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Techno-Economic Analysis of Small Solar-Organic Rankine Cycle for Sustainable Energy Supply in Domestic Buildings.

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Abstract
The techno-economic analysis of small solar-organic rankine cycle for sustainable energy supply in domestic buildings is presented. The objective of the study is to develop a solar based organic Rankine cycle for electricity supply in domestic buildings, based on solar irradiance data obtained from Calabar. The results from the study indicate that a total output of 700 kW can be achieved while the unit cost of energy was estimated at 0.024$kWh with a payback period of 4 years. The results from the annualized life cycle cost and daily energy production was estimated at values 1.2$ x 10^6, and 1.123$ x 10^4 respectively. While the daily energy generation stood at 1241 MWh/day. The study indicate that the daily energy generated from the developed plant can meet the energy requirement for some domestic building studied, hence enhancing livelihood and environmental sustainability.
Keywords: *Building, Calabar, Energy, Solar power, Sustainability.*

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I. Introduction

Energy access and supply is critical for sustainable growth for both advanced and emerging economies of the world. Energy access is the key component for promoting basic services such as clean water lightning, health services, education, and communication. The global economic growth in the last ten decades has exclusively been compelled fossil fuels utilization. The current variability in the world oil prices combined with the rate of fossils fuel depletion of fossils fuel and its environmental problems have floated the global attention to alternative energy use [1].

Additionally, in the past years, Nigeria had been faced with insufficient electricity supply owing to inadequate infrastructure and insufficient gas supply to the power generating plants. This is escalated by youth unrest specifically in the areas of installation of the power generating plants. Likewise, apart from these factors, with the above mentioned dwindling oil reserves and its environmental health concerns rising from fossil fuel utilization demands the need for clean energy development [2]. Emerging economies like Nigeria need a robust access to sustainable and progressive energy services owing to the increasing population and increase socioeconomic activities. The access to sufficient energy supply will reduce poverty level, advance health conditions, improve productivity, uphold competitiveness and stimulate economic development in all levels [1].

Despite Nigeria's enormous oil treasure, majority of the population do not have access to electricity supply. The population linked to the grid supply system are lacking in power supply above 60% of the supply time about a decade ago, and the problem has barely change [3]. This insufficient and unpredictable power has reduce industrial production capacity forcing many to shut down entirely. Some industries or businesses that managed to be on production resorted to self-electrification, subsequently leading to increase in the prices of products. On domestic or residential cases, they result to using two stroke small generators for electricity generation, increasing environmental hazard.

Furthermore, in Africa recent statistics indicate that, urbanization progression has put extra pressure on the existing weak and inadequate grid system. For example, by 2050, about 60% of the population in the African continent will possibly reside in the urban areas, which will result to a rise in electricity demand [4]. Nevertheless, to cushion this effect, that is energy demand and the environmental problems that may arise, the governments may need concentrated efforts by improving the access to green energy and operative environmental regulatory measures through the application of the right strategies, proper planning and regulations, motivations and active decentralized renewable energy platforms. Such concerted efforts in encouraging energy access through the sustainable development goals 7 [5] have shown enhancement in increasing electricity accessibility in some countries, such as, Bangladesh, Kenya, and India [5].

In this study, an organic, Rankine system is developed based on the solar irradiance in Calabar, Nigeria. The objective of the study is to provide green energy for electricity and hot water supply in a domestic building. The study will also determine the cost of electricity supply and the payback period of the developed system under investment. The author have considered this study unique as the study will show the renewable energy potential for the considered location and provide information for policy drive.

1.1 Plant description

The proposed solar-driven ORC system is presented in Fig.1. The system comprises a solar unit, which drives an ORC, an ORC turbine, pump and water heater. Heat from the solar system is absorbed by the solar collectors. The collector encloses a receiver which enthralled the heat to cause a rise in the heat transfer fluid inside the receiver. The fluid maintained at high temperature moves to the vapour generator triggering the working fluid (refrigerant) to boil and thus expand. The hot fluid enters at state 1 into the ORC turbine, producing work and electricity. Moreover, the fluid that enters the condenser at point 2, exit at point 3 as saturated liquid at high temperature. The liquid is directed through the pumped to the VG at point 4 to start the ORC cycle. Likewise, portion of the heat from the VG is utilized to generate steam at point 9, whereas the hot fluid returns back to the receiver for heat addition.

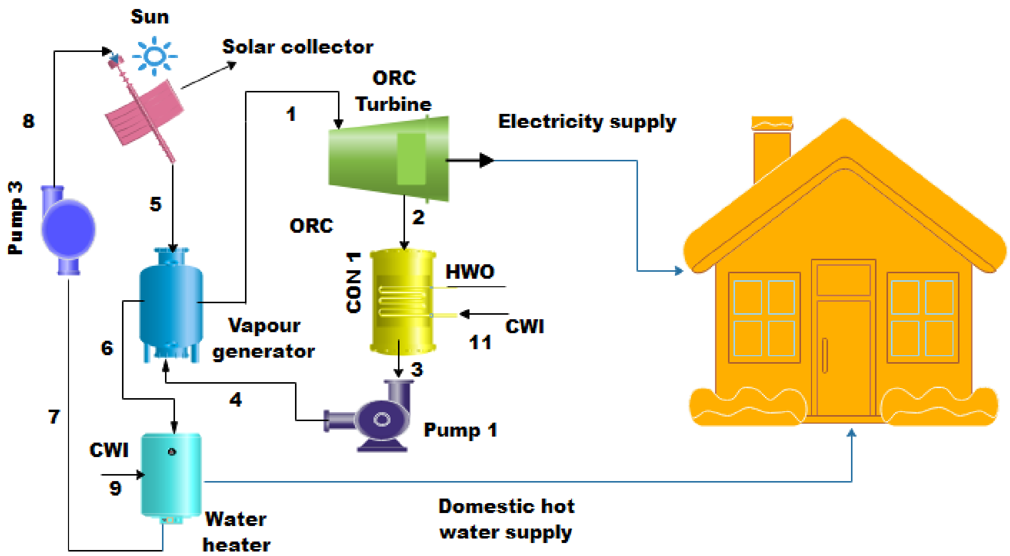


Fig.1. The developed Solar-ORC system

1.2 Thermodynamic and economic models

1.2.1 Thermodynamic model

The mass and energy balance is based on the steady state energy and conservation equations presented as in [6].

$$\sum_i m_i = \sum_j m_j \quad (1)$$

$$\sum \dot{Q} - \sum \dot{W} = \sum m_j h_j - \sum m_i m_i \quad (2)$$

The useful energy gained by the solar collector can be evaluated from:

$$Q_u = F_R[G_B \eta_0 A_a - A_r U_L (T_{in} - T_{amb})] \quad (3)$$

$$Q_u = \dot{m}_{to} Cp_{to}(T_{out} - T_{in}) \quad (4)$$

Where: Cp_{to} T_{out}, T_{in} and $\dot{m}_{to}$ indicates the specific heat of thermal oil, collector outlet temperature, inlet temperature and mass flow of the oil inside the receiver.

The heat removal factorF_R is given as:

$$F_R = \frac{\dot{m}_{to} Cp_{to}}{A_r U_L}\left[1 - exp\left(-\frac{U_L \dot{F} A_r}{\dot{m}_{to} Cp_{to}}\right)\right] \quad (5)$$

Where:

G_B = Total incident radiation

A_a = Aperture plane (activity takes place on an aperture plane)

A_r = Receiver area, given as $\pi * D_{r,0} * L$

UL =Overall Heat loss coefficient

$\dot{F}$ = Efficiency factor of collector, calculated as:

The thermal efficiency of the collector is obtained as:

$$\eta_c = \frac{Q_u}{A_a G_B} \quad (6)$$

1.2.2 Techno economic model

The purchase cost of turbine components for the year 2020 can be calculated by the equations of purchase cost and bare module cost [7]. Also, the relative parameters and coefficients of cost estimation are likewise provided to assist the necessary computation [8]. For the ORC plant, the overall investment cost is mostly evaluated by the cost of the major components, comprising the system evaporator, condenser, turbine, and pump. To calculate, the net power output index, NPI which signifies the ratio of the net power output, W_{net}, to the overall cost of equipments, C_{tot}, of the ORC planted is indicated in Eq.(7).

$$NPI = \frac{W_{turb.} - W_{pump}}{C_{tot}} \quad (7)$$

Manufacturing data for the thermal system were fitted to the following correlation in [7].

$$Log Cp_X = K_{1,X} + K_{2,X} Log(Y) + K_{3,X}(LogY)^2 \quad (8)$$

$$Log\, F_{p,X} = C_{1,X} + C_{2,X} Log(10P - 1) + C_{3,X}[Log(10P - 1)]^2 \quad (9)$$

Where Y is the capacity or parameter which is indicate the component of the ORC system. For the heat exchangers, Y relates to the heat transfer area, while for pumps and turbines this relates with, the power input and output. Also, $K_{1,X}$, $K_{2,X}$, and $K_{3,X}$ are constant manufacturers. The operating pressure and type of material used, correction factors $F_{p,X}$ and $F_{M,X}$ are introduced. The correction factor, $F_{M,X}$ is a constant term for each of the ORC system while $F_{p,X}$ varies according to the relationship [7]. Another term in the techno-economic analysis is the bare module cost takes into account direct (installation of equipment, piping, instrumentation and controls) and indirect costs (engineering and supervision, transportation) and is expressed as:

$$C_{BM,X} = C_{P,X}\left(B_{1,X} + B_{2,X} F_{M,X} F_{P,X}\right) \quad (10)$$

Substituting the value of $C_{BM,X}$ and $C_{P,X}$ from equations (8) and (9), the bare module cost is expressed as,

$$C_{BM,X} = 10^{[K_{1,X} + K_{2,X} Log(Y) + K_{3,X}(LogY)^2]}\left(B_{1,X} + B_{2,X} F_{M,X} 10^{[C_{1,X} + C_{2,X} Log(10P-1) + C_{3,X}[Log(10P-1)]^2]}\right) \quad (11)$$

The relative parameters and coefficients of cost evaluation for equations (8), (9), (10), and (11) are presented in Table 1 [7, 8]

Table 1.
Parameters and coefficients of cost evaluation based on bare module analysis

Component	Evaporator	Super heater	Condenser	Pump	Turbine
Y	Evap. Area (m^2)	Sup. Area (m^2)	Cond. Area (m^2)	$W_{pump}(KW)$	$W_{pump}(KW)$
$K_{1,X}$	4.3247	-	-	3.3892	2.7051
$K_{2,X}$	-0.3030	-	-	0.0536	1.4398
$K_{3,X}$	0.1634	-	-	0.1538	-0.1776
$B_{1,X}$	1.63	-	-	1.89	0
$B_{2,X}$	1.66	-	-	1.35	1
$C_{1,X}$	0.0388	-	-	-0.3935	0
$C_{2,X}$	-0.11272	-	-	0.3957	0
$C_{3,X}$	0.08183	-	-	-0.00226	0

Table 2

$F_{M,X}$	1.4	-	-	1.6	3.4

Source: [7, 8]

II. Results and discussion

2.1 Solar and input data

The results of the techno-economic analysis of small solar-organic rankine cycle for sustainable energy and hot water supply in domestic buildings **is** presented. The engineering equation solver (EES) was applied to solve the developed thermodynamic and cost models. The solar radiation and the input parameters are presented in Tables 2 and 3

Table 2: Summary of solar radiation data in Calabar.

Month	Temperature ^{O}C	H MJ/M^2/month	H W/M^2	n/N	N	RH (%)
January	32.35	14.25	899.42	0.489	4.401	32.35
February	33.81	15.65	1075.78	0.449	4.041	33.81
March	32.72	14.77	1284	0.355	3.195	32.72
April	31.96	14.27	1072	0.411	3.699	31.96
May	31.51	14.85	1137	0.403	3.627	31.51
June	30.16	13.65	1232	0.341	3.069	30.16
July	28.16	11.65	1492	0.241	2.169	28.16
August	28.13	10.80	2,398	0.139	1.251	28.13
September	29.16	12.26	1785	0.212	1.908	29.16
October	30.02	15.18	1599	0.293	2.637	30.02
November	31.06	16.51	1169	0.436	3.924	31.06
December	31.91	15.42	885	0.538	4.842	31.91

Source; Solar measured data 2020 by author

Table 3: Input parameters for the proposed system

Operating parameters	Value	Unit
Ambient temperature	298	K
Ambient pressure	101.3	kPa
Collector length	12.27	m
Collector width	5.76	m
Cover inner diameter	0.115	m
Cover outer diameter	0.21	m
Cover temperature	371	K
Receiver temperature	371	K
Receiver inner diameter	0.06	m
Receiver outer diameter	0.08	m
Transmittance of the glass cover	0.96	-
Absorbance of the receiver	0.96	-
Turbine efficiency	85	%
Pump efficiency	80	%
Mass flow rate of steam	1.8	kg/s
Turbine inlet pressure	500	kPa
Turbine inlet temperature	423	K

Source: *Al-Sulaiman, 2014; El-emam, 2018*

From Table 2 the monthly temperature and solar insulation for the considered location varies between 28.13 and 32.35 ^{O}C, and 11.65 and 16.51 MJ/M^2/month. The months of November, February and May had the highest solar insulation calculate at 16.51, and 15.65 and 14.85 MJ/M^2/month respectively. Similarly, the clearness in these months were found to be highest and promising.

2.2 Economic analysis

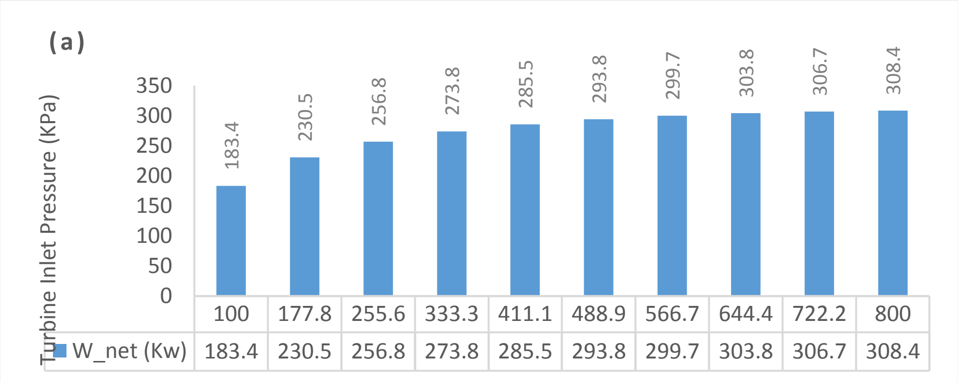
Table 4, shows the results of the economic analysis of the plant. Furthermore, from the results the unit cost of electricity (UCOE) obtained was 0.024$kWh which is equivalent to 16.8 Naira in Nigeria local currency per kilowatt. Other economic values are presented in Table 4, which included the life cycle cost of plant, annualized life cycle cost and daily energy production. These values stood at 1.2$ x 10^6, 1.123$ x 10^4 and 1241 MWh/d respectively.

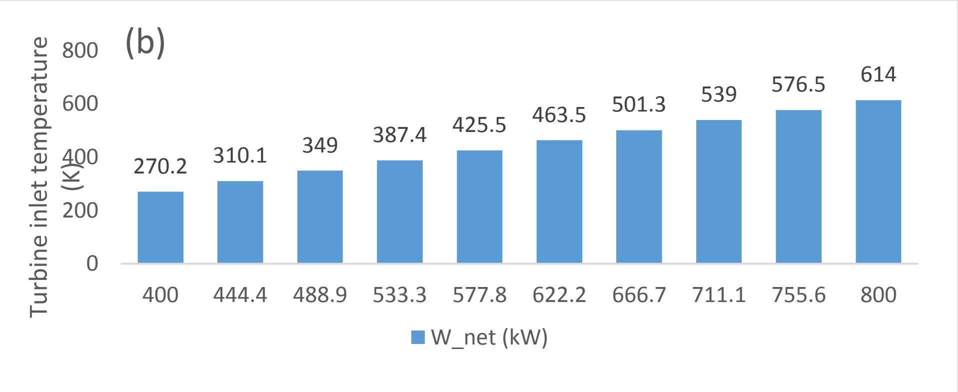
Table 4: Economic parameters of the proposed Solar-ORC plant

Parameter	**Symbol**	**Units**	
unit cost of electricity	UCOE	$/Kwh	0.024
Life cycle cost of plant	Z_{LCC}	$ x 10^6	1.200
Annualized life cycle cost	Z_{ALCC}	$ x 10^4	1.123
Daily energy production	EDP	MWh/d	1241.4
Yearly energy production	EP_{yr}	MWh/y	$0.3006x10^6$
Break even period (Payback period)	BEP	year	4.0

2.3 Sensitivity analysis of operating parameters to the system performance

Fig. 2 (a-c) presents the sensitivity analysis of different operating parameters on power output or network output. Fig.2a, the effect of turbine inlet pressure on power output. The results show that as the turbine inlet pressure increases from 10 to 160 kPa, the power output also increases. From 183.4 kW to 308.4 kW, with maximum output obtained at 160 kPa. Similarly, increase in turbine inlet temperature and turbine inlet mass flow rate increase power out to about 800 kW in both cases for maximum input parameters. This indicate that the solar irradiance from the considered location, is capable of producing sufficient energy that will power an ORC and carter for the domestic energy required.





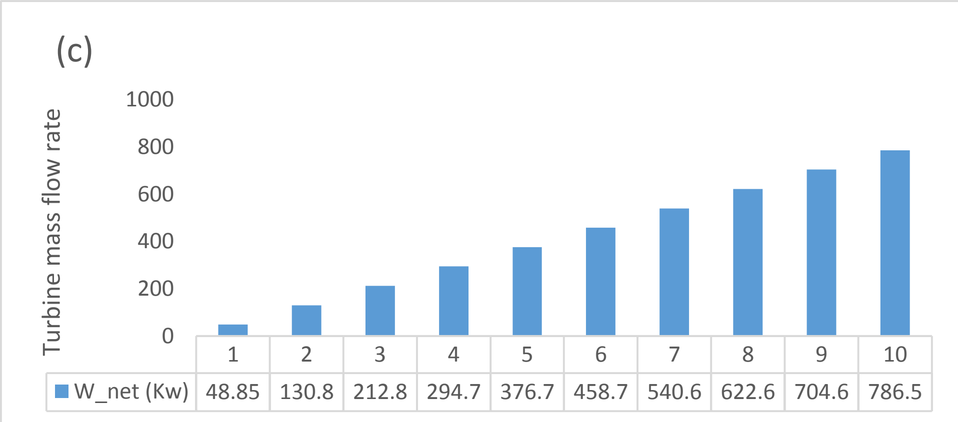


Fig.2. Effect of operating parameters on power output (a) Turbine inlet pressure, (b) Turbine inlet temperature, (c) Turbine inlet mass flow rate

2.3 Household energy profit from the Solar-ORC plant

The monthly energy need for different household in Calabar is presented in Fig.3 the different household's capacity stretching from single apartment (self-contain), one and two bedroom flats, and others are presented with the corresponding monthly energy needs. Fig.3 shows the turbine output of 800 kW can meet the household demand to a large extent in the case study. The result shows that up to nine (one and two bedroom flat residential), and as much as five (three and four bedroom flat residential) can benefit from the Solar-ORC system when operated at highly optimum operating conditions (Fig. 2b and 2c). The maximum power developed in Fig. 2b is about 800 kW, while that produced in Fig. 2c is approximate 780 kW. The fact remains that the system must be optimized at that operating condition to achieve the required for the household resource.

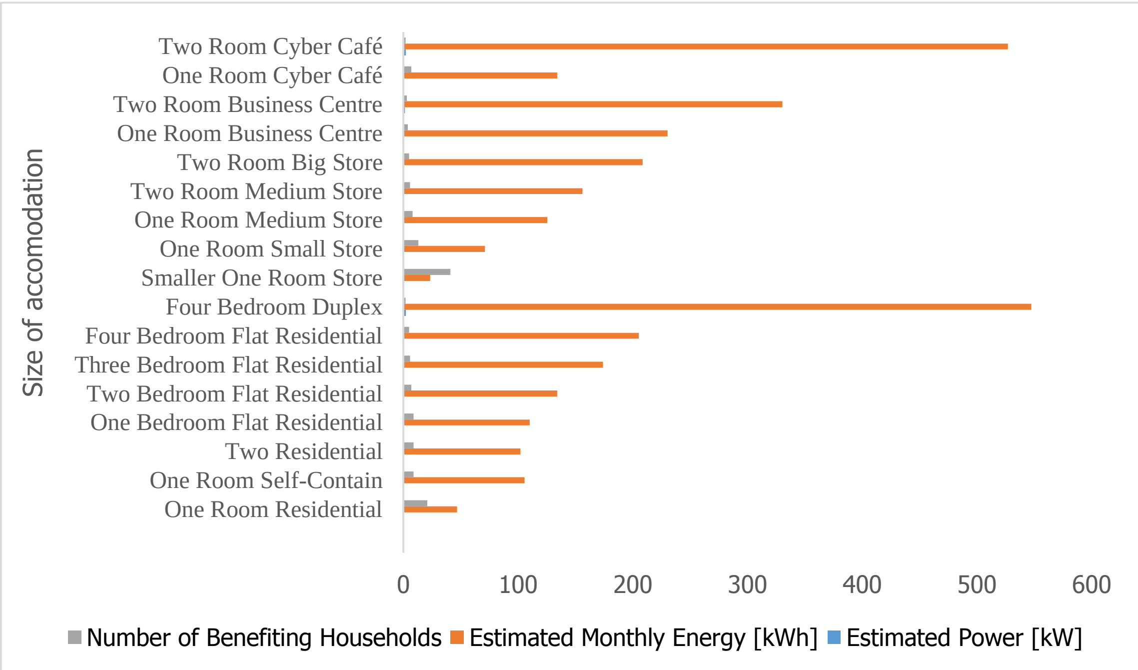


Fig. 2. Household energy profit from the Solar-ORC plant

III. Conclusion

The study on the techno-economic analysis of a solar based ORC system is presented. The study utilizes the solar irradiance in Calabar and indicated that Calabar has the potential for solar energy utilization. The maximum solar irradiance was obtained in the month of November which stood at about 16.51 MJ/M^2/month. This value is capable of producing equivalent turbine output at optimum condition of about 700 kW. Similarly, the efficiency obtained from the plant was not greater than 60 % showing a comparable good energy conversion process. The cost of energy and the payback period were calculated at 0.024$kWh and 4 years respectively. The study concluded that the considered location has prospects for renewable energy utilization and the results obtained can provide information for policy initiative.

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