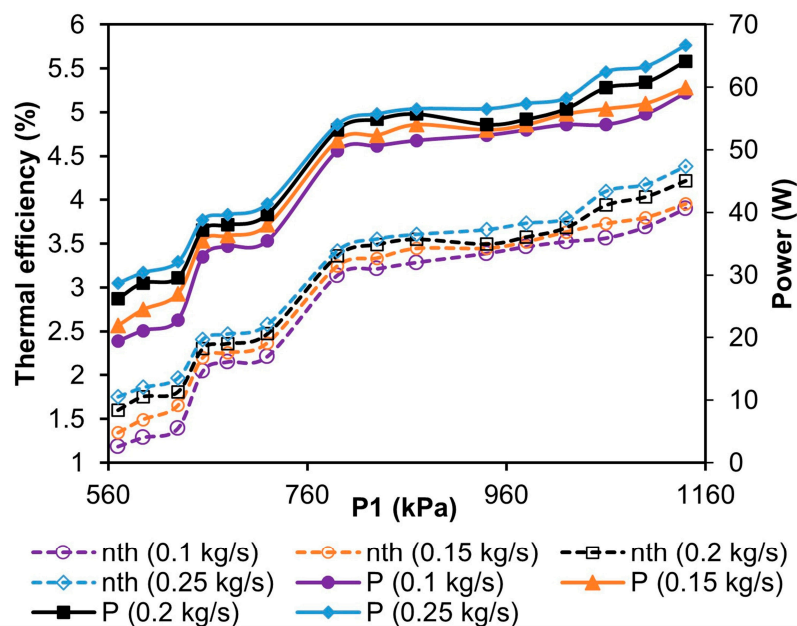


Figure 19. Thermal efficiency of the cycle and power output against the turbine inlet pressure.

Figure 20 shows the effect of the working fluid temperature at the turbine inlet on the thermal efficiency of the system and the power output. The turbine inlet temperature increases when the hot water inlet temperature increases. This is because of improved heat transfer between the hot water and the working fluid due to greater temperature difference between the two fluids [41]. An increase in turbine inlet temperature positively affects the thermal efficiency of the OTEC cycle and the power output of the turbine.

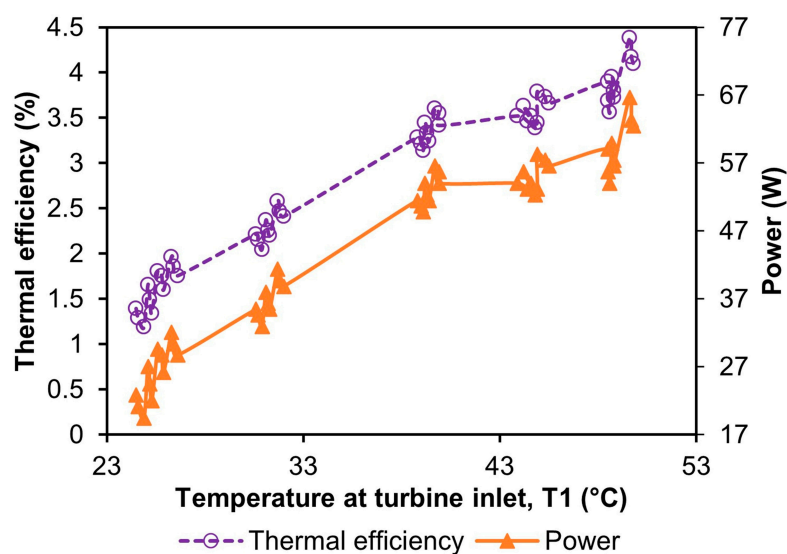


Figure 20. Thermal efficiency and power output at different turbine inlet temperatures.

The effect of the temperature drop of the hot water in the evaporator on the thermal efficiency of the cycle is shown in Figure 21. In this case, the hot water inlet temperature was varied from 30 °C to 70 °C. At any given hot water mass flow rate, the thermal efficiency increases as the temperature drop of the hot water increases. As can be seen in Figure 21A, when the mass flow rate of the hot water is kept constant at 0.25 kg/s and the hot water temperature drop is increased from 7 °C to 12 °C, the thermal efficiency of the OTEC cycle increases from 1.96% to 4.37%. An increase in the temperature drop of the hot water causes an increase in the temperature rise of the working fluid at the turbine inlet, which positively affects the thermal efficiency of the OTEC cycle.

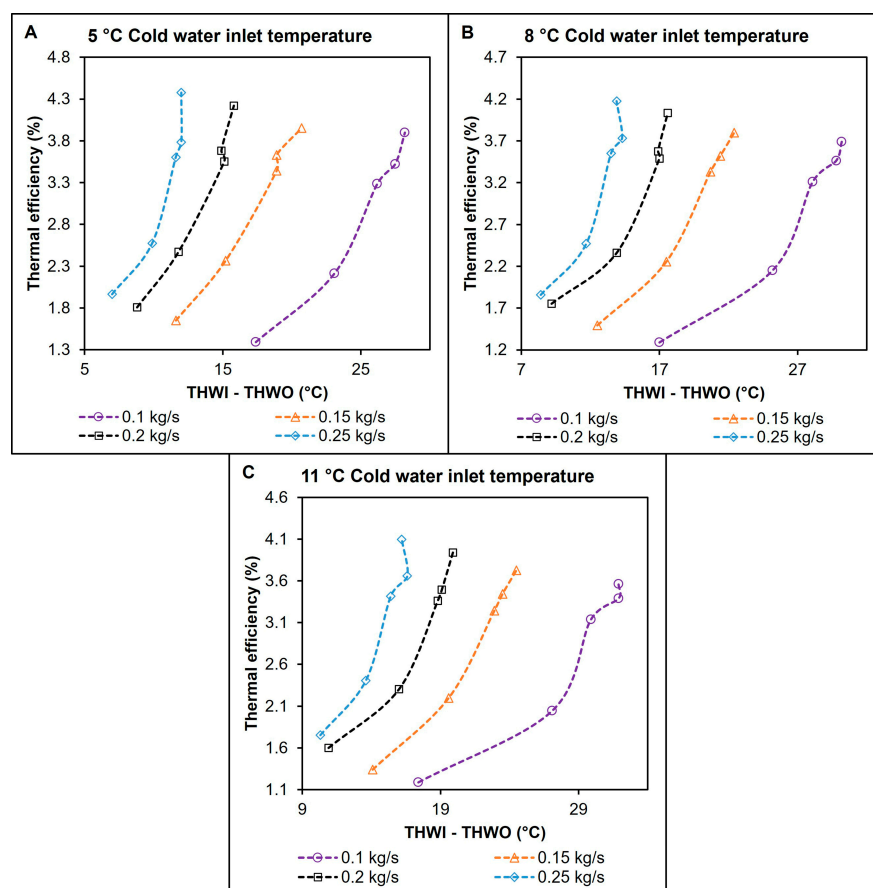


Figure 21. Thermal efficiency as a function of the temperature drop of the hot water at different flow rates at cold water inlet temperatures of 5 °C (A) to 11 °C (C).

One very interesting observation to make is the effects of hot water mass flow rate on the trends presented in Figure 21. For the highest mass flow rate of the hot water, i.e., 0.25 kg/s, the slopes are leaning towards the vertical axis. This indicates that, at higher mass flow rates, the temperature drop of the hot water is less, but the amount of heat transferred per unit time to the working fluid is greater, resulting in an enhancement in thermal efficiency. However, for the lowest hot water mass flow rate, i.e., 0.1 kg/s, the slopes are leaning towards the horizontal axis, indicating the larger temperature drop of the hot water. In this case, since the mass flow rates are lower, the heat transfers to the working fluid are lower, resulting in lower thermal efficiencies. As can be seen in Figure 21A, when the mass flow rate of the hot water was 0.1 kg/s, the maximum temperature drop of the hot water was measured to be 28.2 °C. At this mass flow rate and temperature drop, the thermal efficiency was 3.89%. However, when the mass flow rate of the hot water was 0.25 kg/s, the maximum temperature drop of the hot water was measured to be only 12 °C. At this mass flow rate and temperature drop, the thermal efficiency was 4.37%.

Figure 22 shows the effect of the temperature drop of the hot water in the evaporator on the turbine power output. The trends seen in Figures 21 and 22 are similar. As can be seen in Figure 22A, when the hot water mass flow rate is 0.25 kg/s and the hot water temperature drop increases from 7 °C to 12 °C, the turbine power output increases from 32.07 W to 66.68 W.

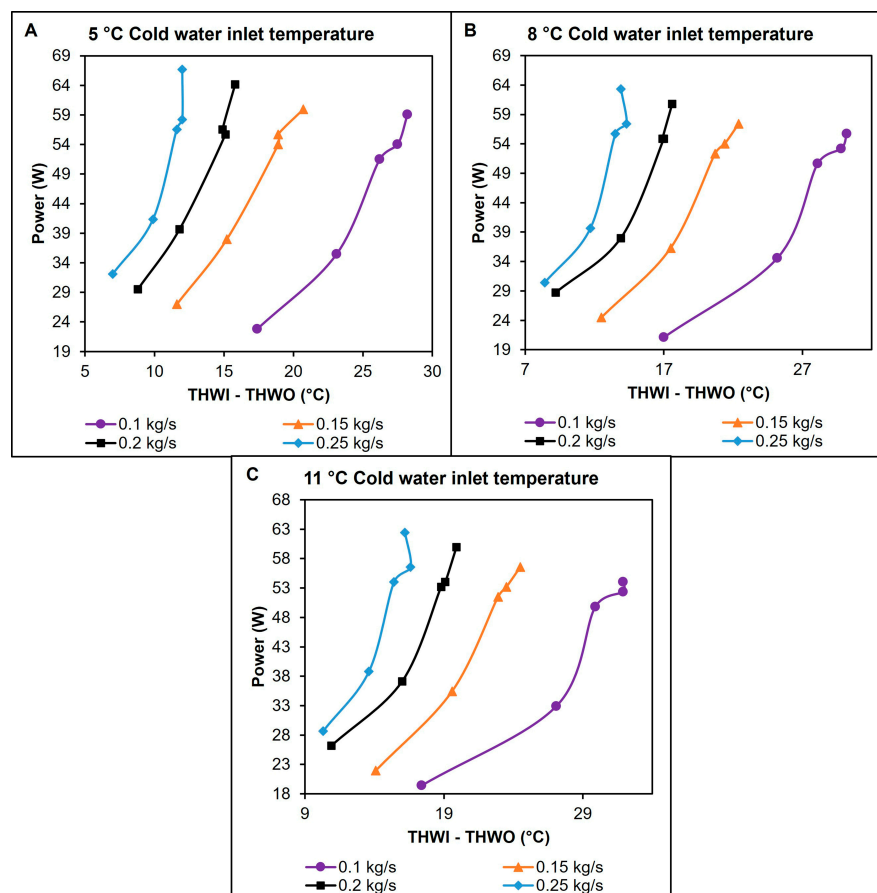


Figure 22. Power output of the system against the temperature drop of the hot water at different flow rates at cold water inlet temperatures of 5 °C (A) to 11 °C (C).

4. Discussion

The evacuated-tube solar tubes used in the heating system were able to provide a high temperature difference in the present work. Yamada et al. [45] investigated the required area of the collector to solar-boost the OTEC plant by 20 K and 40 K. They stated, in their study, that, for a 40 K boost, the area required for a flat plate collector was 5333 m², which was 893 m² larger than the required area of the flat plate collector for a 20 K boost. This was because of the drop in the efficiency of the flat plate collector as the collector area increased. However, for an evacuated-tube collector, the required collector area for a 40 K boost was 100 m² less than the area of the collector for a 20 K boost. This is because the evacuated-tube collector maintains its efficiency regardless of the area.

From Figure 9, it is clear that, on days with high solar insolation, the water temperature rises considerably. At an average solar insolation of 367 W/m², the water temperature increased to 82 °C. Thus, it is clear that higher power output and thermal efficiency can be obtained when the solar insolation is higher due to an increased hot water inlet temperature and the resulting higher temperature difference. This can clearly be seen from the results presented in Figure 10 for the cold water inlet temperature of 5 °C. For the hot water inlet temperature of 70 °C, the thermal efficiency was found to be nearly 3.9% at a mass flow

rate of 0.1 kg/s, which increased to 4.38% when the mass flow rate increased to 0.25 kg/s. The power output increased from 59 W to 66.68 W for this case. This is due to a rate of energy transfer from the hot water to the working fluid in this case. On the other hand, the thermal efficiency and the power output are significantly lower when the cold water inlet temperature is 11 °C; the thermal efficiency is 3.56% for the lowest mass flow rate and increases to 4.1% for the highest mass flow rate. Similar observations were reported by Faizal and Ahmed [41].

The effect of cold water inlet temperature can be more clearly seen from Figure 11. Both the thermal efficiency and the power output reduce when the cold water inlet temperature is increased from 5 °C to 11 °C at all the hot water inlet temperatures. It can be noted that the drop in thermal efficiency is considerable for the mass flow rates of 0.1 kg/s and 0.15 kg/s for all the hot water inlet temperatures.

The gradual increase in the thermal efficiency and the power output with increasing hot water inlet temperature is clearly evident from Figure 12A–C. Amyra et al. [49] presented similar results in their study. Gao et al. [44] tried superheating the working fluid by 11.6 °C to 26.4 °C and reported an increase in thermal efficiency. Idrus et al. [29] also showed a similar trend on the effect that a superheated temperature has on the cycle efficiency. Yuan et al. [43] also carried out similar study and determined that the heating source temperature has the most substantial effect on the thermal efficiency. On the other hand, as the cold water inlet temperature is reduced in the three cases, the drop in the thermal efficiency and the power output is clearly seen. For the cold water inlet temperature of 11 °C, the lowest thermal efficiencies and power outputs can be seen for all the four mass flow rates of the hot fluid. This is due to a reduction in the driving force, which is the difference in the temperatures of the hot and cold water streams. The lowest thermal efficiency can be seen for the case of the 30 °C hot water inlet temperature and 11 °C cold water inlet temperature. In this case, the temperature difference is only 19 degrees, and it is not advisable to install an OTEC plant where the temperature difference is less than 20 degrees.

The turbine inlet pressures and the pressure drops across the turbine, presented in Figures 13 and 14, were plotted for the three cold water inlet temperatures shown in the legends of the two figures. Both the inlet pressure and the pressure drop are higher for a higher operating temperature difference. As the turbine is able to extract more power from the high enthalpy working fluid, the pressure drop is higher. The turbine inlet pressure and the pressure drop across the turbine for all the possible operating temperatures that were experimented are presented in Figure 15. At the highest operating temperature difference, a pressure drop of 255 kPa was recorded. The effect of the operating temperature difference on the thermal efficiency and the power output, as presented in Figures 16 and 17, exhibits an increasing trend as the temperature difference is increased. The higher mass flow rates of the hot fluid result in higher efficiency and power. The lower pressure drops are associated with lower efficiencies and power outputs, as can be seen from Figure 18. As discussed earlier, a higher enthalpy drop results in higher output and efficiency. Higher turbine inlet pressure results in higher thermal efficiency and power output. Ishaq and Dincer [25], in their study, investigated the effect of turbine inlet pressure on the power output. They concluded that raising the turbine inlet pressure causes both the turbine power and the net power to improve. Chen et al. [22] showed an increase in the thermal efficiency and in the output power of OTEC systems when the turbine inlet pressures were increased. Peng et al. [12], in their study, also found that both the thermal efficiency and net power output first increased and then decreased as the turbine inlet pressure increased.

The turbine inlet temperature is an important parameter not only for the OTEC cycle, but also for a number of power plant cycles including the Brayton cycle and the superheated

Rankine cycle. In the case of present cycle, since the operating temperatures are low, the turbine inlet temperature has a marked effect on the thermal efficiency and the power output. At a minimum turbine inlet temperature of 24.5 °C, the thermal efficiency was 1.39% and the turbine power output was 22.78 W, whereas, when the turbine inlet temperature was increased to a maximum value of 49.8 °C, the thermal efficiency increased to 4.09% and the turbine power output was increased to 62.45 W, as shown in Figure 20. Faizal et al. [41] showed similar trends for thermal efficiency and turbine power output against the turbine inlet temperature. Zhang et al. [50] also showed an increasing trend for thermal efficiency and output work when the turbine inlet temperature was increased. They showed that, when the turbine inlet temperature was increased by 4 K, the thermal efficiency improved by 3.3%. They also reported a similar increase in the power output as well when the turbine inlet temperature increased. According to Zhang et al. [50], when the turbine inlet temperature reduces, the quality (dryness fraction) of the working fluid in the whole section reduces as well, which directly affects the thermal efficiency and the power output.

A higher temperature drop of the hot water (for a given mass flow rate) in the evaporator translates into the higher enthalpy gain of the working fluid before it enters the turbine. This will ultimately result in higher output and efficiency. However, in this case, higher temperature drops were recorded for the lower mass flow rates of the hot fluid. Hence, the rate of energy transfer to the working fluid is lower, causing a drop in the thermal efficiency and the power output, as shown in Figures 21 and 22. It is recommended that experiments be performed on a large range of temperature drops of hot water and mass flow rates to find an optimum value at which the thermal efficiency and power output are maximized. It should be noted that, for an actual OTEC power plant, the turbine inlet temperature will vary depending on the time of the day as well as on the season of the year, as reported in [51]. For countries in the tropical region, the maximum temperatures are recorded in the months of January and February; hence, the available energy that can be transferred to the working fluid would also be higher during these months. Experiments on large-scale OTEC systems also need to be performed in tropical countries to assess the maximum power generation at high thermal efficiencies.

5. Conclusions

Lower thermal efficiencies of OTEC plants are always a concern, making governments and investors reluctant to invest in OTEC plants compared to other renewable energy technologies like wind turbines. One of the effective methods of improving the efficiency as well as power output of OTEC plants is to heat the surface water using solar energy. In this work, a solar water heater was employed to increase the operating temperature difference of a closed-cycle OTEC plant. The hot water inlet temperature was increased from 30 °C to 70 °C in increments of 10 degrees and the cold water inlet temperature was varied from 5 °C to 11 °C in increments of 3 degrees. This increase in hot water inlet temperature from 30 °C to 70 °C at a constant cold water inlet temperature of 5 °C increased the power output from 32.07 W to 66.68 W (107.9% increase) and the thermal efficiency from 1.96% to 4.37% (123% increase) at the highest mass flow rate of hot water. This is due to a larger heat transfer from the hot water to the working fluid. The turbine inlet temperature has a strong influence on power output and efficiency, as for most thermal power plants. At greater operating temperature differences between the hot water and cold water and higher mass flow rates, the OTEC system gave higher efficiencies due to a higher transfer of energy to the system. Further research is recommended for a large range of temperature drops of hot water and mass flow rates to find an optimum value such that the thermal efficiency and power output are maximized. It is also recommended to conduct experiments at

kW-sized OTEC plants to evaluate the effect of higher hot water inlet temperatures on the performance of the plant.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en18010127/s1>, it contain additional pictures of the experimental setup and individual components.

Author Contributions: Conceptualization, M.R.A.; methodology, R.D.P. and M.A.; software, R.D.P.; validation, R.D.P. and M.R.A.; formal analysis, R.D.P.; investigation, R.D.P. and M.A.; resources, R.D.P. and M.R.A.; data curation, R.D.P.; writing—original draft preparation, R.D.P.; writing—review and editing, M.R.A.; visualization, R.D.P. and M.R.A.; supervision, M.R.A.; project administration, R.D.P., M.A., and M.R.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Sample data of thermal efficiency and power output under different operating conditions are available at the university repository at the link <https://repository.usp.ac.fj/id/eprint/14674/> (accessed on 20 December 2024).

Acknowledgments: The authors would like to acknowledge the technical support provided by the Technicians of the Division of Mechanical Engineering during the experimental phase of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

Abbreviations

COP	Conference of the Parties
EES	Engineering Equation Solver
LCOE	Levelized cost of electricity
OTEC	Ocean thermal energy conversion
PEM	Proton exchange membrane

Symbols

P	Power output (W)
P1	Pressure at turbine inlet (kPa)
P2	Pressure at turbine outlet (kPa)
s	Entropy (kJ/kg.K)
T1	Temperature at turbine inlet (°C)
THWI	Temperature of hot water at inlet (°C)
THWO	Temperature of hot water at outlet (°C)
TCWI	Temperature of cold water at inlet (°C)
TCWO	Temperature of cold water at outlet (°C)
η_{th}	Thermal efficiency (%)

References

1. Agreement, P. Paris Agreement. In Proceedings of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris), Paris, France, 30 November–13 December 2015. Retrieved December 2015.
2. United-Nations. Key Aspects of the Paris Agreement. Available online: <https://unfccc.int/most-requested/key-aspects-of-the-paris-agreement> (accessed on 20 September 2024).
3. United Nations Environment Programme. Emissions Gap Report 2022: The Closing Window—Climate Crisis Calls for Rapid Transformation of Societies. 2022. Available online: [https://concito.dk/files/media/document/EGR2022%20\(1\).pdf](https://concito.dk/files/media/document/EGR2022%20(1).pdf) (accessed on 14 November 2023).
4. Herzog, A.V.; Lipman, T.E.; Kammen, D.M. Renewable Energy Sources. In *Encyclopedia of Life Support Systems (EOLSS), Forerunner Volume-‘Perspectives and Overview of Life Support Systems and Sustainable Development’*; EOLSS-UNESCO: e-book, 2001; p. 57. Available online: http://rael.berkeley.edu/old_drupal/sites/default/files/old-site-files/2001/Herzog-Lipman-Kammen-RenewableEnergy-2001.pdf (accessed on 24 April 2024).

5. Zereshtkian, S.; Mansoury, D. A Study on the Feasibility of Using Solar Radiation Energy and Ocean Thermal Energy Conversion to Supply Electricity for Offshore Oil and Gas Fields in the Caspian Sea. *Renew. Energy* **2021**, *163*, 66–77. [\[CrossRef\]](#)
6. Wang, L.; Huang, C.-B. Dynamic Stability Analysis of a Grid-Connected Solar-Concentrated Ocean Thermal Energy Conversion System. *IEEE Trans. Sustain. Energy* **2010**, *1*, 10–18. [\[CrossRef\]](#)
7. Rajagopalan, K.; Nihous, G.C. Estimates of Global Ocean Thermal Energy Conversion (OTEC) Resources Using an Ocean General Circulation Model. *Renew. Energy* **2013**, *50*, 532–540. [\[CrossRef\]](#)
8. Kempener, R.; Neumann, F. Ocean Thermal Energy Conversion, Technology Brief. IRENA Ocean Energy Technology Brief. 2014, p. 1. Available online: <https://www.irena.org/Publications/2014/Jun/Ocean-Thermal-Energy-Conversion> (accessed on 20 November 2024).
9. Masutani, S.; Takahashi, P. Ocean Thermal Energy Conversion (OTEC). *Oceanography* **2001**, *22*, 625.
10. Wang, L.; Shi, L.; Dian-Qing, L. Optimization Design About Ocean Thermal Energy Conversion in Coastal Area of East China. *Renew. Energy Resour.* **2010**, *28*, 134–136.
11. Abbas, S.M.; Alhassany, H.D.S.; Vera, D.; Jurado, F. Review of Enhancement for Ocean Thermal Energy Conversion System. *J. Ocean Eng. Sci.* **2022**, *8*, 533–545. [\[CrossRef\]](#)
12. Peng, J.; Ge, Y.; Chen, F.; Liu, L.; Wu, H.; Liu, W. Theoretical and Experimental Study on the Performance of a High-Efficiency Thermodynamic Cycle for Ocean Thermal Energy Conversion. *Renew. Energy* **2022**, *185*, 734–747. [\[CrossRef\]](#)
13. Assareh, E.; Assareh, M.; Alirahmi, S.M.; Jalilinasrabad, S.; Dejdari, A.; Izadi, M. An Extensive Thermo-Economic Evaluation and Optimization of an Integrated System Empowered by Solar-Wind-Ocean Energy Converter for Electricity Generation—Case Study: Bandar Abbas, Iran. *Therm. Sci. Eng. Prog.* **2021**, *25*, 100965. [\[CrossRef\]](#)
14. Faizal, M.; Rafiuddin Ahmed, M. On the Ocean Heat Budget and Ocean Thermal Energy Conversion. *Int. J. Energy Res.* **2011**, *35*, 1119–1144. [\[CrossRef\]](#)
15. Liu, W.; Xu, X.; Chen, F.; Liu, Y.; Li, S.; Liu, L.; Chen, Y. A Review of Research on the Closed Thermodynamic Cycles of Ocean Thermal Energy Conversion. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109581. [\[CrossRef\]](#)
16. Zhang, W.; Li, Y.; Wu, X.; Guo, S. Review of the Applied Mechanical Problems in Ocean Thermal Energy Conversion. *Renew. Sustain. Energy Rev.* **2018**, *93*, 231–244. [\[CrossRef\]](#)
17. Langer, J.; Quist, J.; Blok, K. Recent Progress in the Economics of Ocean Thermal Energy Conversion: Critical Review and Research Agenda. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109960. [\[CrossRef\]](#)
18. Langer, J.; Quist, J.; Blok, K. Upscaling Scenarios for Ocean Thermal Energy Conversion with Technological Learning in Indonesia and Their Global Relevance. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112086. [\[CrossRef\]](#)
19. Arias-Gaviria, J.; Osorio, A.F.; Arango-Aramburo, S. Estimating the Practical Potential for Deep Ocean Water Extraction in the Caribbean. *Renew. Energy* **2020**, *150*, 307–319. [\[CrossRef\]](#)
20. Osorio, A.F.; Arias-Gaviria, J.; Devis-Morales, A.; Acevedo, D.; Velasquez, H.I.; Arango-Aramburo, S. Beyond Electricity: The Potential of Ocean Thermal Energy and Ocean Technology Ecoparks in Small Tropical Islands. *Energy Policy* **2016**, *98*, 713–724. [\[CrossRef\]](#)
21. de Souza, R.V.; Fernandes, E.H.L.; de Azevedo, J.L.L.; dos Santos Passos, M.; Corrêa, R.M. Potential for Conversion of Thermal Energy in Electrical Energy: Highlighting the Brazilian Ocean Thermal Energy Park and the Inverse Anthropogenic Effect. *Renew. Energy* **2020**, *161*, 1155–1175. [\[CrossRef\]](#)
22. Chen, F.; Liu, L.; Peng, J.; Ge, Y.; Wu, H.; Liu, W. Theoretical and Experimental Research on the Thermal Performance of Ocean Thermal Energy Conversion System Using the Rankine Cycle Mode. *Energy* **2019**, *183*, 497–503. [\[CrossRef\]](#)
23. Wang, M.; Jing, R.; Zhang, H.; Meng, C.; Li, N.; Zhao, Y. An Innovative Organic Rankine Cycle (OrC) Based Ocean Thermal Energy Conversion (OTEC) System with Performance Simulation and Multi-Objective Optimization. *Appl. Therm. Eng.* **2018**, *145*, 743–754. [\[CrossRef\]](#)
24. Yang, M.-H.; Yeh, R.-H. Investigation of the Potential of R717 Blends as Working Fluids in the Organic Rankine Cycle (ORC) for Ocean Thermal Energy Conversion (OTEC). *Energy* **2022**, *245*, 123317. [\[CrossRef\]](#)
25. Ishaq, H.; Dincer, I. A Comparative Evaluation of Otec, Solar and Wind Energy Based Systems for Clean Hydrogen Production. *J. Clean. Prod.* **2020**, *246*, 118736. [\[CrossRef\]](#)
26. Hasan, A.; Dincer, I. An Ocean Thermal Energy Conversion Based System for District Cooling, Ammonia and Power Production. *Int. J. Hydrogen Energy* **2020**, *45*, 15878–15887. [\[CrossRef\]](#)
27. Yilmaz, F. Energy, Exergy and Economic Analyses of a Novel Hybrid Ocean Thermal Energy Conversion System for Clean Power Production. *Energy Convers. Manag.* **2019**, *196*, 557–566. [\[CrossRef\]](#)
28. Khanmohammadi, S.; Baseri, M.M.; Ahmadi, P.; Al-Rashed, A.A.; Afrand, M. Proposal of a Novel Integrated Ocean Thermal Energy Conversion System with Flat Plate Solar Collectors and Thermoelectric Generators: Energy, Exergy and Environmental Analyses. *J. Clean. Prod.* **2020**, *256*, 120600. [\[CrossRef\]](#)
29. Idrus, N.M.; Musa, M.; Yahya, W.; Ithnin, A. Geo-Ocean Thermal Energy Conversion (Geotec) Power Cycle/Plant. *Renew. Energy* **2017**, *111*, 372–380. [\[CrossRef\]](#)

30. Aydin, H.; Lee, H.-S.; Kim, H.-J.; Shin, S.K.; Park, K. Off-Design Performance Analysis of a Closed-Cycle Ocean Thermal Energy Conversion System with Solar Thermal Preheating and Superheating. *Renew. Energy* **2014**, *72*, 154–163. [\[CrossRef\]](#)
31. Khosravi, A.; Syri, S.; Assad, M.E.H.; Malekan, M. Thermodynamic and Economic Analysis of a Hybrid Ocean Thermal Energy Conversion/Photovoltaic System with Hydrogen-Based Energy Storage System. *Energy* **2019**, *172*, 304–319. [\[CrossRef\]](#)
32. Malik, M.Z.; Musharavati, F.; Khanmohammadi, S.; Baseri, M.M.; Ahmadi, P.; Nguyen, D.D. Ocean Thermal Energy Conversion (Otec) System Boosted with Solar Energy and Teg Based on Exergy and Exergo-Environment Analysis and Multi-Objective Optimization. *Sol. Energy* **2020**, *208*, 559–572. [\[CrossRef\]](#)
33. Yilmaz, F.; Ozturk, M.; Selbas, R. Thermodynamic Performance Assessment of Ocean Thermal Energy Conversion Based Hydrogen Production and Liquefaction Process. *Int. J. Hydrogen Energy* **2018**, *43*, 10626–10636. [\[CrossRef\]](#)
34. Ahmadi, P.; Dincer, I.; Rosen, M.A. Energy and Exergy Analyses of Hydrogen Production Via Solar-Boosted Ocean Thermal Energy Conversion and Pem Electrolysis. *Int. J. Hydrogen Energy* **2013**, *38*, 1795–1805. [\[CrossRef\]](#)
35. Semmari, H.; Stitou, D.; Mauran, S. A Novel Carnot-Based Cycle for Ocean Thermal Energy Conversion. *Energy* **2012**, *43*, 361–375. [\[CrossRef\]](#)
36. Hu, Z.; Wan, Y.; Zhang, C.; Chen, Y. Compression-Assisted Absorption Refrigeration Using Ocean Thermal Energy. *Renew. Energy* **2022**, *186*, 755–768. [\[CrossRef\]](#)
37. Kim, N.J.; Ng, K.C.; Chun, W. Using the Condenser Effluent from a Nuclear Power Plant for Ocean Thermal Energy Conversion (Otec). *Int. Commun. Heat Mass Transf.* **2009**, *36*, 1008–1013. [\[CrossRef\]](#)
38. Bombarda, P.; Invernizzi, C.; Gaia, M. Performance Analysis of OTEC Plants with Multilevel Organic Rankine Cycle and Solar Hybridization. *J. Eng. Gas Turbines Power* **2013**, *135*, 042302. [\[CrossRef\]](#)
39. Wu, Z.; Feng, H.; Chen, L.; Tang, W.; Shi, J.; Ge, Y. Constructal Thermodynamic Optimization for Ocean Thermal Energy Conversion System with Dual-Pressure Organic Rankine Cycle. *Energy Convers. Manag.* **2020**, *210*, 112727. [\[CrossRef\]](#)
40. Budihardjo, I.; Morrison, G.; Behnia, M. Performance of Single-Ended Evacuated Tube Solar Water Heaters. In Proceedings of the Australian and New Zealand Solar Energy Society Conference 2004, Perth, Australia, 30 November–3 December 2004; pp. 1–10.
41. Faizal, M.; Ahmed, M.R. Experimental Studies on a Closed Cycle Demonstration OTEC Plant Working on Small Temperature Difference. *Renew. Energy* **2013**, *51*, 234–240. [\[CrossRef\]](#)
42. Yang, M.-H.; Yeh, R.-H. Analysis of Optimization in an OTEC Plant Using Organic Rankine Cycle. *Renew. Energy* **2014**, *68*, 25–34. [\[CrossRef\]](#)
43. Yuan, H.; Mei, N.; Hu, S.; Wang, L.; Yang, S. Experimental Investigation on an Ammonia-Water Based Ocean Thermal Energy Conversion System. *Appl. Therm. Eng.* **2013**, *61*, 327–333. [\[CrossRef\]](#)
44. Gao, W.; Wang, F.; Tian, Z.; Zhang, Y. Experimental investigation on the performance of a Solar-Ocean Thermal Energy Conversion system based on the Organic Rankine Cycle. *Appl. Therm. Eng.* **2024**, *245*, 122776. [\[CrossRef\]](#)
45. Yamada, N.; Hoshi, A.; Ikegami, Y. Performance Simulation of Solar-Boosted Ocean Thermal Energy Conversion Plant. *Renew. Energy* **2009**, *34*, 1752–1758. [\[CrossRef\]](#)
46. Nguyen, V.H.; Lee, G.S. Performance Investigation of Solar-Heating Ocean Thermal Energy Conversion (Sh-Otec) in Korea. *Trans. Korean Soc. Mech. Eng. B* **2013**, *37*, 43–49. [\[CrossRef\]](#)
47. Setiawan, I.R.; Purnama, I.; Halim, A. Increasing Efficiency of a 33 MW OTEC in Indonesia Using Flat-Plate Solar Collector for the Seawater Heater. *J. Mechatron. Electr. Power Veh. Technol.* **2017**, *8*, 33–39. [\[CrossRef\]](#)
48. Dejdar, A.; Assareh, E.; Keykhah, S.; Bedakhanian, A.; Lee, M. A Transient Model for Clean Electricity Generation Using Solar Energy and Ocean Thermal Energy Conversion (Otec)-Case Study: Karkheh Dam-Southwest Iran. *Energy Nexus* **2023**, *9*, 100176.
49. Amyra, M.; Sarip, S.; Ikegami, Y.; Chik, M.A.T.; Yacob, R.; Hara, H.; Zakaria, Z. Simulation Study on Enhancing Hydrogen Production in an Ocean Thermal Energy (OTEC) System Utilizing a Solar Collector. *J. Teknol.* **2015**, *77*, 23–31. [\[CrossRef\]](#)
50. Zhang, C.; Wu, Z.; Wang, J.; Ding, C.; Gao, T.; Chen, Y. Thermodynamic Performance of a Radial-Inflow Turbine for Ocean Thermal Energy Conversion Using Ammonia. *Renew. Energy* **2023**, *202*, 907–920. [\[CrossRef\]](#)
51. Costa, M.; Prasad, R.; Ali, M.; Khan, M.G.M.; De Ramon N'Yeurt, A.; Ahmed, M.R. Variation of Power Output From an OTEC Power Plant Based on Longterm Sea Surface Temperature Data Analysis. In Proceedings of the ASME 2022 International Mechanical Engineering Congress and Exposition, Columbus, OH, USA, 30 October–3 November 2022; Volume 6: Energy. V006T08A031. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.