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Thermodynamic Design and Economic Analysis of Ocean Thermal Energy Conversion for Coastal Nigeria

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ABSTRACT:*This paper considers the analysis of ocean thermal energy conversion (OTEC) technique for the production of electricity in Bonga offshore area of Nigeria. It proposes a 50MW OTEC plant to be sited at a latitude of approximately 4º 30′ 01.5″ N and 4º 29′ 58.1″ longitude, with a sea surface water temperature ranging from 26ºC to 29ºC at a depth of about 20m and that at a depth of almost 1021 meters at a temperature range of 3.5ºC to 4ºC, which uses the temperature difference between these depths to produce electricity. The temperature data collected show that the region has the potential for a base load source. Thermodynamic analysis of a Rankine cycle was used and the working fluid (Ammonia) mass flow rate, the plant thermal and cycle efficiencies were calculated to be about 877.19 kg/s, 4.92% and 4.8% respectively. Warm and cold sea water are pumped into the plant at volume flow rates of about 131m³/s and 125m³/s respectively. The plant is billed to run for 35 years, producing a total energy of about 7971.6 GWh throughout its life. An economic analysis showed the plant installed capital cost, its life cycle cost and unit cost to be about ₦152billion and ₦171.95billion and ₦86.24/KWh respectively. At this unit cost, a break-even point was calculated as 7.854years. These show that OTEC technology can go a long way in alleviating the energy problem in Nigeria and also satisfying the demanding energy need of the world if properly harnessed.The unit cost of the plant is found to be far more than the unit cost of power in Nigeria which goes for an average of about ₦32/KWh and this makes the proposed plant presently uneconomical. OTEC technology will be economically feasible if all its other potentials, like clean water production, are utilized.*

KEY WORDS:*Evaporator, Condenser, ocean thermal, Ammonia, Entropy, Enthalpy.*

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I. INTRODUCTION

The oceans of the world have the is a potential of generating more than 80,000 TWh of electricity generated from changes in the ocean temperatures, salt content, movements of tides, current, waves and swells [1]. This energy potential far exceed world energy demand wish is about 17,500 TWh as at 2015[1]. Therefore, the ocean alone is able to cover all energy demand of the world, without having to pollute the environment and, of course, of these forms of energy are renewable. This work deals with ocean thermal energy conversion (OTEC) as a renewable energy resource of the ocean. The ocean has a potential of generating an estimated 83,340 TWh/year from OTEC, and this is about 90% of the global ocean energy potential [2]. This implies that OTEC has the largest energy potential of the different energy technologies available.

This technology Utilizes the temperature difference between the ocean surface, say between 0 to about 25 meters and that at a depth of about 1000 meters and more to produce clean renewable energy.

The warm surface water is meant to heat a working fluid of a low boiling point and the cold sea water is meant to cool it in an enclosed continuous cycle. The working fluid to be used for this system is ammonia. Ammonia is the ideal working fluid for this system because of its low boiling point (-33.34^{0}C ~ - 28.012^{0}F) at atmospheric pressure [3].

The earliest mention of the use of the thermal energy of the ocean for the production of electricity was in 1881 by a French physicist, Jacques Aresen d' Arsonval. But it was d' Arsonval's student, George Claude, who in 1930 built the first open cycle OTEC plant in Cuba, which functions with a temperature difference of 20^{0}C [4].

The approximate temperature difference needed to make the OTEC process sufficiently efficient and cost effective is 20^{0}C, and such temperature difference exist between the ocean surface and depths of about 1000m in most coastal and open ocean areas within latitude of about $\pm$ 20^0 of the equator, and some areas outside that band [17]. This shows that Nigeria has one of the highest potential for ocean thermal energy conversion (OTEC), looking at her geographical location of 9^0 04$'$ 55.2″ North of the equator, with its southern part sitting directly on the Gulf of Guinea on the Atlantic Ocean. According to the United Nations conventions on the laws of the sea, about 200 nautical miles (370 kilometers) from a nation's baseline or shore is denoted as exclusive economic zone, which implies that a coastal nation within that shore or baseline has sole exploitation rights over all natural resources of the sea within this region [5]. That means a lot of potential from OTEC technology abound around Nigeria but the country is still battling with energy crises. This work hope to propose an OTEC plant in Nigerian territorial waters, basically in Bonga offshore region, which is about 120km off the Nigerian shore line (with a latitude of approximately about 4^o 30′ 01.5″ N of the equator and a longitude of about 4^o 29′ 58.1″) and more than 1000m water depth, utilizing the energy potential of the region for the generation of clean electricity that can be a basis for fixing the energy crisis in the country. The environmental implications of its siting is not a problem since the exploration of ocean thermal energy conversion (OTEC) can be of minimal of no adverse effect to aquatic life if properly planned and executed using set environmental guidelines [6]. The plant would be less expensive if it is built as floating offshore plant [7]. It can be seen from the world sea surface temperature map, figure1, that Nigerian offshore regions have favourable OTEC potential.

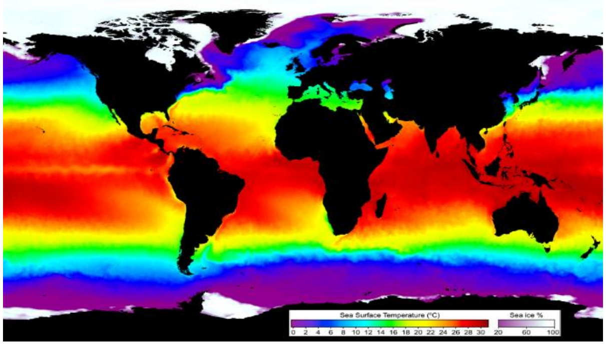

Figure 1: Sea Surface Temperature [8]

Sea water temperature at a given depth, approximately below 500m, does not vary much through all regions of interest for OTEC, since it is a weak function of depth, with typical gradients of about 1^{o}C per 150m between 500m and 1000m as illustrated in figure 2 [9]. This consideration may lead to regarding the cold sea water as nearly constant at about 4^{o}C.

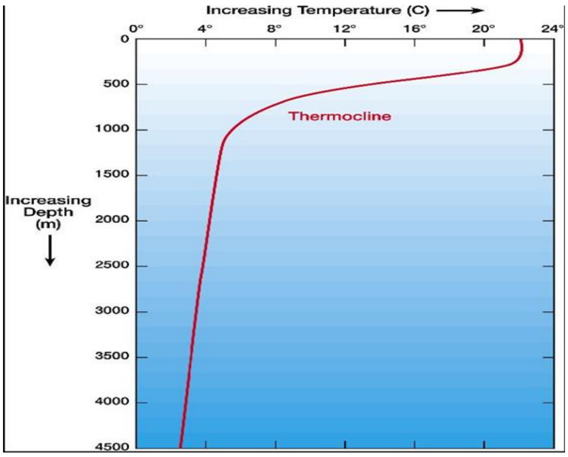

Figure 2: Temperature- Depth Ocean Water Profile [10].

1.1 System Description

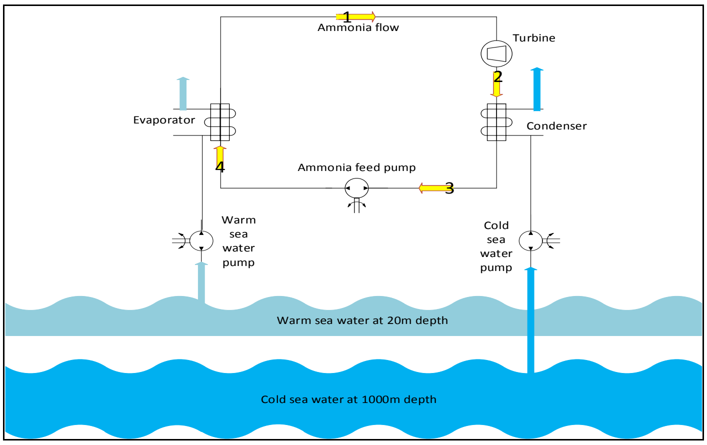

Figure 3: Schematic Diagram of the Close- Cycle OTEC Plant.

The close cycle OTEC (CC-OTEC) plant being proposed, shown in figure 3, operates similar to the conventional Rankin cycle power plant. It comprises of a turbine, a condenser, the working fluid (Ammonia), an ammonia feed pump, an evaporator, and two auxiliary pumps for warm sea surface water and cold sea water at a depth of 1000m.

II. MATERIALS AND METHODS

2.1 Methods

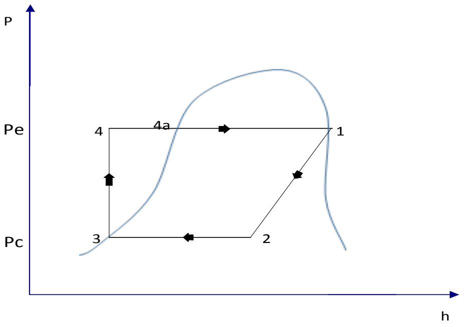

Figure 4: Pressure –Enthalpy Diagram of the Cycle.

The thermodynamic diagram of the plant is shown in figures 4, show the thermodynamic process involved. The saturated ammonia vapour is generated in the evaporator, (4-1), due to the heat exchange between the warm surface sea-water (entering the evaporator through the auxiliary pump for warm sea surface water) and the liquid ammonia entering the evaporator at the saturated pressure, P_e. The saturated ammonia vapour then enters a turbine, (1-2), where it does some shaft work with the impingement of the ammonia vapour on the turbine blades. The turbine rotates driving an electric generator to generate electricity. The wet vapor exiting the turbine at a pressure, Pc is channeled to a condenser, (2-3), where it condenses, loosing heat to the cold water being pumped into the condenser from a depth of 1000m below sea level. The low pressure low temperature liquid ammonia leaving the condenser is then further pressurized via a working fluid feed pump, (3-4), to repeat the cycle.

2.2Thermodynamic Analysis

The thermodynamic processes of a closed cycle OTEC plant, using anhydrous Ammonia as working fluid, are modeled as the saturated Rankine cycle. The analysis is based on the thermodynamic diagram of figure 4.

2.2.1 Heat Analysis

- heat added to the system (process 4-1)

$$q_a = h_1 - h_4 \qquad (1)$$

- heat rejected, (process 2-3)

$$q_a = h_2 - h_3 \qquad (2)$$

- For a perfect heat exchanger, heat transfer rate in the evaporator is

$$Q_a = \dot{m}_{hw} C_{pw} \Delta T = m_a (h_1 - h_4) \qquad (3)$$

Where $\Delta T_h = T_{hi} - T_{ho}$

- The rate of heat rejection in the main condenser is given as

$Q_c = \dot{m}_{cw} C_{pw} \Delta T_c = m_a(h_2 - h_3)$(4)

Where $\Delta T_c = T_{ci} - T_{co}$

2.2.2 Work Analysis

- The turbine work (process 1-2)

$w_T = h_1 - h_2$ (5)

- the pump work, (process 3-4)

$/w_p/= h_4 - h_3 \approx v_3(P_4 - P_3)$ (6)

- The net work

$w_{net} = w_T - /w_p/= h_1 - h_2 - h_3 + h_4$(7)

- The power output of the Ranking power plant

$\dot{W}_{net} = \dot{m}w_{net} = \dot{m}(h_1 - h_2 - h_3 + h_4)$ (8)

- The actual mechanical net work after considering the cycle efficiency.

$\dot{W}_{net} = m_a w_{net} \eta_{ceff}$ (9)

2.2.3 Head Loss and Power Loss Analysis

Work is required to move large quantity of warm water (WW) and cold water (CW) around the plant against friction.

- The head loss due to friction at different section of the pipe

$h_{fi} = \frac{2fl_iU_i^2}{d_ig}$ (10)

- The power loss due to at the different sections

$P_{iw} = h_{fi} m_{iw} g$ (11)

- The Net power produced by the OTEC plant after considering the suction pumps

$\dot{W} = \dot{W}_{net} - P_{iw}$ (12)

(note: i denotes warm surface sea water and cold water. Hence, $P_{iw} = P_{hw} + P_{cw}$)

2.2.4 Efficiency

- The cycle efficiency

$\eta_{ceff} \frac{W_{net}}{\dot{Q}_a} = 1 - \frac{h_2 - h_3}{h_1 - h_4}$ (13)

- Thermal efficiency

$\eta_{th} = \frac{T_1 - T_3}{T_3} \; 1 - \frac{T_3}{T_1}$ (14)

2.2.5 Speed Analysis

- The mean speed of the sea water, i.e. for cold and warm water is given as

$U_i = \frac{\dot{V}_i}{A_i}$ (15)

2.3 Economic Assessment

The Life Cycle Cost (LCC) can be classified into recurring and nonrecurring costs. recurring costs which includes operations and maintenance cost, repair, replacement and other miscellaneous cost are all summed up to be just operations and maintenance cost (O & M_{cost}), while non-recurring costs which includes the initial cost of the plant, the cost of deployment and installation, and cost of commissioning are all denoted as capital cost (C_c).

The capital cost, in dollars per kilowatts, of OTEC close/open cycle plants relate to the plant capacity as follows

$C_c = 53{,}000\, \dot{W}_{net}^{-0.418}$[9] (16)

Operating and maintenance costs are in the other of 1.4%-2.7% of total initial investment costs [11].

This work will assume operation and maintenance costs as 1.5% of capital cost.

The unit cost of electricity or the levelized cost of electricity is given as

$LCOE = \frac{C_c + \sum_0^t \frac{O\&M_{cost}}{(1+r)^t}}{\sum_0^t \frac{E}{(1+r)^t}}$ ₦$/kW$[12] (17)

Where *t* denotes values for each year and *r(%)* is the inflation rate and *n* is the number of years of the plant life.

A simple payback period of money invested can be calculated as follows

$$PBP = \frac{C_c + O\&M_{cost}}{yearly\ \ energy\ \ production\ \ *Unit\ \ cost\ /kWh}$$ [12] (18)

III. RESULTS AND DISCUSSIONS

The table 1 shows the secondary data collected as the monthly average temperature of the region, from an exploration company operating at the region. These temperatures are measured at set depth of about 20m with the aid of Metocean bouy (with a PT 100 current and temperature sensor and an installed conductivity, temperature and depth, CTD sensor).

Table 1: The Monthly Average Sea Surface Temperature of Bonga Offshore

Months	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temp. (^oC)	28.2	28.6	28.8	29.2	28.7	27.6	26.6	26.2	26.4	27.3	28.2	28.4

The temperature at about 1000m depth is almost constant at 4^oC all year round.
Taking warm sea surface water temperature as 26^oC at a depth of about 20m, and cold sea water temperature at approximately 1021m as 4^oC.

3.1Thermodynamics Analysis

Figure 4 shows the thermodynamic cycle of the OTEC plant

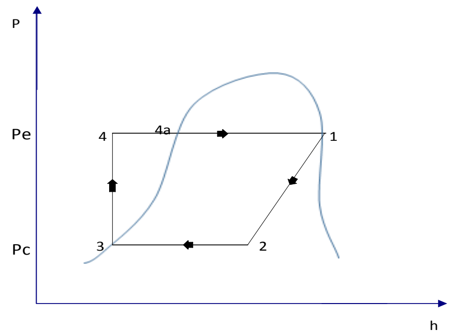

Figure 4: Cycle Pressure-Enthalpy (P-h) Diagram.

Inlet temperature of warm sea surface water, T_{wi} = 26^oC.
Outlet temperature of warm sea surface water, T_{wo} = 24^oC.
Let the minimum temperature difference, that is pinch temperature, ΔT_{mine} = 2^oC.

The evaporator temperatureof working fluid, $T_1 = T_{wo} - \Delta T_{mine}$[13]
T_1=24^oC - 2^oC = 22^oC

At point 3, ammonia is in the saturated liquid state.
Inlet temperature of cold sea water temperature, T_{ci} = 4^oC.
Outlet temperature of cold water, T_{co} = 6^oC.
The pinch temperature difference for the condensers, ΔT_{minc}= 1.5^oC
Thus temperature of the working fluid in the condenser, $T_3 = T_{co} + \Delta T_{min}$ = 6^oC + 1.5^oC = 7.5^oC

Tabulations:

Table 2: Enthalpy (From Ammonia Table)

h_1 (KJ/Kg)	h_2 (KJ/Kg)	h_3 (KJ/Kg)	h_4 (KJ/Kg)
1624.7	1564.8	378.03	378.59

Tables 3: Calculated Results (Thermodynamics Analysis):

Item	**Symbol**	**Unit**	**Value**
Net work	w_{net}	kJ/kg	59.443
Turbine work	w_t	kJ/kg	60
Ammonia pump work	w_{ap}	kJ/kg	-0.557
Cycle efficiency	η_{ceff}	%	4.8
Thermal efficiency	η_{th}	%	4.92
Heat transfer to the system	q_a	kJ/kg	1246.133
Heat rejected	q_c	kJ/kg	1186.77
Ammonia mass flow rate	m_a	kg/s	877.19

Cold sea water mas flow rate	m_{cw}	kg/s	124360.62
Warm sea water mass flow rate	m_{hw}	Kg/s	130579.13
Warm sea water velocity	U_{hw}	m/s	2.05
Cold sea water velocity	U_{cw}	m/s	1.96
Friction loss to cold water pump	h_{fc}	M	1.92
Friction loss to hot water pump	h_{fh}	M	0.042
Power loss to cold water pump	P_{cw}	MW	2.34
Power loss to hot water pump	P_{hw}	MW	0.054
Total net work	W_{net}	MW	47.61

Note the following:

a. The total capital cost per kilowatt of a floating 50MW OTEC plant is estimated at 8430$/kW [9].

b. As at the time of this writing, the exchange of dollar to Nigerian naira (₦) is $1= ₦360.58.

c. Calculations are done with inflation rate, r, kept at 11.14% as at July 2018 [18].

d. The net power availed by OTEC is considered to be around 65% of its gross power generated and its capacity factor is considered to be about 80% [19].

Tables 3.4: Calculated Results (Economic Analysis):

Item	**Symbol**	**Unit**	**Value**
Plant size		MW	50
Installed capital cost	C_c	(₦B)	151.99
Capital cost per kiloWatts	C_c	$/kW	8430
Operation and maintenance cost	$O\&M_{cost}$	(₦B)	2.27
Yearly energy consumption	E	GWh	227.76
Unit cost of energy	U_{um}	₦/kWh	86.24
Pay back period	PBP	Years	7.854

Seasonal weather changes in Nigeria affect the monthly average temperature of the sea surface, and there is relatively very little or no changes in the monthly average temperature at the depth of 1000m. These temperature changes at the surface will not affect the output, since the differences in temperature throughout the year are all above 20^{o}C as shown in the table and graph below. It can be seen from the table and graph that the ΔT all year round are above 20^{o}C, which the limit of OTEC potential. This goes to show that OTEC can be a source of base load power if utilized.

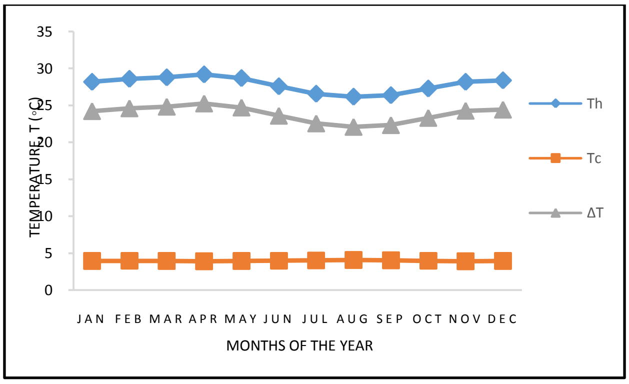

Figure 5 : Variation in Monthly Average Temperaturesof Sea Surface Water, Th, that at 1000m Depth, Tc,and the Difference ΔT.

The following graphs show the relationships between some thermodynamics parameters of the OTEC plant.

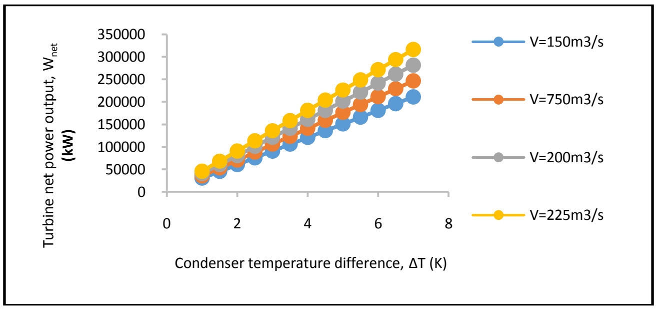

Figure 6: Variation of Net-work, W_{net}, to Evaporator

Temperature Difference, ΔT, at Different Flow RatesVolume Flow.

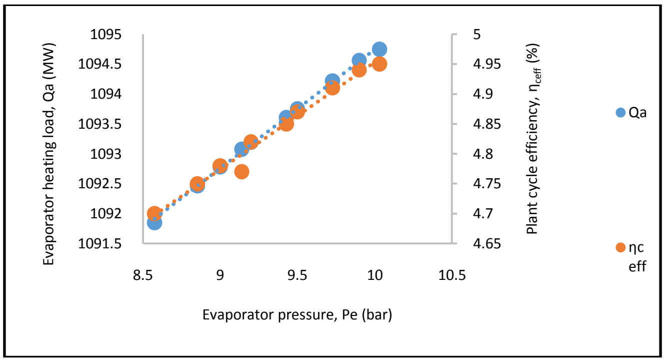

Figure 7: Variation of Evaporator Heating Load, Q_a, Plant Cycle Efficiency, η_{ceff} with Evaporator Pressure, P_e.

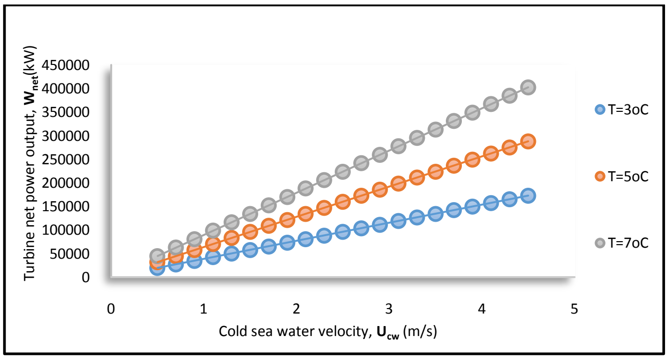

Figure 8: Variation of Turbine Net Power Output, W_{net} with cold Sea water velocity, U_{cw} at Different Temperatures.

Figures 6 show a positive linear variation between the parameters of the evaporator and the net power out of the plant. Figure 8 also show a positive linear relationship between the plant net power output and the velocity of the cold sea water.

IV. CONCLUSION

Thermodynamic analysis of the sea water temperature data collected for the Bonga offshore region show that the average monthly temperature difference between the warm sea water and the cold sea water exceeds the 20^{o}C limit for an OTEC plant be efficient. This means that Bonga offshore region is a potential for a non-fluctuating base load OTEC plant. For a 50MW power plant being proposed, the working fluid mass flowrate of 877.19kg/s, warm and cold sea water volume flowrates of about131m^3/s and 124m^3/s respectively gives an idea of the turbine and pumps to be designed or selected for the plant. The plant will have a capacity of generating about 227.76 GWh and 7971.60 GWh through 35 years life cycle.

A floating offshore vessel, which is less expensive as compared to its onshore counterpart, is the selected design [7]. The unit cost of energy has to be ₦86.24/kWh for a breakeven point of 7.854 years is far more than the average unit cost of electricity in Nigeria which goes for an average cost of about ₦32/kWh [14]. To make OTEC plant uneconomical for Nigeria whose primary energy source comes from fossil fuel [15]. OTEC will be economically viable if other potentials of OTEC technology, like potable water production, Mari culture, refrigeration and air conditioning system and agriculture, are adequately utilized [16].

Figures 3.3 and 3.5 show that the OTEC plant show that improving the efficiency of the heat exchangers will greatly improve the plant overall efficiency.

This research provides overview that potential for Ocean Thermal Energy Resource for the production of electricity for the Bonga offshore area of Nigeria if utilized. It also reveals that OTEC can be the future of energy for other parts of the world.

Acknowledgement

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Nomenclature

Symbol	Definition	Unit
η	efficiency of the system	%
$\dot{m}$	means flow rate of the working fluid	kg/s
$\dot{V}$	volume flow rate	(m^3/s)
$\dot{W}$	Power	kW
$\dot{Q}$	rate of heat transfer	kW
T_w	temperature of warm water before entering the evaporation	K
T_0	temperature of warm water at the exit of the evaporator	K
ΔT_h	evaporator temperature difference	K
i	use of refer to warm and cold warm ie CW and WW	
η_t	turbine efficiency	%
η_{ceff}	Cycle efficiency	%
ρ_w	density of water	m^3/kg
A_{pipe}	Area of the pipe	m^2
C_c	Capital cost	₦
d_{pipe}	diameter of pipe	M

E	Energy production per year	kWh/yr
F	friction loss factor	
G	Acceleration due to gravity	m/s^2
H	specific enthalpy of the working fluid	kJ/kg
L	length of pipe	*M*
LCC	Life cycle cost	₦
LCOE	Levelised cost of electricity	₦/kWh
$O\&M_{cost}$	Operation and maintenance cost	₦
Q	specific heat	kJ/kg
U	velocity of water through the system	*m/s*
U_{um}	Unit cost of electricity	₦/kWh
W	specific work done	kJ/kg
$\Delta T_{min,i}$	The minimum temperature difference for warm and cold fluid respectively	*K*

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