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Assessment of the Influence of Hot Seawater Temperature on OTEC Performance

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ABSTRACT
The study of the influence of hot seawater temperature on the performance of a 40KW OTEC that will be situated in Bonny Island has been conducted. Daytime surface temperatures in these waters range from a warm 24°C to 30°C, while at a depth of 1000 meters, temperatures are a chilly 4°C to 6°C - an impressive thermal gradient approaching 26°C. This substantial ocean temperature difference has rendered the Niger Delta coastal region an ideal site for the study of the proposed Closed cycle conventional OTEC. The results from both Hysys and MATLAB simulations are compared to evaluate the impact of varying sea water temperatures on system performance and it shows that as the temperature increases from 20°C to 40°C: the turbine power output rises dramatically from 14.41 KW to 99.49 KW in the Hysys simulation and from 14.45 KW to 99.53 KW in the MATLAB simulation ; The pump power increases from 0.2037 KW to 0.8148 KW in the Hysys simulation and from 0.2041 KW to 0.8152 KW in the MATLAB simulation and the turbine net power output increases from 14.21 KW to 98.68 KW in the Hysys simulation and from 14.25 kW to 98.72 kW in the MATLAB simulation. It is recommended that the seawater temperature should be controlled within 28^0C – 30^0C for optimum power generation and thermal efficiency.

Keywords*: Assessment, Seawater, Temperature, Performance, OTEC*

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I. INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) is a promising renewable energy technology that taps into the vast temperature difference between warm surface seawater and cold deep ocean water to generate electricity. The warmer surface waters heated by the sun and colder deep ocean waters serve as the boiler and the condenser for the working fluid (refrigerant), respectively, which are required to generate power via heat engines [1]. Energy statistics have shown an estimated 80,000 – 140,000 TWh/year energy potential exists globally from OTEC resources, with the tropics being the most viable[2]. OTEC utilizes the 20-25°C temperature gradient available in tropical seas between surface temperatures of 25-30°C and chilly deep water of 4-5°C from ocean depths beyond 1000m [3]. This thermal difference drives a Rankine cycle to produce electricity, analogous to conventional steam turbines but at lower temperatures. There are three main types of OTEC systems, each with its unique working principles:

Open-Cycle OTEC Systems

Open-Cycle OTEC as shown in **Figure 1** is the simplest and oldest form of OTEC technology. The process begins with the warm surface seawater being pumped into a low-pressure chamber, known as the evaporator. In this chamber, the seawater is vaporized due to the low boiling point of a working fluid, typically ammonia. The resulting vapour then drives a turbine connected to a generator, producing electricity. After driving the turbine, the vapour is condensed using cold seawater from the ocean's depths, and the cycle repeats [4][5].

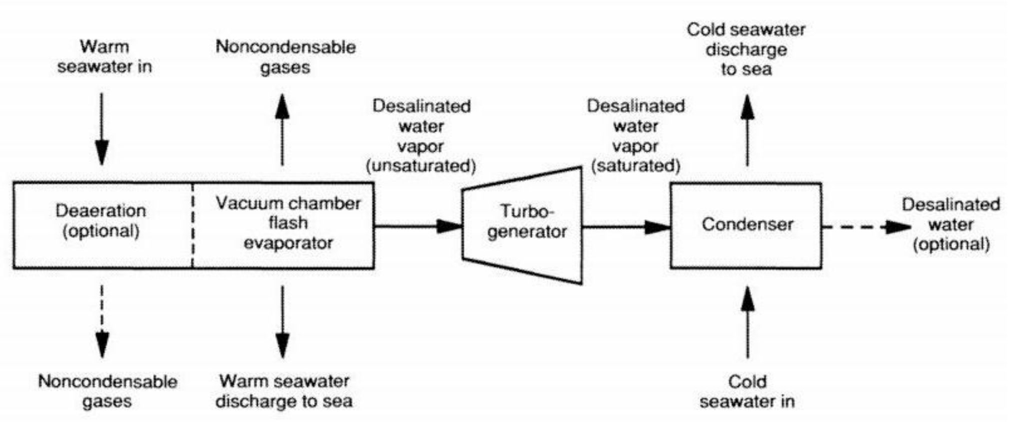

Figure 1: Schematic Diagram of an Open-Cycle OTEC System [6]

Closed-Cycle OTEC Systems

Closed-cycle OTEC systems shown in **Figure 2** use a closed-loop working fluid, such as ammonia or a hydrofluorocarbon, to circulate between the warm surface water and a heat exchanger. The working fluid is vaporized in the heat exchanger when exposed to warm seawater, driving a turbine connected to a generator [7]. The vapor is then condensed using cold seawater from the deep ocean before being returned to the heat exchanger to start the cycle again. Closed-cycle systems offer advantages such as reduced corrosion and fouling issues associated with using seawater directly, but they are more complex and may have higher upfront costs[8][9][10].

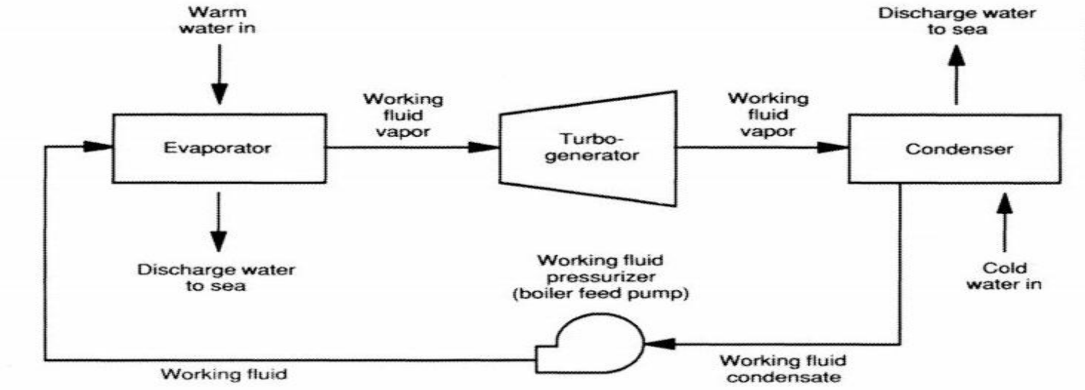

Figure 2: Schematic Diagram of a Closed-Cycle OTEC System [6]

Hybrid OTEC Systems

Figure 3 is a Hybrid OTEC system that combines elements of both open-cycle and closed-cycle designs to optimize efficiency and address specific challenges. These systems typically incorporate a closed-loop working fluid for electricity generation while also utilizing seawater for additional applications, such as desalination or aquaculture. The closed-cycle part focuses on electricity generation, while the open-cycle portion can be used for other purposes, enhancing the overall efficiency and economic viability of the OTEC system [5][7][11].

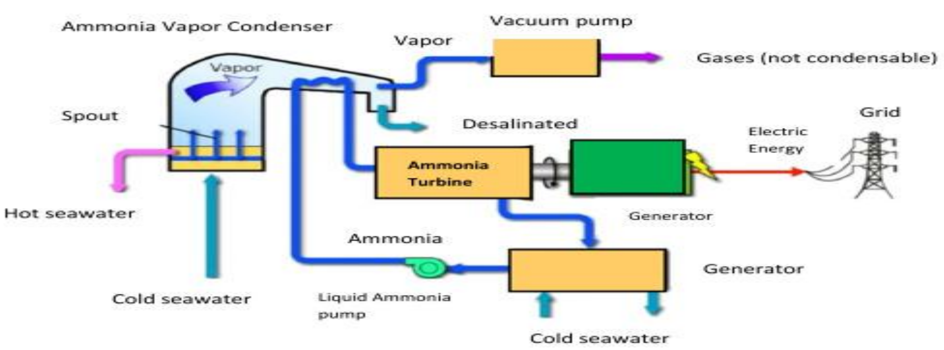

Figure 3: Schematic Diagram of a Hybrid-Cycle OTEC System **[6]**

The thermodynamic development coupled with the economic appraisal of OTEC in coastal Nigeria: Bonga Offshore was done by [12]. The work proposes a 50MW ocean thermal energy conversion system that will be in latitude 4o 30′ 01.5″ together with the longitude 4^{o} 29′ 58.1″ doubled with the seawater upper surface temperature grading 26 ^{0} C- 29^{0}C of twenty meters (20m) deepness coupled with the grading of 3.5^{0}C to 4.0^{0}C of one thousand and twenty-one meters (1021m) deepness, which utilizes the temperature gradient to generate electrical power. Precisely, the erection of a static framework for the energy production of ocean thermal energy systems utilizing the Uehara cycle based on experimental data was conducted by [13]. The work looks at dual types of static frameworks that were propounded. Both frameworks and the interaction through meaningful quantities are expressed in polynomials, which were adjudged by fewer squares for experiment data. The orders of the polynomial depreciate the integral of the complete inaccuracy between the simulated results and the data gotten from the experiment of the energy production embraced. Precisely, it was attested that the simulated results, in comparison with the standard framework of [14], demonstrated the pasturage of the operational working fluid flow rate to be capable of triumphantly performed simulation, which is attainable by severely syncopating the computation period. A case study was conducted on the preliminary development of a 100 MW-net OTEC system using Mentawai Island, Indonesia [15]. The research work presents a conceptual development of the floating structural framework from a turned tanker ship that is used in carrying oil. However, to propound the development process, the common principles of developing a turned floating production storage offshore tanker are shaped and then qualified to deal with OTEC features, and in the development procedure, the plan of the ocean thermal energy conversion configuration is done by coercing delectation techniques together with likely floating structure size, which is diverse utilising Monte Carlo simulation. Meanwhile, the alterable in the development procedure comprises the velocities of coldwater and warm water transport, the size of the plantship together with the position of the ocean thermal energy conversion equipment to the sea water tank, and coerce was presented as a permissible border in determining the adequacy for the case encompassing the given area coupled with the buoyancy and the evaluation of the net energy output. The dependable results indicate that the normal size of a Suezmax Oil Tanker Ship was the best one for the plantship with a velocity of the water transport of 2 m/s to 3 m/s. The review of the present development in the economics of ocean thermal conversion was conducted by [16]. Precisely, in this research work seven cognition voids were fingered, and they include present economic appraisal cynosure on separate systems rather than combine economic possibility within spatial boundaries; the omission of nature's position on the precise effects of the actual net power output; and the incertitude of the capital cost on both plants together with constituent level coupled with costs of operation. Also, the perspectives together with the economic effect appraisal of an ocean in Nigeria because of renewable energy were looked by [5]. While, the study reveals that acclimatizing ocean energy in Nigeria can meaningfully generate the required energy; irrespective of the large amount it is required at the initial stage. While [17] performed research together with design exertion of OTEC goaded design in Malaysia to encourage capable investors in transforming the ocean thermal energy to power supply or hydrogen. Hence, this study will look at the assessment of the influence of hot sea water temperature on the Close Cycle Conventional OTEC performance used for electrical power generation in Bonny Island.

II. MATERIAL AND METHODS

Preamble of the Methodology

OTEC is an innovative renewable energy technology that exploits the natural temperature differential between warm surface seawater and cold deep ocean water to generate clean electricity by driving a low-pressure turbine [18][19]. The OTEC process harnesses the thermal gradient that exists between the sun-heated upper ocean layers and the colder waters at depth. As highlighted by [20], this temperature difference can be effectively harnessed through renewable energy conversion technologies to produce emissions-free electrical power. The coastal location selected for this study exhibits highly favourable conditions. Daytime surface temperatures in these waters range from a warm 24°C to 30°C, while at a depth of 1000 meters, temperatures are a chilly 4°C to 6°C - an impressive thermal gradient approaching 26°C. This substantial ocean temperature difference has rendered the Niger Delta coastal region an ideal site for constructing the proposed OTEC facility [5][6] [21]. However, optimizing OTEC plant performance remains a critical challenge, as the technologies inherently low thermal efficiency has hindered advancements in cycle design and engineering. This challenge has spurred a multitude of research efforts focused on boosting OTEC efficiency, forming the core motivation for the current investigation [22][23][24][25][26][27][28][29].

Performance Analysis

Performance Assessment of the Major OTEC System Equipment

The thermodynamic appraisal of the Close Cycle Conventional OTEC system constituents in **Figure 2** is conducted by assessing the thermodynamic state points mappable onto a temperature-entropy (T-S) diagram as shown in **Figure 4** together with the utilization of steady state equation [29].

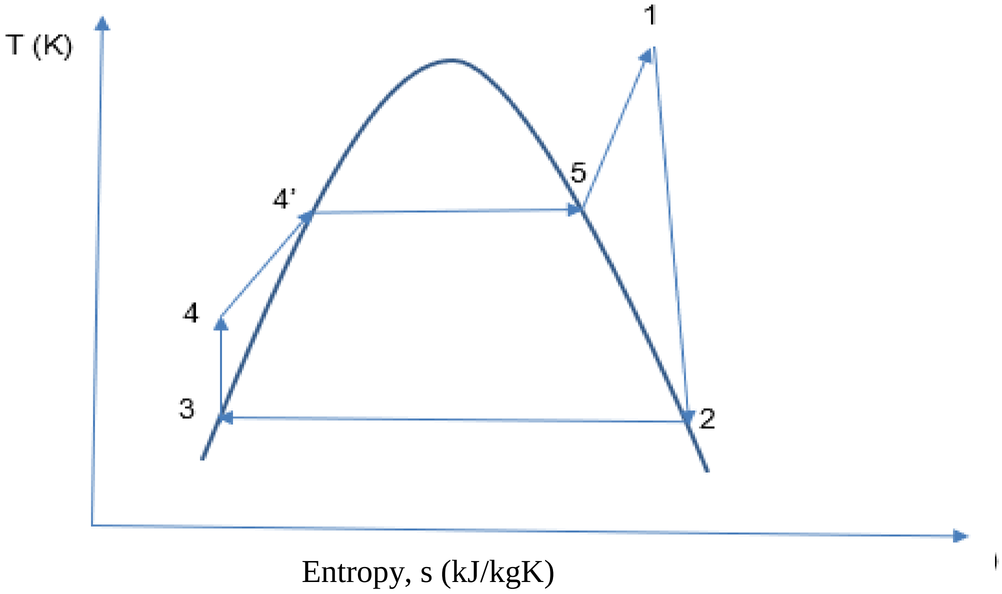

Figure 4: Temperature-Entropy Diagram of the Ocean Thermal Energy Conversion Plant [29]

$$\mathrm{Q} + \mathrm{m}(\text{internal energy} + \text{Flow work} + \mathrm{K.E} + \mathrm{P.E}) = \mathrm{W} + \mathrm{m}(\text{internal energy} + \text{Flow work} + \mathrm{K.E} + \mathrm{P.E}) \tag{1}$$

$$\mathrm{Q} - \mathrm{W} = \mathrm{m}[\Delta \mathrm{h} + \Delta \mathrm{K.E} + \Delta \mathrm{P.E}] \tag{2}$$

The energy equation for the evaporator is expressed as:

Tube side

$$Q_{Ets} = \dot{m}_{wsw} C_p \Delta T_{wsw} \tag{3i}$$

Tube side

$$Q_{Ess} = \dot{m}_f (h_1 - h_5) \tag{3ii}$$

The work output equation for the turbine can be expressed as

$$W_t = \dot{m}_f (h_2 - h_1) \tag{4}$$

The energy equation for the condenser can be expressed as:

Tube side

$$Q_{cts} = \dot{m}_{csw} C_p \Delta T_{csw} \tag{5i}$$

Tube side

$$Q_{css} = \dot{m}_f (h_3 - h_2) \tag{5ii}$$

The work consumed by the following:

The working fluid pump work is expressed as:

$$W_{p,f} = \frac{\dot{m}_f (h_4 - h_3)}{n_p} \tag{6}$$

The warm sea water pump work is expressed as:

$$W_{p,w} = \dot{m}_{wsw} C_p (T_{w2} - T_{w1}) \tag{7}$$

The cold sea water pump work is expressed as:

$$W_{p,c} = \dot{m}_{csw} C_p (T_{c2} - T_{c1}) \tag{8}$$

Note: Equations 6 and 8 will be given .

The net power of OTEC W_{net} is as follows:

$$W_{net} = W_t - (W_{p,f} + W_{p,w} + W_{p,c}) \tag{9}$$

The thermal efficiency is expressed as:

$$\eta_t = \frac{W_{net}}{Q_T} \tag{10}$$

Head loss of the pump

$$h_{fi} = \frac{f_{di} L_i V_i^2}{2 D_i g} \tag{11}$$

Where :

$$f_{di} = \frac{64}{Re} \tag{12}$$

Pump power loss

$$P_{li} = h_{fi}\dot{m}_i g \tag{13}$$

III. RESULTS AND DISCUSSION

RESULTS

Table 1 encompasses working design data for a 40KW OTEC plant that will be situated in Bonny Island, Rivers State, Nigeria. **Table 2** the monthly average daily temperature live data from 2021 to 2024 gotten from [29][30] of Bonny Island waters and calculated and recorded. **Table 3** is results of the MATLAB v8.5a and Aspen Hysys v11 software simulation of the Ocean Thermal Energy Conversion (OTEC) system utilizing **Table 1** and **Table 2** respectively. Precisely, in the Simulations, different conditions like sea surface water temperatures, pressures, mass flow rates, cooling water temperatures, and pressures. The investigation of the influence of hot sea water temperature on the OTEC system's performance is carried out. The results from both Hysys and MATLAB simulations are compared to evaluate the impact of varying sea water temperatures on system performance. Sea water temperature is a critical parameter in OTEC systems, as it directly affects the thermal energy available for conversion and the efficiency of the thermodynamic cycle.

Table 1: Working Design Data for the 40 KW OTEC Plant

Parameters	**Values**	**Unit**
Working fluid	Ammonia	
Ammonia Density	597.908	Kg/m^3
Ammonia Specific heat capacity	4.87	KJ/KgK
Turbine Efficiency	0.796	%
Turbine Rated Power	40	KW
Generator Efficiency	0.946	%
Pumps Efficiency	0.895	%
Warm seawater inlet temperature	25 and 29	^{o}C
Cold seawater inlet temperature	9 and 10	^{o}C
Pipe length of warm seawater	101	m
Pipe diameter of warm seawater	102	m
Pipe length of cold seawater	670	m
Pipe diameter of cold seawater	101	m
Heat exchangers conductivity	14	W/m K
Surface sea water temperature	29	^{o}C
Deep cold water temperature	9	^{o}C
Water Density	1025	Kg/m^3
Water Specific Heat Capacity	4.182	KJ/KgK
Evaporator Pressure	9.78	Bar
Condenser Pressure	7	Bar
Friction loss factor	0.02	

Table 2: Monthly Average Sea Surface Temperature of Bonny Island.

S/No.	Year/ Month/ Degree Celcius	2021 (^{0}C)	2022 (^{0}C)	2023(^{0}C)	2024(^{0}C)
1.	January	27.2	27.4	28.3	27.7
2.	Febuary	28.6	28.5	29.2	28.4
3.	March	28.4	29.1	29.0	28.7
4.	April	28.7	29.1	29.1	28.9
5.	May	29.0	31.2	29.0	29.0
6.	June	26.9	28.0	28.3	28.0
7.	July	27.0	27.0	27.3	26.9
8.	August	26.0	26.7	26.5	26.2
9.	September	26.7	26.5	27.0	26.6
10.	October	27.6	26.8	27.9	27.3
11.	November	28.4	26.9	27.4	27.7
12.	December	28.5	27.1	27.5	27.9

Table 3 : Simulated Values

Hot Sea Water Temperature (^{o}C)	Turbine Power (KW)-Hysys	Pump - Power	Wnet (KW)- Hysys	Wnet (KW)- Matlab	Turbine Power (KW)-Matlab
20	14.41	0.2037	14.2063	15.7287454	16.0749163
25	29.13	0.3565	28.7735	30.0836862	30.017415

30	44.21	0.5092	43.7008	43.8307512	45.7292644
35	73.92	0.662	73.258	74.8972661	74.2546904
40	99.49	0.8148	98.6752	99.184122	99.5738381

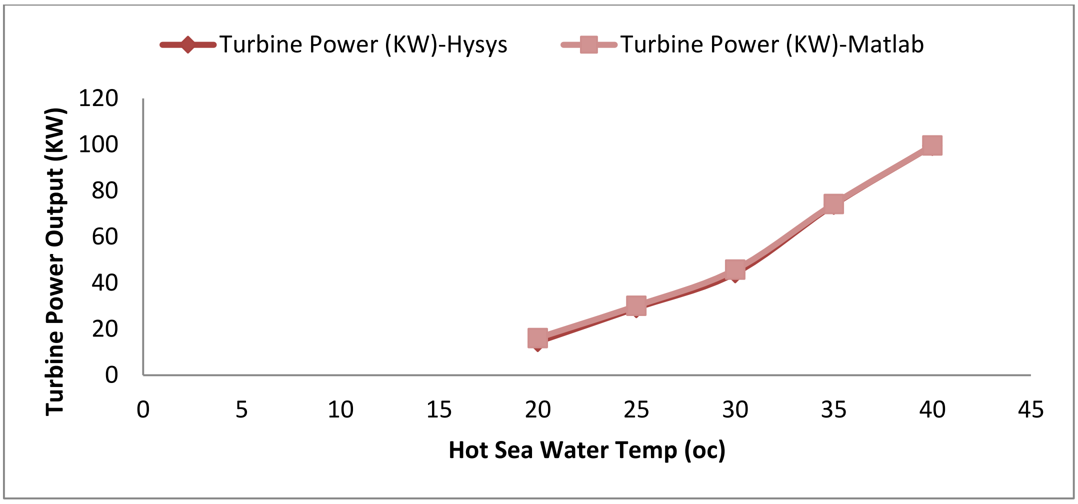

Figure 5: Turbine Power against Hot Sea Water Temperature

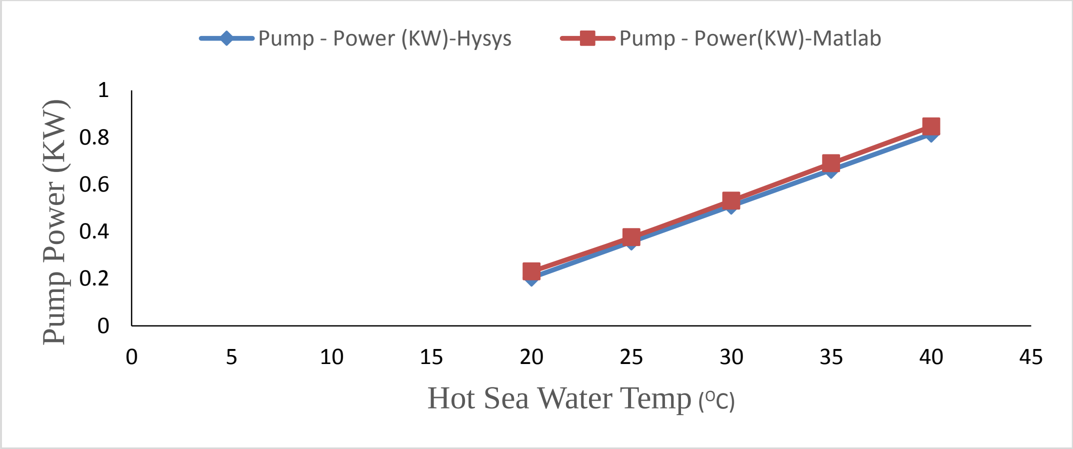

Figure 6: Pump Power against Hot Sea Water Temperature

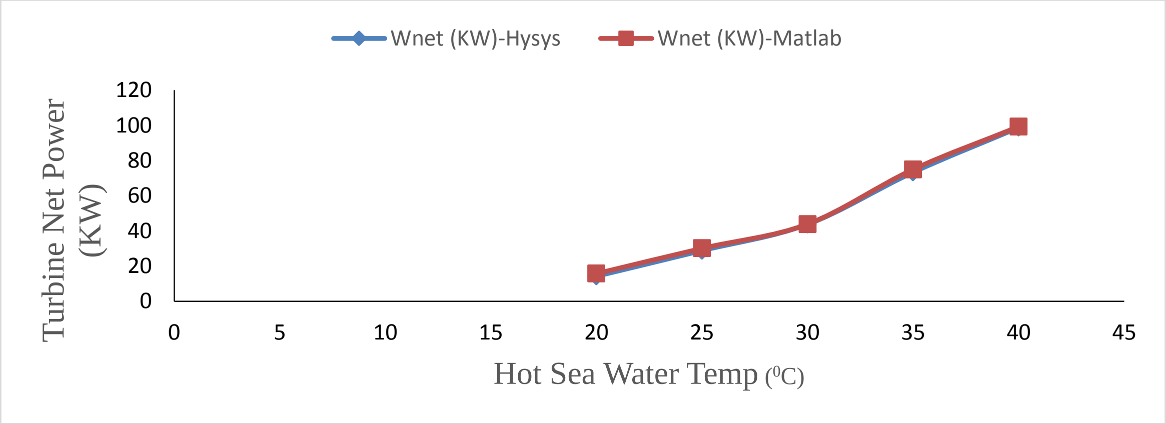

Figure 7 Turbine Net Power against Hot Sea Water Temperature

IV. DISCUSSION AND CONCLUSION

DISCUSSION

The turbine power output is a direct measure of the system's ability to convert thermal energy from the ocean into mechanical energy. **Figure 5** illustrates the effect of hot sea water temperature on turbine power output. As the temperature increases from 20°C to 40°C, the turbine power output rises dramatically from 14.41 KW to 99.49 KW in the Hysys simulation and from 14.45 KW to 99.53 KW in the MATLAB simulation. This significant increase in turbine power output with rising sea water temperature can be attributed to the higher thermal energy available for conversion at higher temperatures. The increased temperature difference between the hot and cold-water streams enhances the thermodynamic efficiency of the working fluid cycle, resulting in greater power output. The close alignment of results from both simulations further validates the observed trend, indicating that the findings are robust and consistent.

Pump power is a measure of the energy required to circulate the working fluid and cooling water through the OTEC system. It directly impacts the overall energy efficiency and net power output of the system. The relationship between hot sea water temperature and pump power is shown in **Figure 6** As the temperature rises from 20°C to 40°C, the pump power increases from 0.2037 KW to 0.8148 KW in the Hysys simulation and from 0.2041 KW to 0.8152 KW in the MATLAB simulation. The increase in pump power with rising sea water temperature is expected, as higher temperatures require more energy to circulate the working fluid through the system. This is due to the increased viscosity and density of the working fluid at higher temperatures, which increases the frictional losses and energy required for circulation. The close correspondence between the Hysys and MATLAB results suggests that the observed trend is reliable and consistent, further validating the impact of sea water temperature on pump power.

Turbine net power output is a measure of the actual usable power generated by the OTEC system, accounting for the energy consumed by the pump. **Figure 7** shows the effect of hot sea water temperature on turbine net power output. As the temperature increases from 20°C to 40°C, the turbine net power output increases from 14.21 KW to 98.68 KW in the Hysys simulation and from 14.25 kW to 98.72 kW in the MATLAB simulation. The substantial rise in net power output with increasing sea water temperature highlights the positive impact of higher thermal energy availability on overall system performance. The increased temperature difference between the hot and Coldwater streams enhances the thermodynamic efficiency of the working fluid cycle, resulting in greater net power output. The close agreement between the Hysys and MATLAB results reinforces the reliability of the findings, indicating that the observed trend is robust and consistent. The analysis of hot sea water temperature effects on the OTEC system reveals several key insights. Firstly, increasing the sea water temperature significantly enhances the turbine power output, indicating that higher temperatures improve the energy conversion efficiency of the system. This improvement is due to the increased thermal energy available for conversion at higher temperatures, which enhances the thermodynamic efficiency of the working fluid cycle. Secondly, the pump power also increases with rising sea water temperature, reflecting the higher energy required to circulate the working fluid through the system. The close agreement between the Hysys and MATLAB results suggests that the observed trends are reliable and consistent, indicating that the findings can be confidently applied to optimize the OTEC system. Finally, the increase in turbine net power output with rising sea water temperature highlights the importance of optimizing the system design to handle higher thermal loads. Ensuring efficient heat transfer and minimizing frictional losses at higher temperatures is crucial for maximizing the energy conversion efficiency of the OTEC system.

V. CONCLUSION

The study of the influence of hot seawater temperature on the performance of a 40KW OTEC that will be situated in Bonny Island has been conducted. The results from both Hysys and MATLAB simulations are compared to evaluate the impact of varying sea water temperatures on system performance and it shows that as the temperature increases from 20°C to 40°C: the turbine power output rises dramatically from 14.41 KW to 99.49 KW in the Hysys simulation and from 14.45 KW to 99.53 KW in the MATLAB simulation ; The pump power increases from 0.2037 KW to 0.8148 KW in the Hysys simulation and from 0.2041 KW to 0.8152 KW in the MATLAB simulation and the turbine net power output increases from 14.21 KW to 98.68 KW in the Hysys simulation and from 14.25 kW to 98.72 kW in the MATLAB simulation (**Figure 5 – Figure 7**). It is recommended that the seawater temperature should be controlled within 28^0C – 30^0C for optimum power generation and thermal efficiency.

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Nomenclature

$\dot{m}_{wsw}$ = the mass flow rate of the warm seawater,

C_P = the specific heat capacity of seawater,

ΔT_{wsw} = the temperature difference between the inlet and the outlet of warm seawater in the evaporator,

$\dot{m}_f$ = the mass flow of working fluid,

h_1 and h_5 = enthalpies of working fluid at the outlet and the inlet of the evaporator respectively.

$\dot{m}_{csw}$ = the mass flow rate of the cold seawater,

C_P = the specific heat capacity of seawater

ΔT_{csw} = the temperature difference between the inlet and the outlet of cold seawater in the evaporator,

$\dot{m}_f$ = the mass flow of working fluid,

h_3 and h_2 = are enthalpies of working fluid at the outlet and the inlet of the evaporator respectively.

h_4 and h_3 = the enthalpies of working fluid at the outlet and the inlet of the working fluid pump,

$\dot{m}_f$ = the mass flow of working fluid,

n_p = the efficiency of the pump.
f_{di} = frictional factor which is function of velocity, roughness factor, viscosity of the fluid and pipe diameter.
L_i = length of pipe (m),
V_i = velocity of water (m/s),
D_i = diameter of pipe (m),
g = acceleration due to gravity.
$i = 1,2,3,\ldots,n$ sections