# Techno-economic efficiencies and environmental criteria of Ocean Thermal Energy Conversion closed Rankine cycle using different working fluids

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**Abstract.** Ocean Thermal Energy Conversion (OTEC) is a foundation for an appealing renewable energy technology owing to its vast and inexhaustible resources of energy, stability, and sustainable output. Development of OTEC power plant is to exploit the energy accumulated in between the top layer of warm surface seawater (heat source), and the cold layer of deep seawater (heat sink). It operates based on Rankine cycle to produce electricity between the source and the sink at the smallest temperature difference of approximately 20 K. OTEC power plant commonly utilized ammonia as working fluid. Nevertheless, ammonia poses potential lethal health risks and hazardous fluid. Hence, the effect of the working fluid types and the subsequent operation conditions may be critical and therefore become the subject of this study. In addition to OTEC power plant's thermodynamic efficiencies study, this research also explores the economic efficiencies in term of capital cost per net power output ($/kW) and environmental criteria of different working fluids including that of ammonia, ammonia-water mixture (0.9), propane, and refrigerants (R22, R32, R134a, R143a, and R410a). The results showed that ammonia-water mixture gave the excellent performance with regard to the characteristics of heat transfer with the best thermodynamic efficiency of 4.04% compared to pure ammonia with 3.21%, propane with 3.09%, followed by refrigerants from 3.03% to 3.13%. Capital cost of using propane was economically efficient with 15730 $/kW compared to ammonia-water mixture at 16201$/kW, refrigerants from 16990 $/kW to 21400 $/kW, and pure ammonia being the costliest at 21700 $/kW. Despite being lower in its thermodynamic efficiency, propane gave the lowest capital cost and had the lowest toxicity in contrast to all other working fluids. Therefore, propane has the potential to be used as a clean and safe working fluid that would further enhance the OTEC technology.

Keywords: ocean, thermal energy, renewable, heat sink, power plant

## 1. Introduction

Ocean Thermal Energy Conversion (OTEC) has tremendous prospective in deep ocean water area, in which a sufficiently high temperature difference between the surface water and a specific depth is required to effectively run an OTEC power plant. In 1881, Arsonval's initial concept specified that the optimum temperature difference needed for the installation of an OTEC plant is larger than 20 K [1]. The system will work between the surface seawater at 30°C (known as heat source), and seawater at

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1000 m depth with temperature of 4°C (known as heat sink) [2-4]. OTEC power plant technology is developed on a basis of open (OC-OTEC) and closed Rankine cycles (CC-OTEC). Previous research reported that the process have to be founded upon the Uehara cycle for optimal power plant output, implementing ammonia-water mixture as the working fluid with smaller than 20 K of temperature difference, and at 5-6% thermal efficiency [5].

Additionally, the selection of suitable working fluids has a significant impact on the entire system viability and efficiency. Ammonia has been considered as the best working fluid because it has a suitable boiling temperature (28°C - 32°C) for the OTEC purpose [6]. However, it is toxic and therefore can be hazardous to the environment. Recent development of working fluids shows that ammonia can be replaced by other working fluids with zero Ozone Depletion Potential (ODP) and zero Global Warming Potential (GWP). Finding other suitable substitutes is a big challenge to this study. Several studies have been done which have shown better results with the use of other working fluids such as hydrocarbon (HC) and hydrofluorocarbons (HFCs) [7-10]. The other findings reported that R123 displayed the best performance but the fluid contributes to the ODP and GWP. Therefore, isopentane is suggested as it showed the second best performance and regarded as environmental friendly working fluid for the system. However, the applications of their research are for waste heat systems, but can still be operated at low temperature.

A paper that reviews about 35 working fluids and analyzes the effect of fluid properties on the cycle efficiency is written by Chen at al. [11]. They have categorized the working fluids under three characteristics which are dry, isotropic, or wet fluid according to the T-s diagram. Understanding the characteristic of the working fluids eases the process of selecting the appropriate working fluid for the cycle. Calm and Hourahan [12] has interpreted the data of working fluids into a table with ODP and GWP of selected refrigerant. Figure 1 shows the numbers of OTEC previous research focusing on different working fluids from 1979 to 2016.

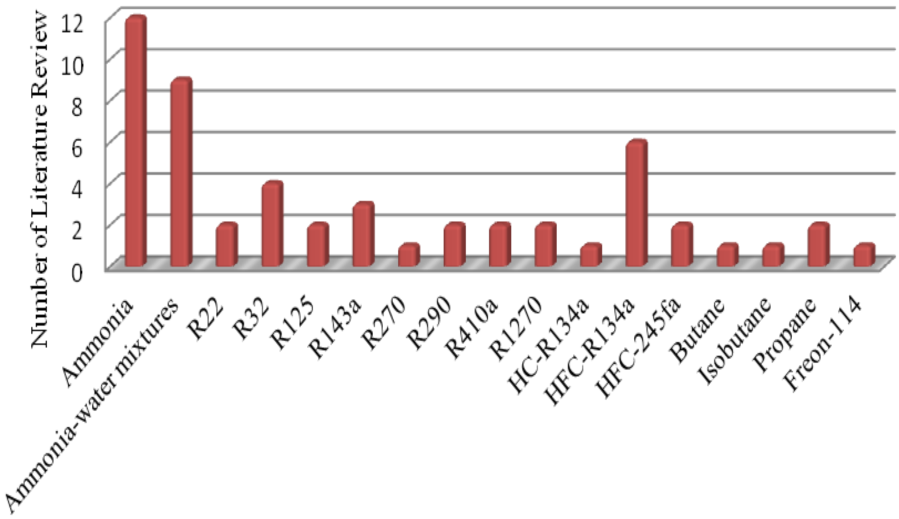


**Figure 1.** The numbers of OTEC previous research focusing on different working fluids from 1979 to 2016.

Plant operation for OTEC technology does not use any fuel. Therefore, the major cost component could be construction cost of the infrastructure. According to the findings by Lennard [13] a 10 MW capacity of floating OTEC power plant would cost 10,000USD/kW. The closed rankine cycle and ammonia as the working fluid was used. A 10MW floating plant had been designed using plate-fin heat exchanger which estimated to consume the highest percentage of cost component of the plant. This research had been stopped because of the exorbitant estimated cost until further development of the design of the demonstration plant until it would be suitable for production. Similarly, Rogers et. al [14] stated that a land based of 1 MW OTEC plant would cost 18,000 USD/kW. The study conducted to enhance the economic prospect for both open cycle and closed rankine cycle. They highlighted the key importance was the demonstration of technical feasibility of using the OTEC flash evaporation to produce seawater. Thus, from the findings of such 'by-product' of fresh water, notably improves the cost effectiveness in producing electrical energy. Subsequently, from the research of 'Economics of Ocean Thermal Energy Conversion' by Vega [15], it was found that for the 10 MW open cycle plant with second stage water production estimated by 14,700 USD/kW for the capital cost of the plant. The research continues by Vega [16] for 100 MW floating plant for 7900 USD/kW. The capital cost of 53.5 MW is just about 8430 USD/kW for this study. The differential value of the plant cost was calculated by converting to the present day cost using the USA 20-year average for equipment price-index inflation. The estimated cost value also relied on the application of the same technologies, that new generation design will achieve cost savings of as much as 30% because in the past, the OTEC work did not yield a single order because there were no real customers for the technology. According to the previous literature, the capital cost was calculated based on ammonia as working fluid. Evidently, the current research will come out with the comparison for economic efficiency by using different working fluids.

Therefore, the objective of this paper is to examine the efficiency in terms of techno-economic and environmental criteria of the OTEC basic closed Rankine cycle using varying working fluids. At the initial stage of the study, preliminary simulation was conducted to confirm the simulation model with the reference from past OTEC studies. The similar developed model was implemented to analyze the efficiency of the OTEC basic closed Rankine cycle using eight varying working fluids.

## 2. Methodology

### *2.1. Introduction*

Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is a platform design framework created by National Instruments that is employed as languages of visual programming. Its implementation in numerous fields of engineering (e.g. aeronautical, mechanical, electrical, etc.) has led to the advancement of the world's largest and most complex applications to fulfil future demands. LabVIEW offers the users with flexibility through intuitive graphical programming which helps to reduce the time needed for test development. The thermodynamic model has been created in LabVIEW and linked to the working fluid data base in National Institute of Standards and Technologies (NIST) RefProp 9 and PROPATH. The thermodynamic model of OTEC cycle is created in LabVIEW to run numerical calculation, simulations and compare the working fluids from a thermophysical perspective..

### *2.2. Analytical Techniques of Thermodynamics*

The simulation was based upon the thermodynamic analysis of the OTEC Rankine cycle performance. The Rankine cycle comprises of four major components, which are condenser, coolant pump, turbine, and evaporator. Several assumptions were included to facilitate the simulation analysis and assessment [17,18], which are described as follows:

i. Every component is in steady state.
ii. Any heat loss and pressure drop are disregarded.
iii. The system is completely insulated.
iv. All pumps and turbines are given isentropic efficiency.

For the steady state energy balance equation, the total energy entering a system is equal to the total energy exiting the system, as expressed in Eq. 1

$$E_{in} = E_{out} \tag{1}$$

or it can be elaborated as in Eq. 2

$$W_{in} + Q_{in} + \sum \dot{m}_{in} = W_{out} + Q_{out} + \sum \dot{m}_{out} \tag{2}$$

where $\dot{Q}$ represents heat transfer rate; $\dot{m}_{in}$ and $\dot{m}_{out}$ is inlet and outlet mass flow rate; whereas $W_{in}$ and $W_{out}$ is work inlet and outlet, respectively. By assuming the system is completely insulated and any

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heat losses are neglected; $Q_{in}$ = 0, $Q_{out}$ = 0 and $W_{out}$ =0; the energy balance in the pump is expressed as in Eq. 3

$$W_{in} + \sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3}$$

From Eq. 3, the work supplied is given as in Eq. 4

$$W_{in} = \sum \dot{m}_{out} - \sum \dot{m}_{in} \tag{4}$$

Rate of heat supplied to the cycle (evaporator), $\dot{Q}_e$ is expressed as in Eq. 5

$$\dot{Q}_e = \dot{m}_{wf}\ \Delta h_e \tag{5}$$

Rate of heat rejected from the cycle (condenser), $\dot{Q}_c$ is indicated as in Eq. 6

$$\dot{Q}_c = \dot{m}_{wf}\ \Delta h_c \tag{6}$$

Rate of heat absorbed from the warm seawater, $\dot{Q}_{e,ws}$ is expressed as in Eq. 7

$$\dot{Q}_{e,ws} = \dot{m}_{ws}\, c_p \Delta T_{ws} \tag{7}$$

Rate of heat rejected into the cold seawater, $\dot{Q}_{c,cw}$ is indicated as in Eq. 8

$$\dot{Q}_{c,cw} = \dot{m}_{cs}\, c_p \Delta T_{cs} \tag{8}$$

where $\dot{m}_{ws}$ and $\dot{m}_{cs}$ are the mass flow rate of warm and cold seawater, respectively. $c_p$ is the seawater specific heat capacity at constant pressure.

The working fluid pump, $W_{P_{wf}}$ and the turbine work, $W_T$ is written as in Eq. 9 and Eq. 10

$$W_{P_{wf}} = \dot{m}_{wf}\ v(P_2 - P_1) \tag{9}$$

$$W_T = \dot{m}_{wf}\ \Delta h \tag{10}$$

where $\Delta h$ represents the enthalpy difference in the turbine system.

Referring to Uehara and Ikegami [18], the working fluid pumping power, $P_{Pwf}$ is given as in Eq. 11. The pumping power of warm seawater, $P_{ws}$ is indicated as in Eq. 12; whereas the pumping power of cold seawater, $P_{cs}$ is expressed as in Eq. 13

$$P_{Pwf} = \frac{\dot{m}_{wf}\ \Delta H_{wf}\, g}{\eta_{wf,p}} \tag{11}$$

$$P_{ws} = \frac{\dot{m}_{ws}\ \Delta H_{ws}\, g}{\eta_{ws,p}} \tag{12}$$

$$P_{cs} = \frac{\dot{m}_{cs}\ \Delta H_{cs}\, g}{\eta_{cs,p}} \tag{13}$$

where $\Delta H$ refers to the difference in pressure.
The net power output, $P_n$ is indicated as in Eq. 14

$$P_n = P_G - P_{ws} - P_{cs} - P_{p_{wf}} \tag{14}$$

*2.3. Selection of Working Fluid*
An ideal working fluid should have the relevant thermophysical properties corresponding with its application, besides sustaining its chemical stability within the specified range of temperature. Working fluid selection plays a major part on the system in terms of its performance, operating conditions, effects on the environment and economic feasibility. In this section, the parameters for identifying a suitable working fluid for the cycle system are described. Sami [19] has listed the main factors affecting the properties of thermodynamic and thermophysical of the system, among which are thermal conductivity, chemical stability, specific heat, boiling temperature, latent heat, toxicity, as well as flash point, as outlined in Figure 2.

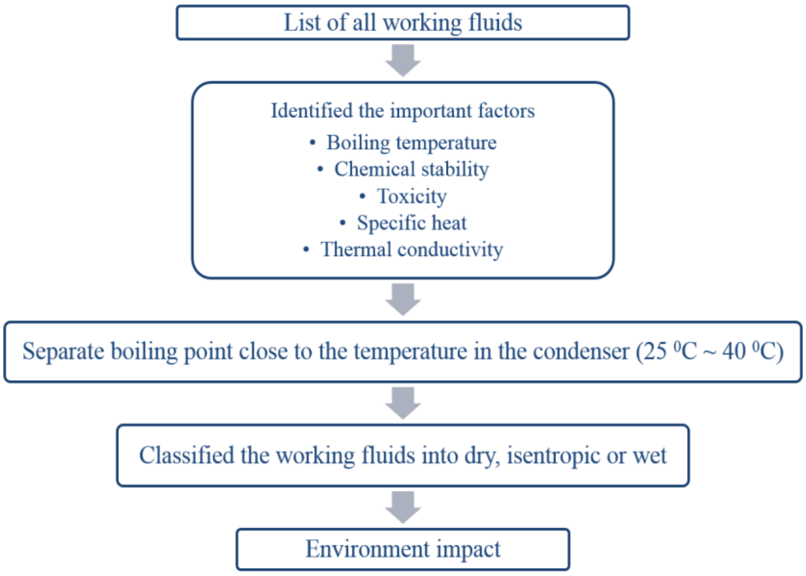

**Figure 2.** Steps in selecting the working fluids [15].

The OTEC closed Rankine cycle in this study utilized the boiling point of the working fluid near the evaporator operating temperature, that is about 25°C to 40°C [20]. In addition, the fluids were classified as dry, isentropic or wet relative to the saturation curve (dT/ds). A dry or isentropic fluid is appropriate to be implemented in OTEC closed Rankine cycle [21]. The purpose of separating the type of fluids is to make sure that the fluids are totally superheated after isentropic expansion, intended to avoid the appearance of liquid drops on the blades of the turbine.

*2.4. Types of Working Fluid*
There are dual kinds of working fluid, namely pure fluid (pure compound) and pseudo-pure fluid (a mix of several pure compounds of fluid). Ammonia, propane, R22, R134a, and R143a, are marked as pure fluid, and are not combined with some other compounds. Meanwhile, ammonia-water mixture, R404a, R410a, R470c, and R507a are a pseudo-pure fluid. Figure 3 and Figure 4 show that the highest enthalpy difference can be discovered in ammonia-water mixture, followed by ammonia, propane and R32.

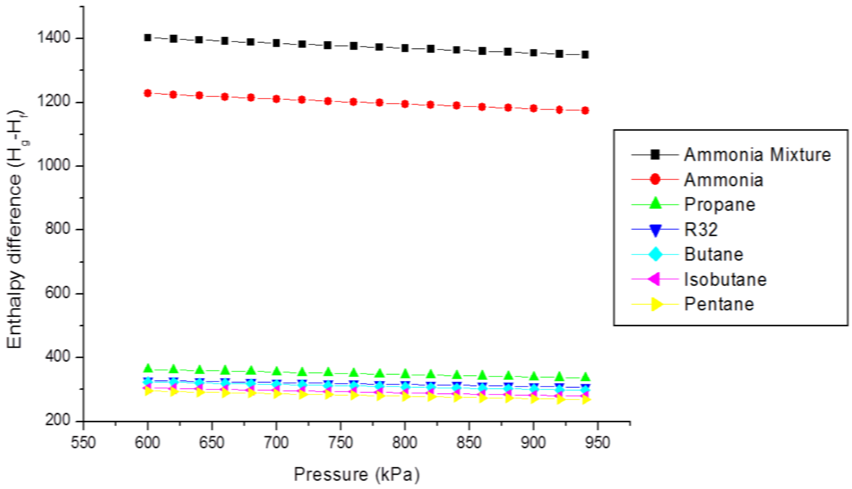


**Figure 3.** Latent heat-pressure diagram of pure fluid and pseudo-pure fluid.

According to Figure 4, in contrast with other working fluids, ammonia-water mixture has the highest quantity of heat applied. This situation is caused by its greater latent heat value, also can be defined as the amount of heat that a liquid absorbs to stay at a constant pressure or temperature throughout the process of vaporization.

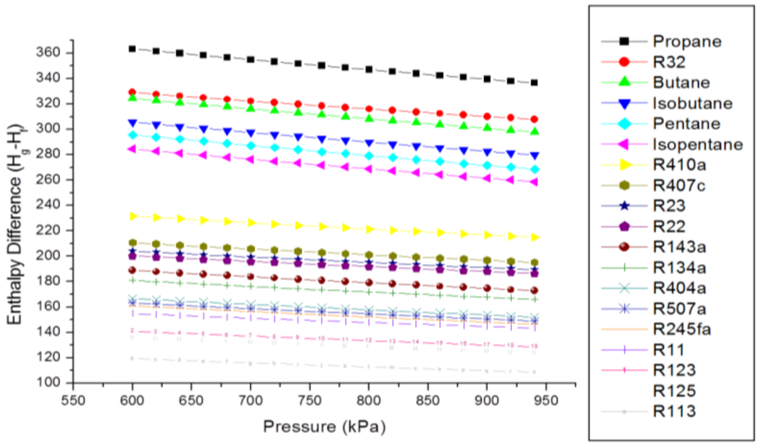


**Figure 4.** Close up of latent heat-pressure diagram of pure fluid and pseudo-pure fluid.

*2.5. Preliminary Simulation*

A preliminary design model for simulation of a 1 MWe OTEC closed Rankine cycle was conducted using ammonia as working fluid. This preliminary simulation is to validate the model developed by Yeh et al. [22]. Apart from that, the preliminary design model allows the estimation for 5 MWe and 10 MWe OTEC closed Rankine cycle.

**Table 1.** Parameters for three OTEC cycles to be investigated.

| **Parameter** | **Symbol** | **Unit** | **Value** |
|---|---|---|---|
| Evaporating temperature | $T_E$ | °C | 28 |
| Condensing temperature | $T_C$ | °C | 8 |
| Warm seawater inlet temperature | $T_{wsw}$ | °C | 30 |
| Cold deep seawater inlet temperature | $T_{csw}$ | °C | 5 |

| | | | |
|---|---|---|---|
| Working fluid pump efficiency | $\eta_{wf}$ | % | 0.75 |
| Turbine efficiency | $\eta_T$ | % | 0.82 |
| Generator efficiency | $\eta_G$ | % | 0.95 |
| Warm seawater pump efficiency | $\eta_{pump,wsw}$ | % | 0.80 |
| Cold deep seawater pump efficiency | $\eta_{pump,csw}$ | % | 0.80 |

The OTEC closed Rankine cycle simulation based on Uehara and Ikegami [18] was conducted according to the fixed condition parameters as tabulated in Table 1, in which the ammonia is in a steady state. The graph that represents the simulated model is shown in Figure 5 (b). When comparing the reference case with the preliminary analysis, it was found that ammonia generated the maximum total work output. Such results are reinforced by the point that ammonia possessed the maximum as well as the most appropriate value of latent heat for the OTEC cycle system.

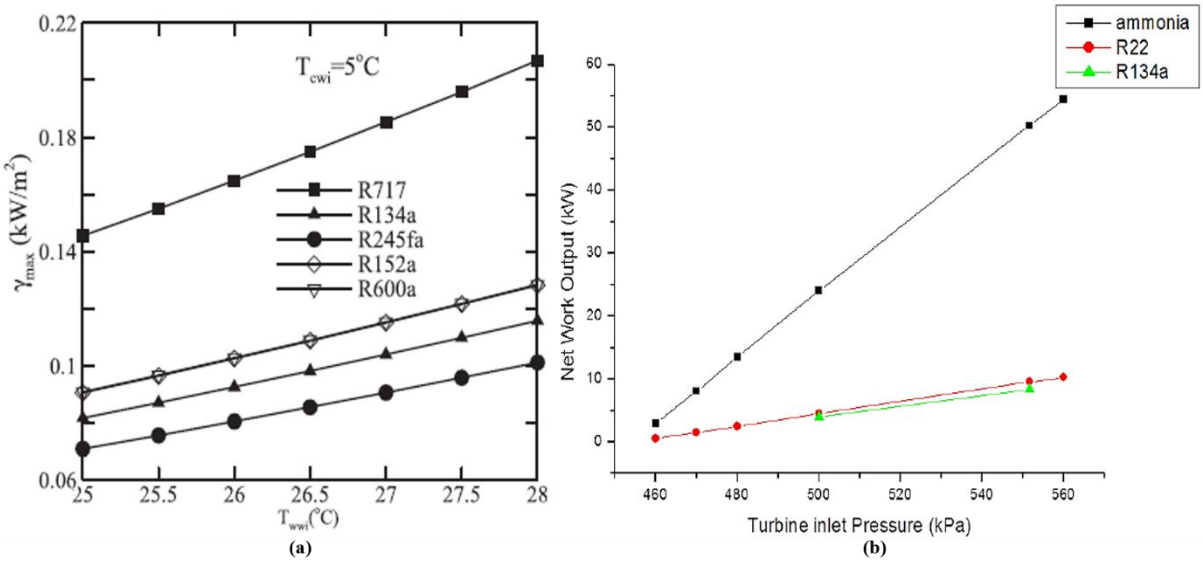


**Figure 5.** The net work output of closed Rankine cycle using several working fluids; (a) reported by Yeh et al. [22]; (b) simulation model using LabVIEW and RefProp.

As can be seen from Table 2, the net power output increased significantly when the system was scaled up [23]. This will later increase the value of capital cost unless the heat exchangers are able to transfer large amount of energy at minimum pumping power. The preliminary study acts as an initiation to the visualization procedure used in the subsequent assessment in Section 3. On the other hand, the preliminary simulation is shown to explain the sufficiency of the parameters used in this study.

**Table 2.** Analysis of OTEC Closed Rankine cycle using ammonia as working fluid.

| Parameter | Unit | 1 MWe | 5 MWe | 10 MWe |
|---|---|---|---|---|
| $Q_{in}$ | kW | 19724.40 | 81375.50 | 162751.00 |
| $Q_{out}$ | kW | 18685.00 | 76166.90 | 152334.00 |
| $W_{p(wf)}$ | kW | 13.22 | 54.53 | 109.06 |
| $W_{p(wsw)}$ | kW | 96.74 | 399.12 | 798.24 |
| $W_{p(cws)}$ | kW | 118.76 | 484.11 | 968.21 |
| $\dot{m}_{wf}$ | kg/s | 15.82 | 65.25 | 130.50 |
| $\dot{m}_{WSW}$ | kg/s | 1793.01 | 7397.29 | 14794.60 |
| $\dot{m}_{CSW}$ | kg/s | 1587.67 | 6471.91 | 12943.80 |
| $W_T$ | kW | 905.00 | 4525.00 | 9050.00 |
| $W_{net}$ | kW | 676.28 | 3587.24 | 7174.48 |

## 3. Results and Discussion

### *3.1. OTEC Closed Rankine Cycle using Different Working Fluids*

The simulated net power output of eight varying working fluids produced by a work pump of deep seawater is shown in Figure 6. It was noticeable that the net power output for ammonia-water mixture was the maximum with 740 kW, and that the power needed for the cooling system to pump deep seawater was also small. A feature which is widely recognized in the OTEC power cycle is the point that ammonia resulted in the second highest net power output value. The third highest net power output was R134a followed by R22 and propane. R134a was the possible candidate to replace the ammonia as it possessed the highest net power output among the other five working fluids; however it has the biggest value of work pump for deep seawater. Therefore, it required a big pipe to pump from the deep seawater to condense R134a. R22 has the higher net power output but lower pumping power for deep seawater compared to propane. R32 was the fourth possible candidate to replace ammonia. As the graph shown, R32 gaves the lowest pumping power than the other working fluids including pure ammonia. The graph also indicated that R410a and R143a have low pumping power compared to pure ammonia, but it has the lowest net power output. Even so, a substitute working fluid must be introduced to replace ammonia which is detrimental to the ecosystem and needs a special substance to be preserved.

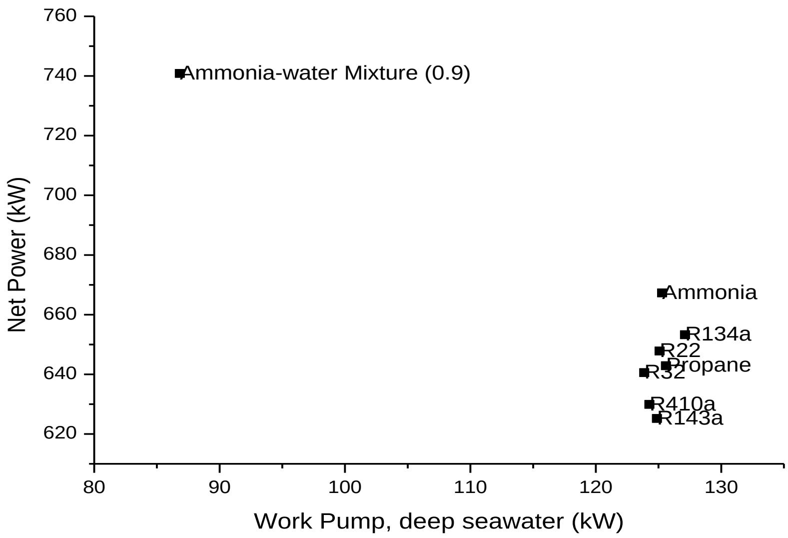


**Figure 6.** The simulated net power output of eight varying working fluids produced by a work pump of deep seawater.

The relationship between the net work output and efficiency is shown in Figure 7. Although both ammonia and ammonia-water mixture have greater net work output and efficiency in contrast to the other working fluids, they need a separator to make sure that water vapour from the fluid (particularly for ammonia-water mixture) does not affect the blade of the turbine. When propane and R32 were implemented as working fluids, the resulting performance was poorer. However, in comparison with R22, R134a, R143a, and R410a, both propane and R32 have a comparatively broader range of working pressure as well as a more stable working range.

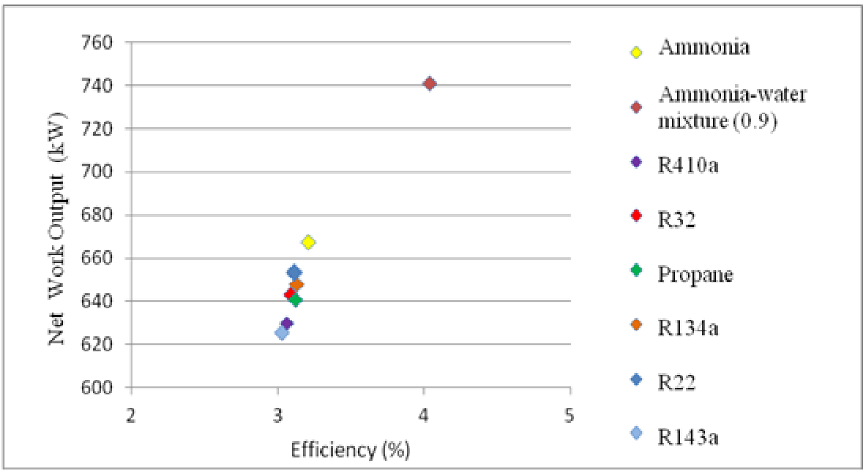


**Figure 7.** The relationship between the net work output and efficiency of eight varying working fluids.

### *3.2. Techno-economic Efficiencies and Environmental Criteria of Different Working Fluids*

The simulated net power output of eight varying working fluids produced by a work pump of deep Figure 8 shows the simulated result of thermal efficiency and capital cost (USD/kW) for eight different working fluids. Meanwhile, Table 3 is generated from Figure 8 for the exact value of the capital cost per net power output. The data from the simulation results indicated that in contrast to ammonia, ammonia-water mixture has a greater value of net power generated and main product with relatively low cost. Ammonia-water mixture was regarded as the best working fluid owing to its net power efficiency and low capital cost. It is because of these 3 factors which are; ammonia water mixture has the highest efficiency among the other fluids, a lowest pumping power needed and a lowest capital cost

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to build an OTEC system. However, the ammonia water mixture needs a proper maintenance on the turbine because of water droplet will be occurred in the turbine. Therefore, recommendation for further study on the maintenance cost of using ammonia water mixture is needed for further improvement. Ammonia has become the second highest of thermal efficiency but the highest capital cost because of its higher pumping power needed and the cost of special material to handle with pure ammonia. The net power output of propane is much lower than that of ammonia and ammonia-water mixture. Nevertheless, in contrast to the other working fluids, propane has the least capital cost of main system components, making it the better choice to substitute ammonia.

The simulation result shown in Figure 8 indicated that propane and R32 are possible fluids which can serve as an ammonia substitute, attributed by their lower cost and non-toxic feature. Furthermore, the environmental criteria of different working fluids tabulated in Table 4 showed that propane is regarded as a highly flammable fluid. Nevertheless, such issue can be neglected and does not prevent its implementation in OTEC closed Rankine cycle system as the maximum temperature reaches is only 40 °C. R32 is the second best option to replace ammonia. At normal boiling point, it possesses high specific heat value, and an immediate effect of saturated vapour pressure on temperature. R32 is also distinguished by its high productivity at cold temperature and high energy efficiency, even though these properties are marginally lower than R22 and ammonia. Propane and R32 have the ability to efficiently meet the safety and environmental criteria of the system. They are potentially the ideal choices to be deployed as the working fluid in the OTEC cycle in the future, replacing ammonia or ammonia-water mixture.

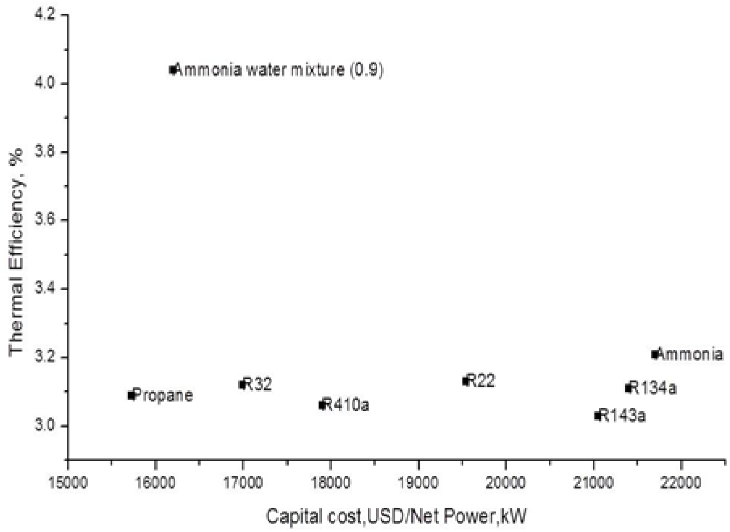


**Figure 8.** The simulated result of thermal efficiency and capital cost (USD/kW) for eight different working fluids.

**Table 3.** Calculated result of the different working fluid with the capital cost per net power ($/kW).

| Working Fluid | Capital Cost/Net Power ($/kW) |
|---|---|
| Ammonia | 21700 |
| Ammonia-water mixture | 16201 |
| Propane | 15730 |
| R22 | 19540 |
| R32 | 16990 |
| R134a | 20025 |
| R143a | 21400 |
| R410a | 17900 |

**Table 4.** Environmental criteria of different working fluids [24].

| Working Fluid | Flammability | Toxicity | ODP | GWP |
|---|---|---|---|---|
| Ammonia | Low | High | 0 | 1.00 |
| Ammonia-water mixture (0.9) | Low | High | 0 | 1.00 |
| Propane | High | Low | 0 | 3 |
| R32 | Low | Low | 0 | 675 |
| R22 | Non | Low | 0.055 | 1900 |
| R134a | Non | Non | 0 | 1300 |
| R143a | Non | Non | 0 | 4470 |

## 4. Conclusions

In conclusion, a model which incorporated LabVIEW and Refprop softwares was successfully developed and deployed for a preliminary assessment of the OTEC cycle efficiency. The preliminary analysis of a test run at a net power output of 1 MW showed a close agreement with that of exiting data. The similar developed model was implemented to analyze the efficiency of the OTEC basic closed Rankine cycle using eight varying working fluids. The analyzed working fluids, including that of ammonia, are ammonia-water mixture (0.9), propane, and refrigerants (R22, R32, R134a, R143a, and R410a). Accordingly, the results showed that ammonia-water mixture gave the excellent performance with regard to the characteristics of heat transfer with the best thermodynamic efficiency of 4.04% compared to pure ammonia with 3.21%, propane with 3.09%, followed by refrigerants from 3.03% to 3.13%. In terms of capital cost, propane was economically efficient with 15730 $/kW compared to cost of ammonia-water mixture at 16201$/kW, refrigerants from 16990 $/kW to 21400 $/kW, and pure ammonia being the costliest at 21700 $/kW. Despite being lower in its thermodynamic efficiency, propane gave the lowest capital cost and had the lowest toxicity in contrast to all other working fluids. Therefore, propane has the potential to be used as a clean and safe working fluid to substitute ammonia, thus further enhance the OTEC technology.

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