Abstract— Ocean Thermal Energy Conversion (OTEC) is the use of a high surface temperature of the water with the low temperature of the water at a certain depth thus creating a heat engine. The working fluid in such a cycle will need to have a low boiling point. Ammonia will be used as the working fluid in this cycle. The cycle will be a Rankine cycle similar to that of a steam power plant. There will be a pump, boiler (in this case the oceans surface water), turbine, and condenser (in this case the oceans water from 1000 meters deep). After numerical analysis of the system, it is found that the overall efficiency of this configuration is relatively low in comparison to the most widely used power generation technologies. In the first analysis, the Carnot Efficiency was found to be 8.03% while the Rankine cycle efficiency was 6.99%. In the second analysis of the system, there was a mass flow rate of 1000 kg/s. The working fluid and temperature difference were accounted for in the heat exchange of the warmer surface water to the cold water used in the condenser. In this analysis the Rankine cycle efficiency was found to be 3.97% and the Carnot efficiency in this example was 4.35%. In a real application the pump uses up most of the power generated due to having to pump water from 1000 meters deep.

Keywords— Ocean Energy Conversion; OTEC, Renewable Energy.

I. INTRODUCTION

This research is based on the concept of an alternative renewable energy source. This renewable source is Ocean Thermal Energy Conversion (OTEC). This is a power cycle that is in turn a heat engine, which powers a low-pressure turbine. Ammonia will be used as the working fluid in the cycle due to its low boiling point. The idea is very simple. Surface water temperature is enough to cause the working fluid to boil, then cold water from approximately 1000 meters deep will be pumped to the surface to condense the working fluid. The system analyzed here will operate in a closed cycle. There are also open cycle OTEC platforms, which can be beneficial as well. In the open cycle warm seawater is located in a low-pressure tank and caused to then boil [1]. The steam that comes from the low-pressure boiling system is enough to power a turbine thus creating work [1]. The cold seawater is used to condense the steam [1]. One benefit to the open cycle is that desalinated water is created in the cycle as a byproduct.

This water can be used for drinking water or irrigation in locations that have a water shortage. Power output and efficiency will be examined and compared to current power production sources in the US.

II. BACKGROUND

According to OTECnews.org one of the first working models of this concept was built and designed by French inventor Georges Claude [2]. His first model was a failure and cold not produce a net power output [2]. His second attempt in 1935 was lacking as well due to the difficulties of installing the cold water pipe (CWP) in order to pump the cold deep water to the surface [2]. In 1993 a small open cycle OTEC plant was designed and constructed by L. A. Vega in Hawaii [3]. This was a small plant that was more of a testing plant. The plant closed in 1998. It was a model of an actual working plant and did not produce enough power to be funded and kept in operation [3]. Open cycle meant the working fluid was only used per one cycle. The byproduct of this working fluid was desalinated water. This water could be used for drinking water or irrigation. This plant operated for six years and had a gross of 255 Kilowatts of electrical energy (kWe) [3].

There have been a number of different OTEC system designs ranging from floating barges, land based plants, continental shelf towers and other structures out at sea. The most reasonable would be a close to shore floating plant with a submarine power cable that would deliver power to the commercial grid.

In the past and current models of the OTEC system a great deal of work is needed for the pump. The pump must deliver water from a substantial depth and this requires a great deal of work. This is one reason why the work output of such systems is low and therefore so is the efficiency. Although the network and efficiency is low, it is a renewable source of power little to no impact on the environment [2]. With only small concerns being the building construction and the impact on fishing and the ecosystem of the ocean.

Current advancements in OTEC power generation are slow moving. When compared to modern power generation OTEC cannot compete with fossil fuel sources or power.
However, Lockheed Martin a company that has paired up with The Reignwood Group to build a commercial 10 MW OTEC system which will be the largest OTEC system in operation to date [4]. This will be a floating platform constructed off the coast of China where conditions are prime for an OTEC plant, which means a warm surface water temperature and a low water temperature at 1000 meters deep [4].

III. THEORY

The closed cycle OTEC system uses Ammonia as a working fluid. Ammonia has a much lower boiling point than that of water. The water on the surface of the ocean is warm enough to heat the working fluid and cause a thermodynamic cycle of a heat engine to occur [7]. The condenser will also consist of deep water from the ocean. This water will be pumped from the sea floor approximately 1000 meters deep. The schematic of the cycle is presented in Figure 1. Data from a buoy off the coast of Hawaii has been selected for the target OTEC plant location with optimal conditions. The average surface water temp is 26.9 °C [5]. The depth at this location is 4,919 meters. Water from 1000 meters deep will be approximately 5 °C. This is just above freezing and will be enough to condense the working fluid so that it can go through another cycle. Figures 2 and 3 show a better depiction of this temperature fluctuation. This location and these parameters will be evaluated and mathematically analyzed. It will then be determined if the OTEC plant can produce enough power to sustain itself and provide power output. The efficiency will be examined in comparison to the Carnot efficiency and work of the pump and turbine will be examined at as well.

![Figure 1. Schematic of OTEC System](image)

![Figure 2. The temperature profile of ocean water](image)

![Figure 3. Global Ocean Surface Temperature](image)

IV. PROCEDURE

Buoy number 51003 is located off the coast of Hawaii [5]. The warm surface water is recorded to be 26.9 °C. The depth at this location is recorded to be 4,919 meters deep [5]. The temperature of this water at 1000 meters deep is said to be 5 °C [8]. This temperature difference will be enough to provide an ideal Rankine cycle mathematical model of this OTEC system at this location. We will examine the system and find the cycle’s efficiency and the Carnot efficiency and compare the two for analysis. Figures 4 and 5 below show global surface water temperatures and global water temperatures at 1000 meters deep [8].
V. CALCULATION

There are several equations needed for analysis of the OTEC System [1]. Ammonia Steam tables will be used to evaluate the system at different points [1]. The numerical analysis is detailed below in Table 1 and Table 2. Figure 6 represents the T vs. S diagram of the cycle involved in the calculations.

### Table 1: Properties of ammonia

<table>
<thead>
<tr>
<th>$T_1$=5 °C, $T_3$=26.9 °C</th>
<th>$h_1$ [kJ/kg]</th>
<th>$h_2$ [kJ/kg]</th>
<th>$h_3$ [kJ/kg]</th>
<th>$h_4$ [kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Ammonia Tables</td>
<td>298.25</td>
<td>299.021</td>
<td>1463.5</td>
<td>1381.28</td>
</tr>
</tbody>
</table>

Turbine Work (1) =

\[ (h_3 - h_4) = 1463.5 - 1381.28 = 82.22 \text{ kJ/kg} \]

Pump Work (1) = \[ \int v dp = v(P_2 - P_1) = \frac{0.001583(1003.2 - 515.9)}{0.771396} = \frac{82.22}{0.771396} \text{ kJ/kg} \]

For pump work referenced above: $P_2$ = Pressure at the boiler and $P_1$ = Pressure at the condenser.

\[ Q_H (1) = (h_3 - h_2) = (1463.5 - 299.01) = 1164.8 \text{ kJ/kg} \]

\[ Q_L (1) = (h_4 - h_2) = (1381.28 - 298.25) = 1083.03 \text{ kJ/kg} \]

\[ W_{net} = (W_T - W_p) (1) = (82.22 - 0.771396) = 81.4486 \text{ kJ/kg} \]

Cycle Efficiency (1) =

\[ \frac{W_T - W_p}{Q_H} \times 100 = \frac{82.22 - 0.771396}{1164.8} \times 100 = 6.9942\% \]

Carnot Efficiency (1) =

\[ \frac{T_H - T_C}{T_H} = \frac{(29.6 + 273.15) - (5 + 273.15)}{29.6 + 273.15} \times 100 = 8.0264\% \]
VI. FURTHER ANALYSIS OF EXAMPLE 1

To get a better idea of what the actual cycle would produce we will examine the system a little further. Figure 7 represents a cycle, which exhibits the data collected for the analysis. In this analysis, there will be a mass flow rate of the working fluid of 1000 kg/s. We will calculate the enthalpy at different stages, turbine power output, pump power input, the cycle efficiency and Carnot efficiency.

Table 2: Calculation results

<table>
<thead>
<tr>
<th>W_{net} (kJ/kg)</th>
<th>W_{pump} (kJ/kg)</th>
<th>W_{turbine} (kJ/kg)</th>
<th>\zeta_{thermal}</th>
<th>Z_{carnot}</th>
</tr>
</thead>
<tbody>
<tr>
<td>82.22</td>
<td>77.139</td>
<td>82.22</td>
<td>6.99%</td>
<td>8.0264%</td>
</tr>
</tbody>
</table>

At Point 3 in the schematic, the temperature is 10 °C and the ammonia is in a saturated liquid state. Values for enthalpy, entropy and specific volume of the ammonia can be obtained from the saturated ammonia tables.

1. \( h_3 = 227.8 \text{ kJ/kg} \)
2. \( s_3 = 0.881 \text{ kJ/kg} \)
3. \( P_4 = P_1 = 615.2 \text{ kPa} \)
4. \( v = 0.0016 \text{ m}^3/\text{kg} \)

In order to solve for enthalpy at Point 2 we will need to use the equation for quality \( (x_2) \). Since the process from 1 to 2 is adiabatic and constant entropy we can solve for enthalpy at Point 2.

\[
\begin{align*}
\frac{s}{s_f} + x_2 \left( s_{fg} \right) & \rightarrow 5.072 = 0.881 \\
& \rightarrow x_2 \left( 4.3266 \right)
\end{align*}
\]

\[
\begin{align*}
1. & \quad x_2 = 0.9686 = 96.86\% \\
2. & \quad h_2 = h_f + x_2 (h_{fg}) \\
& \quad \text{yields} \\
& \quad 227.8 + 0.9686(1225.1) = 1414.43 \text{ kJ/kg}
\end{align*}
\]

Now we can solve for the power output of the turbine with the following equation.

\[
\begin{align*}
W_T & = m(h_3 - h_2) \\
& \text{yields} \\
& \frac{-0.0016(913.4 - 615.2)}{49470} = -47712 \text{ kw}
\end{align*}
\]

Next the pump power input and the total pump power input will be calculated along with the enthalpy at Point 4.

\[
\begin{align*}
W_p & = -v(P_4 - P_3) \\
& \text{yields} \\
& \frac{-0.0016(913.4 - 615.2)}{47712} = 227.8 \\
& \text{h} \_4 = 228.277 \text{ kJ/kg}
\end{align*}
\]

\[
\begin{align*}
W_{Pump-Total} & = -m(W_p) \\
& \text{yields} \\
& \frac{1000(47712)}{47712} = -477.12 \text{ kw}
\end{align*}
\]

We can now solve for the heat supplied and specific heat to the heat exchanger known as \( q_h \) and \( Q_h \), respectively.

\[
\begin{align*}
q_h & = h_1 - h_4 \\
& \text{yields} \\
& 1463.9 - 228.277 = 1235.62 \text{ kJ/kg}
\end{align*}
\]
The efficiency of the cycle can now be calculated along with the Carnot efficiency for comparison purposes.

\[
\eta_{\text{cycle}} = \frac{\frac{w_{\text{net}}}{\theta_h}}{\frac{w_f + w_p}{\theta_h}} = \frac{94470 - 47712}{1235.62 \times 10^3} = 0.0396504 \approx 3.97\%
\]

\[
\eta_{\text{carnot}} = \frac{\theta_h - \theta_c}{\theta_h} \frac{[229.173.145] - [10.123.145]}{229.173.145} = 0.0435737 \approx 4.35\%
\]

### VII. Conclusion

OTEC power sources are gaining popularity across the globe due to the demand of renewable energy. Much research and testing is needed to further explore these systems. The first cycle that was analyzed was an ideal cycle and will be similar to actual results but there is a caveat. In order to pump the water from 1000 meters deep, it takes an incredible amount of work. Such large volumes of work can be attributed to the work needed to pump the water from such a depth. Friction losses would also need to be accounted for. This has been an issue with the OTEC system. However, the power generated from the actual system is enough to power the pump and still produce usable energy. This energy amount is low thus lowering the efficiency of the system. The second analysis with more accurate temperatures and mass flow rate has a lower cycle efficiency as to be expected. This is due to the more accurate temperatures across the model and the actual mass flow rate. The other side of that coin is that there is no need for fuel to be burned or consumed. This is a fully self-sustainable power-generating device. It cannot be compared to fossil fuels because they produce volumes of power in comparison to the OTEC system. However, when compared to say, a fossil fuel power source, the lack of the fuel cost to generate power would be a major benefit to this system as no external fuel is needed to produce power. The OTEC system from an environmental standpoint is one of the best. There are no toxic emissions, no use for fossil fuel retention, and it is a totally renewable power source. Having said that, there is hope for the OTEC system. Lockheed Martin will be a pioneer in the industry when they launch their fully operational floating OTEC power plant in the coming years.

### References


