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EXERGO-ENVIRONMENTAL SUSTAINABILITY ASSESSMENTS OF ORGANIC RANKINE CYCLE PLANTS POWERED BY A TYPICAL ABANDONED OIL WELL

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ABSTRACT

Economic and technical factors often force players in the oil and gas sectors to abandon oil wells with significant but minimal energy contents. To promote energy efficiency, efforts are ongoing to explore viable means of recovering such residual energy, basically as geotherms, for power generation. However, there are sparse studies in the literature that assess the exergo-environmental sustainability potentials of power generation from ORC using abandoned oil wells as the primary energy source, thereby necessitating this study.

The exergetic sustainability and exergo-environmental performance of non-recuperative and recuperative organic Rankine cycle (ORC) plants were assessed in this study for the production of electricity from abandoned oil wells. The geomechanical properties of a typical oil well in Nigeria were employed as inputs into an established COMSOL model to determine the thermal profile of the heat source. For the ORC plant, the mass, energy, and exergy balance equations defined by the Thermodynamics laws were implemented in MATLAB. Also, MATLAB was adopted for computing the exergetic sustainability and exergo-environmental metrics for the individual components and the entire system.

Results showed that the condenser exhibited the least exergo-environmental sustainability for both ORC schemes assessed, meaning that it contributed the most to energy wastages among the system components. Furthermore, results showed that the exergo-environmental impact rates of the condenser are highest in both cases. Generally, results showed that the inclusion of a recuperator would improve the exergy-based environmental sustainability of the ORC plant. Specifically, the overall rate of exergo-environmental impact would decrease from around 86 Pt/h to about 76 Pt/h, amounting to approximately 13% decrease.

1 INTRODUCTION

An essential part of the oil and gas exploration process is the drilling of wells for scooping the desired products deposited in the earth. However, the quality and quantity of crude oil and gas producible from wells diminish over time due to several geological and mechanical challenges associated with the age of oil and gas wells [1]. Close to the end of life of oil and gas wells when the water contents in the wells have increased tremendously, operators have the choice of deploying enhanced oil recovery (EOR) technologies to optimize oil and gas outputs from wells and of course the profits accruable to the company [2], [3], [4]. However, oil and gas players in several developing countries such as Nigeria consider the costs of EOR too intensive, and considering the availability of vast oil and gas reserves in other virgin fields, they tend to simply abandon depleting wells and move on to develop new ones. Consequently, huge thermal energy available in the abandoned wells is wasted, and the oil wells so abandoned without adequate decommissioning are major sources of environmental degradation. Thus, researchers have been investigating other potential uses of heat in abandoned oil and gas wells, in which case the conversion to geothermal sources for power production is at the fore [5], [6], thereby placing this study in a proper perspective.

The organic Rankine cycle (ORC) is today ubiquitous energy conversion technology that plays a critical role in the conversion of low-temperature thermal energy to electricity [7], [8], [9]. Besides the ORC, there are other methods for low-temperature conversion to useful energy, Agberegha et al. [10] proposed a novel combined-cascade steam-to-steam trigeneration cycle integrated with vapour absorption refrigeration (VAR) and district heating systems. The proposed trigeneration system incorporated a binary NH_3-H_2O VAR system, emphasizing its significance in low-temperature energy systems. The VAR system achieved a cycle exergetic efficiency of 92.25% at a cooling capacity of 2.07 MW, utilizing recovered waste heat at 88 ◦C for district hot water. The recovered heat minimizes overall exergy destruction, enhancing thermal plant performance.

ORC is synonymous with the conventional steam Rankine cycle in its processes, differing only in the use of organic working fluid instead of water used in the steam Rankine cycle [11], [12]. Several researchers have tipped the ORC as a viable technology for exploiting the residual thermal energy in abandoned oil wells for electricity production [13], [14], [15], [16]. However, most of the previous studies on the subject have been limited to techno-economic feasibility studies based on the First Law of Thermodynamics [17], without much recourse to the environmental aspects. Considering the potential threat that such systems could pose to the environment, it is vital to incorporate environmental assessment [18] into the technical feasibility studies of power production from abandoned oil wells using ORC plants.

Researchers have postulated exergetic approaches, derived from the 2nd Law of Thermodynamics, for integrating environmental assessment with technical analysis of energy systems, in the form of exergetic sustainability assessments [19], [20], [21] and exergo-environmental analysis [22], [23]. A few studies on ORC plants that have incorporated both the exergetic sustainability and exergo-environmental methods are summarized here. Parham et al. [24] employed the exergetic sustainability method to examine the roles of evaporator temperature on the output power of an ORC plant and hydrogen production rate from an electrolyzer in a tri-generation system using an open absorption heat transformer (OAHT) as the heat source. The authors affirmed that increasing the evaporator inlet temperature is in favor of the environment by the increase in exergetic sustainability factor and decrease in exergo-environmental impact. Abam et al. [25] adopted the exergy-based sustainability indicators to determine an optimum amongst several ORC configurations utilizing low-temperature energy sources. They reported specifically that system configuration and working fluid choice play significant roles in the sustainability of ORC plants. In another study, Abam et al. [26] used the exergetic sustainability indices to compare the performance of R245fa, R1234yf, and R1234ze when employed as working media in ORC plants. The authors again reiterated that either of the refrigerants compared could give optimal sustainability performance depending on the actual ORC configuration in focus. Also, Abam et al. [27] investigated the effects of evaporator pressure and heat source temperature on the exergetic sustainability of several ORC configurations, reporting that strong correlations exist between the varied cycle parameters and its sustainability, as would be expected. Adebayo et al. [28] identified the current density in a multi-generation energy system comprising a solid oxide fuel cell, an ORC, and an absorption chiller as a major factor affecting exergetic sustainability and environmental impact. Specifically, the authors reported that increasing the current density would harm the sustainability of such a system. Nasruddin et al. [29] analyzed the exogoenvironmental performance of a binary geothermal ORC plant operational in Indonesia, reporting a total environmental impact of about 0.3 Pt/s for the system. Also, Alibaba et al. [30] employed the exergy-based method to investigate the impacts of a solar-geothermal ORC system on the environment. They obtained that the solar system had the highest environmental impact on the hybrid plant and that exergy destruction contributed the most to the overall environmental impact of the system. Ding et al. [31] reported the significance of working fluid leakage in the environmental impacts of ORC systems. Specifically, for R245fa, R134a, R152a, and R227ea compared in the study, the authors obtained that between 2.6% and 26% of the environmental impact is directly linked with the working fluids, between 36% and 78% of which are due to leakages. Fergani et al. [32] used the exergo-environmental method to study the optimization potentials in an ORC plant for waste heat recovery in the cement industry. They reported that from the exergo-environmental viewpoint, the heat exchangers should be optimized, for the overall improvement of the entire ORC system.

It is explicit from the foregoing that ORC can be employed to optimally produce electricity from abandoned oil wells. Also, the exergetic sustainability and the exergo-environmental methodologies are being explored widely for integrated environmental assessments of ORC plants for different applications. However, no study has been found in the literature that assessed the exergo-environmental sustainability potentials of power generation from ORC using abandoned oil wells as the primary energy source. Considering the importance of the environmental performance of ORC plants for such an application, its environmental assessment based on the Second Law of Thermodynamics is a vital research gap that is aimed to be bridged in this article. Specifically, two different ORC configurations are proposed and assessed using both the sustainability and environmental approaches derived from the Second Law. The first ORC configuration is a basic subcritical ORC without internal heat recuperation, named here as SUB ORC, while the second is a recuperative subcritical ORC plant tagged here as SUB-REGEN ORC. The tangential study objectives are:

- To quantify the exergo-environmental sustainability indices for a defined SUB ORC plant generating electricity from an abandoned oil well in Nigeria;
- To quantify the exergo-environmental sustainability indices for a defined SUB-REGEN ORC plant;
- To quantify the effects of incorporating an internal heat recuperator on the exergy-based environmental sustainability of the ORC plant for power production from an abandoned oil well.

2 MATERIALS AND METHODS

2.1 System Configurations

Thermal energy content in an abandoned oil well was considered in this study as the heat source for electricity generation by an organic Rankine cycle (ORC) power plant. Specifically, a coaxial borehole heat exchanger (BHE) was plugged into the abandoned well for heat energy exploitation and connected to the ORC power plant through its evaporator and preheater. A numerical analysis of the BHE already established in the literature [33] was adopted in this study using as input parameters the geometrical features of a typical oil well already abandoned in the oil-rich Delta State of Nigeria [34].The main features of the BHE employed in this study are highlighted in Table 1. The temperature of the geothermal brine interfacing the ORC plant was determined from the simulation of the BHE in COMSOL as presented in [33], adapting the geometrical characteristics of the reference oil well.

The ORC plants analyzed in this study assumed two configurations: a subcritical ORC plant without internal heat recuperation, tagged here as SUB ORC, and another one with heat recuperation, dubbed in this study as SUB-REGEN ORC. As aforementioned, the ORC plant, irrespective of the configuration assumed, received the residual thermal energy exploited from the abandoned oil well through the geothermal fluid. The geothermal brine enters the evaporator of the ORC plant and exchanges heat with the organic working fluid of the ORC and the remaining thermal content of the geothermal fluid is further exchanged with the ORC plant in the preheater before the brine is re-circulated in the oil well. The fluid R236fa was considered in this study as the ORC working medium. After it has been preheated and evaporated at high pressure by the geothermal brine, the high-temperature

R236fa vapor is expanded in the turbine (turbogenerator) for electrical power production. The expanded ORC working fluid, still in a vapor state, is then condensed back to liquid in the condenser for the non-recuperative ORC configuration (SUB ORC) by discharging its thermal energy to a heat sink. In the case of the recuperative ORC configuration (SUB-REGEN ORC), the heat of the expanded working fluid vapor is recovered internally within the cycle by the recuperator, for the initial preheating of the working fluid at the pump exit, after which the expanded vapor is condensed to a liquid. In both cases, the liquid working fluid leaving the condenser is pressurized in the pump to increase pressure from the lower to the upper cycle pressure, and the cycle repeats. Compressed air was considered as the heat sink in both cases due to the scarcity of water in the location of the abandoned oil well being exploited. The organic working fluid R236fa was selected based on its good thermal stability, low environmental impact, and ultimately its common application in practical ORC systems [35], [36], [37].The SUB ORC and SUB-REGEN ORC configurations are illustrated in Figure 1a and 1b.

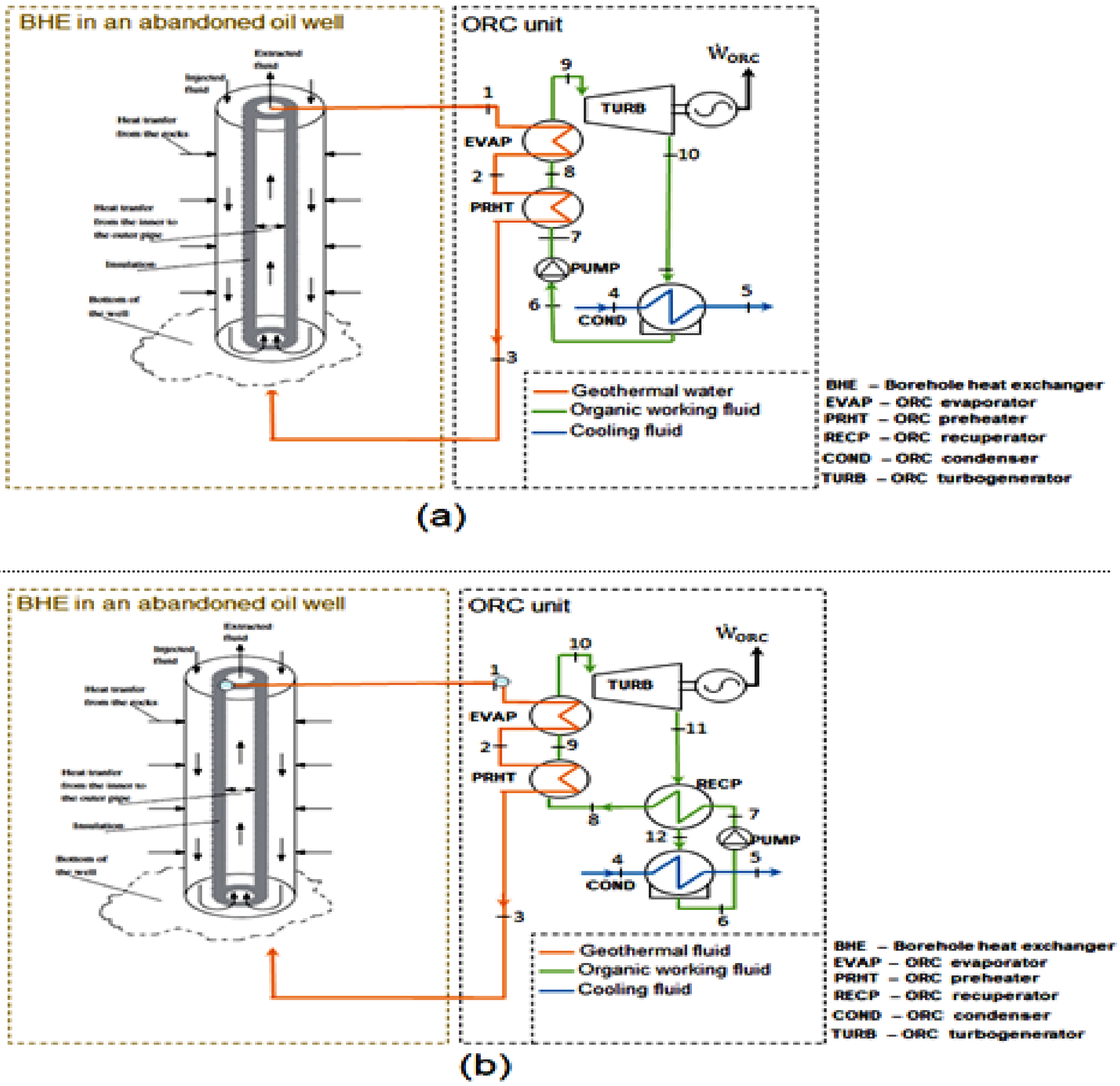

Figure 1*. The non-recuperative and recuperative ORC units.*

2.2 Exergetic Sustainability Analysis

To assess the sustainability of energy systems from the exergy perspective [20], comprehensive exergy analysis is first required, which entails each component and the overall system satisfying the mass and energy balance equations mandated by the First Law of Thermodynamics and the exergy balance equation enforced by the Second Law, as expressed in equations 1, 2, and 3, respectively:

$$\sum \dot{m}_i = \sum \dot{m}_o \tag{1}$$

$$\sum \dot{m}_i h_i + \dot{Q} = \sum \dot{m}_o h_o + \dot{W} \tag{2}$$

$$\sum \dot{m}_i e_i + \dot{Q}\left(1 - \frac{T_a}{T_c}\right) = \sum \dot{m}_o e_o + \dot{W} + \dot{I} \quad (3)$$

where *T* symbolizes the temperature at any given state, *e* symbolizes specific exergy, $\dot{I}$ for any component denotes the rate of exergy destroyed, $\dot{Q}$ symbolizes heat flow, $\dot{W}$is the rate of workflow, *h* symbolizes enthalpy per unit mass, and $\dot{m}$ is the rate of mass flow of the working fluid.

All the parameters with subscript *i* account for the inlet flow into a component while those with *o* account for exit flows. The ambient parameters are symbolized by subscript a while those for the surface of the respective components are denoted by *c*.

The potential exergy (e_{pe}), chemical exergy (e_{ch}), kinetic exergy (e_{ke}), and physical exergy (e_{ph}), are the four primary components that make up the specific exergy, fundamentally (T. J. Kotas, 1985). Analysis of most energy systems fixed in position do not include the kinetic and potential exergy components, and most systems without actual chemical reactions - like the ORC systems being studied herein - have zero chemical exergy. Therefore, the physical exergy sufficiently models the total exergy per unit mass herein, defined by:

$$e_{ph} = (h\text{-}h_a)\text{- } T_a(s\text{-}s_a) \quad (4)$$

where for each stream, defined by distinct thermal-fluid properties, *s* connotes entropy per unit mass. Table 1 reports, for the plants being investigated herein, the fundamental design elements.

***Table 1**. Abandoned oil well and ORC basic design features.*

Abandoned oil well and BHE		ORC unit	
Well head	4500 m	Working fluid	R236fa
BHE tube radius	3.8 cm	Heat sink	Air
BHE annulus radius	8.9 cm	Net electrical power	Optimized
BHE thickness	1 cm	Nominal input thermal power	Decision variable
Brine temperature	155°C	Nominal HTF flow rate	Decision variable
		Isentropic efficiency - pump	0.80
		Motor efficiency - pump	0.98
		Isentropic efficiency - turbine	0.85
		Electromechanical efficiency	0.92
		Mechanical efficiency - cooling fan	0.60
		Pinch point temperature difference	5 °C

2.3 Exergy-Based Sustainability Performance Metrics

This study compared the two ORC configurations using four exergy-based sustainability indicators, which are explained below [38]. In any component *k*, product exergy ($\dot{E}_P$) to fuel exergy ($\dot{E}_F$) ratio defined the exergy efficiency (η_{ex}). The net exergy used on the component defines its fuel exergy; on the other hand, the net exergy generated by the component is its product exergy. One of the fundamental propositions of the 2nd Law of Thermodynamics is that the useful energy (exergy) entering and exiting a component (k) cannot be equal because all real systems are irreversible, meaning that some exergy must be destroyed in the component. The fuel exergy and product exergy per unit mass have been defined for each of the components of the systems under investigation herein, as highlighted in Tables 2 for the SUB ORC and Table 3 for the SUB-REGEN ORC configurations.

One popular performance indicator of exergy-based environmental sustainability of energy systems is the Exergy Sustainability Index (ESI), expressed by:

$$ESI = \frac{\eta_{ex}}{1 - \eta_{ex}} \quad (5)$$

A component bears greater weight in the overall sustainability of the system the higher its ESI value. Conversely, a component's environmental impact increases with decreasing ESI value. Consequently, the Environmental Effect Factor (EEF), which is yet a common performance metric for exergy-based sustainability of a system, was calculated herein by inversing the ESI.

To further enhance exergy-based sustainability, a different metric was employed to specify the amount of exergy losses and destruction in a particular component k that could be recovered. Here, it is known as the exergy-based improvement potential rate (IPR), and its computation is as follows:

$$IPR = (1 - \eta_{ex})(\dot{E}_F - \dot{E}_P) \quad (6)$$

The fourth metric, the Exergetic Recoverability Ratio (RECR), was defined for each component k as:

$$RECR = \frac{IP}{\dot{E}_F} \quad (7)$$

2.4 Exergo-Environmental Analysis

The exergo-environmental approach combines life cycle assessment (LCA) and theoretical exergy principles to measure the environmental implications of irreversibility and the usable energy in and out of a system and accompanying components. Herein, the LCA approach was used in addition to the traditional exergy analysis, as previously mentioned, to evaluate the environmental effects of the various ORC components. These were then combined in accordance with the conventional exergo-environmental methodology's definition [22].

The standard life cycle assessment approach, which consists of four major stages and is used to investigate the environmental impacts of a product or process over its entire life cycle, was applied to characterise the environmental impacts of the ORC plants [39]. The first stage involves defining the study goal and scope, as well as the effect categories, characterization elements, and boundary of analysis. A life cycle inventory study, which estimates all material and energy fluxes into and out of a component or system, is included in the second stage. Impact evaluations are conducted in the third stage with the use of suitable impact assessment techniques, many of which are integrated into Life Cycle Assessment (LCA) software. In the final step, the findings from the earlier phases are analysed to estimate the system's environmental impact.

Exergo-environmental analysis necessitates assigning environmental implications to each exergy stream for the system's individual components and as a whole. Thus, a point-based environmental impact method for energy streams is frequently employed in addition to objective and scope definition and inventory analysis based on the system model. The environmental impact of component/system streams was assigned in this study using the eco-indicator-99 (EI-99) impact identifier. The EI-99 technique uses a hierarchical weighting system to create a single environmental index for processes and products, correlated with key harm aspects: natural resources, human health, and ecosystem quality [40]. The approach defines indices in millipoints (mPts) or points (Pts) for various processes and products, based on the LCA international standards. The more environmental harm a process or system component causes, the higher the EI-99 points that are awarded for that exergy stream or component. Following the assignment of environmental impacts in points to system components/streams for the exergy-based Life Cycle Assessment (LCA) of the system, the exergo-environmental variables are computed.

Meyer et al. [22], developed the exergo-environmental approach and suggested a balance equation that is similar to the exergoeconomic cost balance equation. Equations 8 and 9, which establish the component-level balancing equation, are the foundation of exergo-environmental analysis nowadays.

$$\sum B_i + B_q + (Y + B^{PF}) = \sum B_o + B_w \quad (8)$$

$$\sum b_i E_i + b_q Q + (Y + B^{PF}) = \sum b_o E_o + b_w W \quad (9)$$

with B denoting environmental impact rate, obtainable by multiplying the environmental impact per unit mass of a stream (b, Pts/kWh) with its exergy rate (E, kW), subscripts q and w denote specific heat and work flow to and from a component, respectively, B^{PF}symbolizes the contribution of pollutants formed in a component to its environmental impact rate, and aggregating the impact rates resulting from component's construction Y^{CO}, maintenance/operation, Y^{OM},and end-of-life disposal, Y^{DI}, would yield Y (component's environmental impact rate).Also, $B^{PF}$is defined for each component as:

$$B^{PF} = \sum_n b_n{}^{PF} \left(\dot{m}_{n,out} - \dot{m}_{n,in}\right) \quad (10)$$

with$b_n{}^{PF}$representing the environmental impact per unit mass emanating froma pollutant n produced by a component (Pts/kg), with $\dot{m}_{n,in}$ and $\dot{m}_{n,out}$denoting inlet and exit mass flow rates of the pollutant, respectively.

The exergo-environmental balance equations for the SUB ORC and SUB-REGEN ORC components are equally defined respectively in Tables 2 and 3. Based on the weight and material composition of each component, the environmental consequences were computed in EI-99 points. Applying the inventory analysis and manufacturer specifications for the corresponding plant units, the ecoinvent database was utilised to calculate the weight and composition of the ORC components/sub-units[41], [42]. Auxiliary equations were defined using the product-fuel (P-F) rule, supplemented by the environmental balance equations, to arrive at the definitions for environmental impact per unit mass (b) for the individual thermodynamic streams of the system [43], highlighted also in Tables 2 and 3 for each of the ORC configurations being investigated. The final step involves setting up all the auxiliary and balance equations for all system components and solving them simultaneously, as a stream's specific cost would be determined using the popular specific exergy costing (SPECO) method of exergoeconomic analysis [44].

2.5 Exergo-Environmental Evaluation Parameters

The total exergo-environmental impact rate (BRT), exergo-environmental factor (f_b), specific exergo-environmental impact relative difference (r_b), exergo-environmental impact per unit energy produced (EIE), exergo-environmental impact rate due to irreversibility in system component ($\dot{B}_D$), exergo-environmental impact per unit fuel consumed(b_f), andthe exergo-environmental impact per unit product exergy (b_p) were employed herein to compare the two ORC configurations. The appendix defines the previously described exergo-environmental evaluation parameters for any system component k.

When the values for b have been determined for all thermodynamic streams, the P-F ruled aided the calculations of the exergo-environmental impact rates for fuel ($B_{f,k}$) and product ($B_{p,k}$). Once more, subtracting the fuel and product exergy rates for any component k would yield the irreversibility there in(I_k).

Table 2. *SUB ORC components - definitions of fuel and product, exergo-environmental rate balance, and auxiliary equations.*

Specific component/Abbreviation	Fuel exergy	Product exergy	Exergo-environmental rate balance equation	Auxiliary equation
Evaporator (EVAP)	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_9 - \dot{E}_8$	$\dot{B}_1 + \dot{B}_8 + \dot{Y}_{EVAP} = \dot{B}_2 + \dot{B}_9$	$b_1 = b_2$ = 0.0425 Pt/kWh [45]
ORC preheater (PRHT)	$\dot{E}_2 - \dot{E}_3$	$\dot{E}_8 - \dot{E}_7$	$\dot{B}_2 + \dot{B}_7 + \dot{Y}_{PRHT} = \dot{B}_3 + \dot{B}_8$	$b_2 = b_3$
Condenser (COND)	$\dot{E}_{10} - \dot{E}_6 + \dot{W}_{FAN}$	$\dot{E}_5 - \dot{E}_4$	$\dot{B}_{10} + \dot{B}_4 + \dot{B}_{W,F} + \dot{Y}_{COND} = \dot{B}_5 + \dot{B}_6$	$b_4 = 0; b_{10} = b_6$
Pump (PUMP)	$\dot{W}_{PUMP}$	$\dot{E}_7 - \dot{E}_6$	$\dot{B}_6 + \dot{B}_{w,p} + \dot{Y}_{PUMP} = \dot{B}_7$	$b_{w,p} = b_{w,T} = b_{w,F}$
Turbine (TURB)	$\dot{E}_9 - \dot{E}_{10}$	$\dot{W}_{TURB}$	$\dot{B}_9 + \dot{Y}_{TURB} = \dot{B}_{w,T} + \dot{B}_{10}$	$b_9 = b_{10}$

***Table 3**. SUB-REGEN ORC components - definitions of fuel and product, exergo-environmental rate balance, and auxiliary equations.*

Component (abbreviation)	Fuel exergy	Product exergy	Exergo-environmental rate balance equation	Auxiliary equation
Evaporator (EVAP)	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_{10} - \dot{E}_9$	$\dot{B}_1 + \dot{B}_9 + \dot{Y}_{EVAP} = \dot{B}_2 + \dot{B}_{10}$	$b_1 = b_2$ = 0.0425 Pt/kWh[45]
ORC preheater (PRHT)	$\dot{E}_2 - \dot{E}_3$	$\dot{E}_9 - \dot{E}_8$	$\dot{B}_2 + \dot{B}_8 + \dot{Y}_{PRHT} = \dot{B}_3 + \dot{B}_9$	$b_2 = b_3$
Condenser (COND)	$\dot{E}_{12} - \dot{E}_6 + \dot{W}_{FAN}$	$\dot{E}_5 - \dot{E}_4$	$\dot{B}_{12} + \dot{B}_4 + \dot{B}_{W,F} + \dot{Y}_{COND} = \dot{B}_5 + \dot{B}_6$	$b_4 = 0; b_{12} = b_6$
Pump (PUMP)	$\dot{W}_{PUMP}$	$\dot{E}_7 - \dot{E}_6$	$\dot{B}_6 + \dot{B}_{w,p} + \dot{Y}_{PUMP} = \dot{B}_7$	$b_{w,p} = b_{w,T} = b_{w,F}$
Recuperator (RECP)	$\dot{E}_{11} - \dot{E}_{12}$	$\dot{E}_8 - \dot{E}_7$	$\dot{B}_{11} + \dot{B}_7 + \dot{Y}_{RECP} = \dot{B}_8 + \dot{B}_{12}$	$b_{11} = b_{12}$
Turbine (TURB)	$\dot{E}_{10} - \dot{E}_{11}$	$\dot{W}_{TURB}$	$\dot{B}_{10} + \dot{Y}_{TURB} = \dot{B}_{w,T} + \dot{B}_{11}$	$b_{11} = b_{10}$

3 RESULTS AND DISCUSSION

3.1 Results of Exergy-based Sustainability and Exergo-environmental Assessment for The Non-recuperative ORC Scheme

The basic exergy and exergo-environmental properties obtained for each state of the SUB ORC configuration are highlighted in Table 4. The pressure and temperature parameters derived directly from the design of the ORC plant, leading also to the determination of the exergy rate. The specific exergo-environmental rate (b) values were obtained by solving simultaneously the exergo-environmental balance and auxiliary equations for all the system components as aforementioned. The multiple of b with the exergy rate at each thermodynamic state gave the exergo-environmental rate ($\dot{B}$) following the model defined above in section 2.

***Table 4**. State exergy and exergo-environmental data for the SUB ORC configuration.*

Stream No	Working substance	Temperature (K)	Pressure (MPa)	Exergy rate (kW)	b (Pt/kWh)	$\dot{B}$ (Pt/h)
1	Geothermal brine	428.15	0.84	2832.5	0.043	120.4
2	Geothermal brine	400.50	0.84	1836.7	0.043	78.1
3	Geothermal brine	325.03	0.84	165.8	0.043	7.0
4	Air	298.15	0.1	0	0	0
5	Air	303.15	0.1	5.0	8.835	44.2
6	R236fa	303.15	0.32	1130.1	0.054	60.5
7	R236fa	304.73	2.88	1269.6	0.059	75.3
8	R236fa	392.84	2.88	2704.0	0.054	146.9
9	R236fa	393.84	2.88	3561.0	0.054	190.7
10	R236fa	317.56	0.32	1338.8	0.054	71.7

The main parameters used for the exergetic sustainability assessments are highlighted in Table 5 for the SUB ORC components. As can be seen, the exergetic sustainability index is lowest in the condenser and highest in the evaporator. The low sustainability of the condenser is associated with high exergy destruction resulting from the use of air as the heat sink. The same reason can be given for the high environmental effect factor obtained in the condenser, which is again the worst among the ORC system components. It is however obtained that about 717 kW of the irreversibility in the condenser can be recovered, amounting to about 99% of the fuel exergy entering the component. For the components with a relatively higher sustainability index and lower environmental effect factor such as the evaporator, preheater, and turbine, results showed that only about 2% of irreversibilities could be recovered in each. Thus, the higher the ESI of a component, the lower its EEF, and the lesser the need for structural adjustment to it for the improvement of the overall ORC plant.

***Table 5**. Results of exergy-based sustainability analysis results for the SUB ORC system.*

Component	$\dot{E}_f$ (kW)	$\dot{E}_p$ (kW)	$\dot{E}_D$ (kW)	ε (%)	ESI	IPR *(kW)*	EEF	RECR
Condenser	727.3	5.0	722.3	0.69	0.007	717.3	144.25	0.99
Evaporator	995.8	856.9	138.9	86.06	6.17	19.4	0.16	0.02
ORC reheater	1670.9	1434.5	236.4	85.85	6.07	33.5	0.16	0.02
Pump	233.9	139.6	94.3	59.65	1.48	38.1	0.68	0.16
Turbine	2222.2	1881.1	341.1	84.65	5.52	52.3	0.18	0.02

Similarly, the main exergo-environmental parameters are reported in Table 6 for each component of the SUB ORC plant. As can be seen, the exergo-environmental impact rate due to irreversibility is highest in the condenser still, as would be expected, followed by the turbine, preheater, pump, and evaporator. Adding the exergo-environmental impacts resulting from the construction and operation of each of the components ($\dot{Y}$) to those resulting from irreversibility gave the total exergo-environmental rate (**BRT**). The values of $\dot{Y}$ for most of the components were obtained to be much lower relative to those of $\dot{B}_D$, such that the position of each component on the $\dot{B}_D$ column in Table 6 is almost the same as on the one for **BRT**, except in the turbine where the $\dot{Y}$ is highest. Also, results showed that the condenser yielded the highest of about 39 exergo-environmental points for each MW of electricity generated by the ORC plant, while the pump yielded the least of about 5 points. Additionally, the exergo-environmental factor defined for the system components showed that environmental impacts due to component construction and pollutant emissions are insignificant in the condenser, turbine, and the pump, compared to impacts due to irreversibility. However, the environmental effects of construction should be reckoned with in the evaporator and preheater where the highest f_b values were obtained at 19% and 5.6%, respectively. Additionally, the product exergy in the condenser contributes substantially to its exergo-environmental effect resulting in a very high value of r_b.

Table 6. *Results of the exergo-environmental analysis for the SUB ORC system.*

Component	b_f (Pt/kWh)	b_p (Pt/kWh)	$\dot{B}_D$ (Pt/h)	$\dot{Y}$ (Pt/h)	BRT (Pt/h)	EIE (Pts/kWh)	f_b (%)	r_b
Condenser	0.061	8.84	43.69	0.24	43.93	0.039	0.55	145.0
Evaporator	0.043	0.051	5.90	1.41	7.31	0.007	19.0	0.20
ORC preheater	0.043	0.050	10.05	0.60	10.65	0.009	5.60	0.17
Pump	0.063	0.11	5.97	0.003	5.97	0.005	0.051	0.68
Turbine	0.054	0.063	18.26	0.08	18.34	0.016	0.41	0.18

3.2 Results of The Exergy-based Sustainability and Exergo-environmental Analyses for The Recuperative ORC Scheme

The parameters employed for the exergo-environmental analysis in this case are reported in Table 7 for each thermodynamic state of the SUB-REGEN ORC configuration, obtained from design and resulting from the definitions given earlier for the featured parameters. It should be observed that the proximity in the design criteria employed for the SUB ORC and the SUB-REGEN ORC made Table 5 and Table 7 quite similar. The main differences between the two tables are direct consequences of the introduction of an additional heat exchanger serving as the recuperator in the SUB-REGEN ORC configuration.

Table 7*. State exergy and exergo-environmental data for the SUB-REGEN ORC scheme.*

Stream No	Working substance	Temperature (K)	Pressure (MPa)	Exergy rate (kW)	b (Pt/kWh)	$\dot{B}$ (Pt/h)
1	Geothermal brine	428.15	0.84	2832.5	0.043	120.4
2	Geothermal brine	400.50	0.84	1836.7	0.043	78.0
3	Geothermal brine	329.15	0.84	211.4	0.043	9.0
4	Air	298.15	0.1	0	0	0
5	Air	303.15	0.1	5.0	6.757	33.8
6	R236fa	303.15	0.32	1130.1	0.054	60.6
7	R236fa	304.73	2.88	1269.6	0.059	75.4
8	R236fa	310.41	2.88	1285.4	0.060	77.5
9	R236fa	392.84	2.88	2704.0	0.054	147.1
10	R236fa	393.84	2.88	3561.0	0.054	190.9
11	R236fa	317.56	0.32	1338.8	0.054	71.8

The exergetic sustainability performance metrics are reported in Table 8 for the SUB-REGEN ORC components. Again, results showed that the ESI is lowest in the condenser at less than 1%, and of course with the highest EEF of about 110. However, about 98% of the fuel exergy destroyed in the condenser can be recovered, making it the main component to be focused on for the overall improvement of the ORC plant. The highest ESI is recorded in this case in the preheater, resulting also in the least EEF. Generally, the components of the SUB-REGEN ORC plant can be ranked in descending order of sustainability as Preheater, evaporator, turbine, recuperator, pump, and condenser.

***Table 8**. Results of the exergy-based sustainability analysis for the SUB-REGEN ORC system.*

Component	$\dot{E}_f$ (kW)	$\dot{E}_p$ (kW)	$\dot{E}_D$ (kW)	ε (%)	ESI	IPR (kW)	EEF	RECR
Condenser	557.80	5.00	552.80	0.90	0.009	547.9	110.41	0.98
Evaporator	995.8	856.9	138.9	86.06	6.171	19.4	0.16	0.02
ORC preheater	1625.3	1418.6	206.6	87.29	6.865	26.3	0.15	0.02
Pump	233.9	139.6	94.3	59.66	1.479	38.1	0.68	0.16
Recuperator	25.5	15.8	9.7	61.97	1.630	3.7	0.61	0.14

Furthermore, the exergo-environmental parameters are reported in Table 9 for the SUB-REGEN ORC configuration. Again, the condenser contributed the most to the exergo-environmental impact of the ORC system due to high irreversibility therein, leading also to the highest BRT of 33.5 Pt/h. It is noteworthy that the least BRT of 1.2 Pt/h is recorded in the newly introduced component, the recuperator, signifying that its addition should not have an adverse environmental impact on the ORC plant. The highest exergo-environmental impact of about 26 points was obtained in the condenser for the ORC plant generating 1 MW of electrical energy, and the least of about 0.9 points was obtained in the recuperator. Additionally, the recuperator recorded the highest f_b, implying that most of the little impacts it has on the environment resulted from the component's construction and might not be avoidable. In this regard, the pump and the condenser showed the worst exergo-environmental factor values. Here too, the product exergy contributed substantially to the environmental effects of the condenser; the effects in all other components are due majorly to the fuel exergy.

***Table 9**. Results of the exergo-environmental analysis for the SUBREGEN ORC system.*

Component	b_f (Pt/kWh)	b_p (Pt/kWh)	$\dot{B}_D$ (Pt/h)	$\dot{Y}$ (Pt/h)	BRT (Pt/h)	EIE (Pt/kWh)	f_b (%)	r_b
Condenser	0.060	6.76	33.29	0.24	33.53	0.026	0.72	111.21
Evaporator	0.043	0.051	5.90	1.41	7.31	0.006	19.31	0.20
ORC preheater	0.043	0.049	8.78	0.60	9.38	0.007	6.40	0.16
Pump	0.064	0.11	5.99	0.0030	5.99	0.005	0.051	0.68
Recuperator	0.054	0.13	0.52	0.68	1.20	0.0009	56.53	1.41
Turbine	0.054	0.064	18.44	0.076	18.51	0.014	0.041	0.18

3.3 Exergetic Sustainability Implications of The Integration of a Recuperator

The main impacts of adopting a recuperative ORC configuration (SUB-REGEN ORC) over the non-recuperative one (SUB ORC) are reported in this section using selected exergetic sustainability and exergo-environmental parameters.

The exergetic sustainability index (ESI) values are compared in Figure 2 for the SUB ORC and SUB-REGEN ORC configurations, at component and system levels. Results showed that a switch from the SUB ORC to the SUB-REGEN ORC would increase the ESI of the ORC plant by about 17%, from about 1.2 in the SUB ORC to around 1.4 in the SUB-REGEN ORC. As can be seen, the preheater is the main component that contributed to the increase in ESI for the SUB-REGEN ORC configuration, apart from the recuperator which is added entirely. The ESI is infinitesimally small in the condenser, the reason it is insignificant in Figure 2.

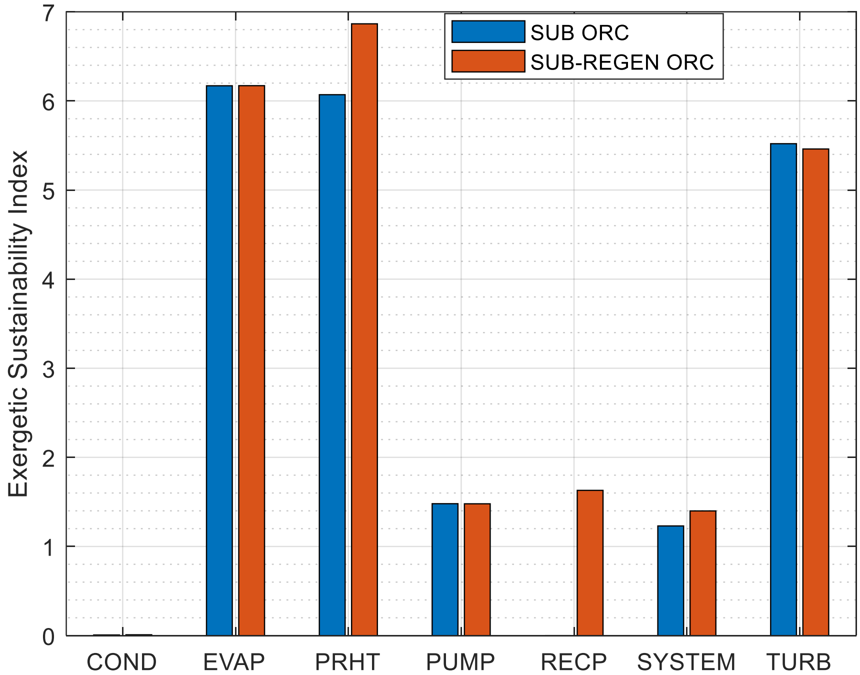

***Figure 2**. Exergy sustainability index (ESI) comparison for the SUB ORC and SUB-REGEN ORC configurations.*

Also, the effects of introducing a recuperator on the recoverability ratio in the ORC components and the system as a whole are illustrated in Figure 3. Results showed that more opportunity exists for overall sustainability improvement in the SUB ORC system than in the SUB-REGEN ORC configuration. Specifically, the use of the SUB-REGEN ORC configuration reduced RECR by about 7%, from about 0.45 to about 0.42. In this case, the effect is substantially due to the introduction of the recuperator which improved the exergetic performance of the SUB-REGEN ORC plant. As can be seen at the component level, the RECR values are almost the same for the two ORC configurations.

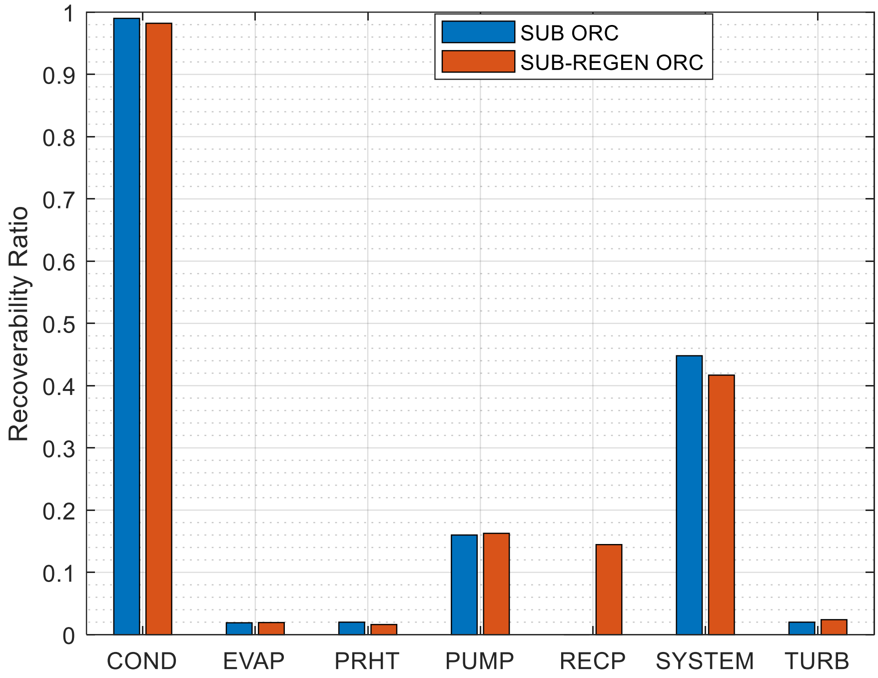

***Figure 3**. Comparison of recoverability ratios (RECR) for the SUB ORC and SUB-REGEN ORC configurations.*

Furthermore, Figure 4 shows the impacts of the switch from the SUB ORC to the SUB-REGEN ORC configurations on the EIE. Results showed that the environmental impact of electricity is improved by about 0.02 Pts/kWh in the SUB-REGEN ORC configuration due to the improvement in the condenser and slightly in the evaporator, preheater, and turbine.

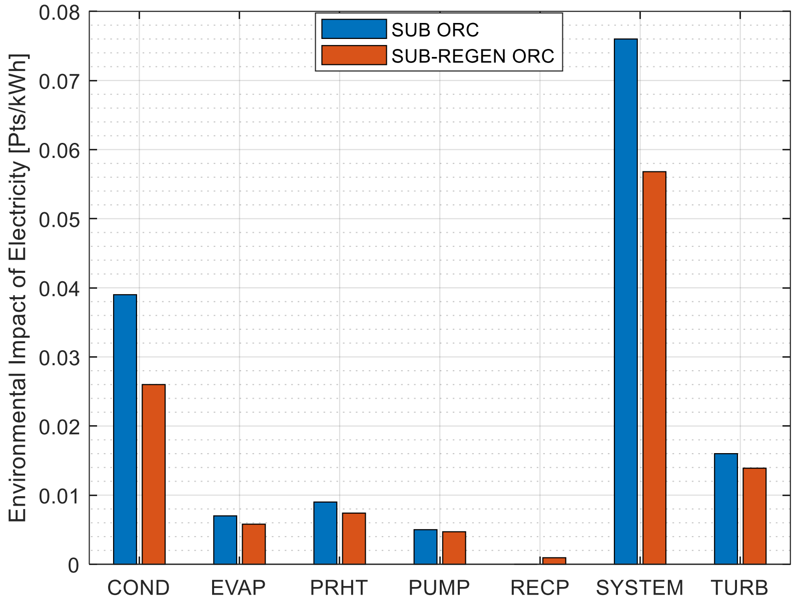

Figure 4*. The environmental impact of electricity (EIE) comparison for the SUB ORC and SUB-REGEN ORC systems.*

Lastly, the implication of the results in Figure 5 is that the total exergo-environmental rate can be reduced in the SUB-REGEN ORC plant by about 10 Pts/h, amounting to about a 13% decrease in the environmental impact. As can be seen, the introduction of the recuperator contributed very little to this effect; the condenser showed the highest reduction at the component level, followed by the preheater. The effects appear insignificant in the other system components.

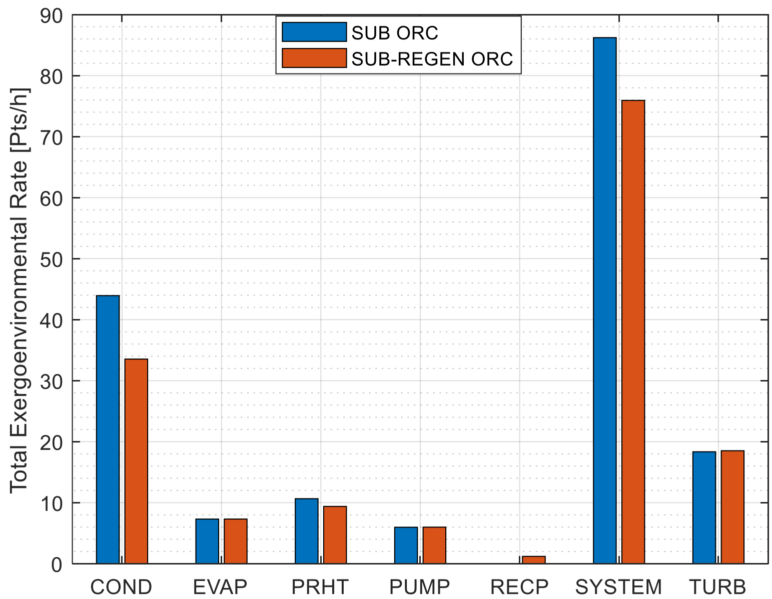

Figure 5*. Comparison of total exergo-environmental rate (BRT) for the SUB ORC and SUB-REGEN ORC configurations.*

4 CONCLUSIONS

The possibilities of producing electricity with organic Rankine cycle (ORC) plants from residual thermal energy in abandoned oil wells were assessed in this study using exergy-based environmental sustainability performance metrics. A lot of previous studies had tipped the ORC to be techno-economically feasible for energy generation from abandoned oil wells, but the environmental performance of such systems is not feasible in the state-of-the-art. Thus, exergy-based sustainability and exergo-environmental approaches were used herein for performance comparison of non-recuperative (SUB ORC) and recuperative subcritical ORC (SUB-REGEN ORC) configurations for the aforementioned application. The design of the ORC plants was implemented in MATLAB by solving the mass, energy, and exergy balance equations imposed by the First and Second Laws of Thermodynamics. Furthermore, the exergy-based sustainability and exergo-environmental performance metrics were assessed first for each of the two ORC configurations, followed by comparative analysis to substantiate the potential effects on the environment for choosing one ORC configuration over the other. The main results obtained from the study are:

- For the SUB ORC, the condenser showed the lowest exergetic sustainability index of 0.007 due to high irreversibility, and the evaporator had the highest sustainability index of 6.17. However, about 99% of the irreversibility in the condenser can be recovered by structural optimization, while only about 2% is achievable in most of the other components. Additionally, the exergo-environmental results showed that the condenser contributed the highest environmental impact to the SUB ORC plant at about 44 Pt/h, amounting to about 39 Pts for each 1 MW of electrical power the plant generates;
- Also, for the SUB-REGEN ORC, the condenser had the highest exergetic sustainability index which has increased to 0.009, and the preheater recorded the highest sustainability index of about 6.9. For the exergo-environmental assessment, results showed that the impact of the condenser could be reduced to 33.5 Pt/h, amounting to about 26 Pt for 1 MW of electricity produced by the ORC plant;
- The comparative analysis results showed that incorporating a recuperator into the ORC plant would increase the exergetic sustainability index of the

ORC plant by about 17%, from about 1.2 in the SUB ORC to around 1.4 in the SUB-REGEN ORC; and reduce RECR by about 7%, from about 0.45 in the SUB ORC to about 0.42 in the SUB-REGEN ORC; and improve the environmental impact of electricity by about 0.02 Pts/kWh; and reduce the overall exergo-environmental impact rate by approximately 13%, from about 86 Pts/h in the SUB ORC to around 76 Pts/h in the SUB-REGEN ORC.

In sum, the use of a recuperative ORC configuration would provide a more environmentally sustainable solution than a non-recuperative one, to produce electricity from abandoned oil wells.

Conflict of Interests

The corresponding author states, on behalf of all authors, that there is no competing interest.

Authors Contributions

J. Oyekale conceived the study and carried out the analysis. He also drafted the first version of the manuscript. Larry O. Agberegha assisted in the analysis and wrote the revised version of the manuscript.

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Statement of Research and Publication Ethics

The study complies with research and publication ethics.

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NOMENCLATURE

Symbols

$\dot{RE}_D$	relative destroyed exergy (irreversibility)
$\dot{m}$	mass flow rate (kg/s)
$\dot{q}$	heat flux (W/m^2)
$\dot{W}$	electrical power (kW)
$\dot{B}$	exergo-environmental rate (€/h)
$\dot{E}$	rate of exergy (kW)
$\dot{I}$	rate of destroyed exergy (kW)
$\dot{Q}$	thermal power (kW)

b	specificexergo-environmental impact (Pt/kWh)
e	specific exergy (kJ/kg)
f_b	exergo-environmental factor
h	enthalpy (kJ/kg)
int	interest rate
MF	maintenance factor
N	plant lifetime (years)
s	entropy (kJ/kgK)
SUB ORC	subcritical ORC without a recuperator
SUB-REGEN ORC	subcritical ORC with a recuperator
T	temperature (°C)
Y	environmental impact point (Pt)

Greek letters

ε	exergetic (rational) efficiency
δ	efficiency defect

Subscripts

i	inlet side
o	outlet side

Abbreviations

ORC	organic Rankine cycle

APPENDIX

Definitions of exergo-environmental metrics employed in the study for a generic component k:

$$b_{f,k} = \frac{B_{f,k}}{E_{f,k}}$$

$$b_{p,k} = \frac{B_{p,k}}{E_{p,k}}$$

$$B_{D,k} = b_{f,k} \times I_k$$

$$BRT_k = B_{D,k} + Y_k$$

$$f_{b,k} = \frac{Y_k}{B_{I,k}+Y_k}$$

$$r_{b,k} = \frac{b_{p,k}-b_{f,k}}{b_{f,k}}$$

$$EIE_k = \frac{BRT_k}{\dot{W}_{net}}$$