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Research Article

Comparative Thermodynamic Optimization of Organic Rankine Cycle Configurations for Geothermal Power Generation from an Abandoned Oil Well

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Abstract: This study was aimed at quantifying the net electrical power producible from an abandoned oil well in Nigeria using different organic Rankine cycle (ORC) configurations and working fluids. The geological features of a typical Nigerian oil well were employed in the study and a borehole heat exchanger was used for simulating the thermodynamic parameters of the heat source. Specifically, a subcritical ORC without a recuperator (SBC), a subcritical ORC with a recuperator (SBC-R), a supercritical ORC without a recuperator (SPC), and a supercritical ORC with a recuperator (SPC-R) were analyzed, using R115, R236fa, and R1234yf as working fluids. Results showed that between 272 kW and 875 kW of electrical power could be produced from the abandoned oil well using the most basic ORC configuration (SBC). Furthermore, it was obtained that the introduction of a recuperator would increase the ORC net power by about 13% for R236fa, 33% for R1234yf, and 107% for R115. Similarly, a switch from a subcritical ORC to a supercritical ORC configuration would increase net power for all the working fluids. Specifically, an increase in net power was estimated at 3.6% for R236fa, 46% for R1234yf, and 152% for R115 regarding a switch from the SBC to the SPC. Moreover, decreasing the condensation pressure of the ORC plants was observed to improve net power in all cases.

Keywords: Abandoned Oil Well Retrofit, Geothermal Power Production, Organic Rankine Cycle, Energy Efficiency, Sustainable Energy System.

Terk Edilmiş Bir Petrol Kuyusundan Jeotermal Enerji Üretimi İçin Organik Rankine Çevrim Konfigürasyonlarının Karşılaştırmalı Termodinamik Optimizasyonu

Öz . Bu çalışma, farklı organik Rankine çevrimi (ORC) konfigürasyonları ve çalışma sıvıları kullanılarak Nijerya'da terk edilmiş bir petrol kuyusundan üretilebilen net elektrik gücünü ölçmeyi amaçlıyordu. Çalışmada tipik bir Nijerya petrol kuyusunun jeolojik özellikleri kullanılmış ve ısı kaynağının termodinamik parametrelerini simüle etmek için bir sondaj kuyusu ısı eşanjörü kullanılmıştır. Spesifik olarak, geri kazanım cihazı olmayan bir kritik altı ORC (SBC), bir geri kazanım cihazı olan bir kritik altı ORC (SBC-R), bir geri kazanım cihazı olmayan bir süper kritik ORC (SPC) ve bir geri kazanım cihazı olan bir süper kritik ORC (SPC-R) kullanılarak analiz edildi. Çalışma sıvıları olarak R115, R236fa ve R1234yf. Sonuçlar, en temel ORC konfigürasyonu (SBC) kullanılarak terk edilmiş petrol kuyusundan 272 kW ile 875 kW arasında elektrik enerjisinin üretilebileceğini gösterdi. Ayrıca, bir geri kazanım cihazının eklenmesinin ORC net gücünü R236fa için yaklaşık %13, R1234yf için %33 ve R115 için %107 artıracağı elde edildi. Benzer şekilde, kritik altı bir ORC'den süper kritik bir ORC konfigürasyonuna geçiş, tüm çalışma sıvıları için net gücü artıracaktır. Spesifik olarak,

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SBC'den SPC'ye geçişle ilgili olarak net güçteki artışın R236fa için %3,6, R1234yf için %46 ve R115 için %152 olduğu tahmin edilmiştir. Ayrıca, ORC tesislerinin yoğuşma basıncının düşürülmesinin her durumda net gücü iyileştirdiği gözlemlenmiştir.

Anahtar Kelimeler: Terk Edilmiş Petrol Kuyusu Güçlendirmesi, Jeotermal Enerji Üretimi, Organik Rankine Çevrimi, Enerji Verimliliği, Sürdürülebilir Enerji Sistemi.

1. Introduction

Crude oil and gas are among the most sought-after fossil fuels due to their substantial contribution to powering the world and the enormous economic benefits that accrue to any nation where they are deposited [1]. Depending on the geological features of the earth containing oil and gas reserves, wells are to be dug in varying degrees of depth for profitable oil and gas explorations [2]. But since oil reserves are non-renewable and would deplete from the wells over time [3], adequate measures are statutorily required for proper decommissioning and termination of wells at their end of life [4]. However, standard oil decommissioning processes add sizeable costs to the operational expenses of oil well development [5]. Also, it is common for oil and gas wells to simply be abandoned in some regions with weak legal frameworks on such practices, thereby contributing hazards to the environment [6]. Thus, alternative ways of elongating the useful life of oil and gas wells are currently being researched in the literature [7], [8], [9] to minimize production costs and environmental impacts in the oil and gas industry.

The conversion of abandoned oil wells to geothermal energy sources is one viable way being explored in the literature to prolong the useful life of oil and gas wells [10]. As the oil and gas reserves in a typical well approach depletion, continuous production becomes unprofitable, and it is believed that a modification of the oil well's purpose to generate geothermal energy can be a viable alternative. The geothermal energy so generated can be used directly for heating purposes and it can be converted to electrical power using a power cycle such as the organic Rankine cycle (ORC). The ORC is particularly suited for the production of power from geothermal energy of an abandoned oil well due to the use of an organic working fluid with a low boiling point, which can be evaporated by a low-temperature heat source. Several studies have proposed and analyzed different possible schemes for the conversion of abandoned oil wells to geothermal energy sources and profitable production of useful energy products therefrom. The most striking of such studies are succinctly reviewed in the following paragraph.

Liu et al. [11] reviewed critically the oil and gas reservoirs globally where heat energy is being harnessed for power production in practice, or the potential being investigated. They then proposed a roadmap that could be used to screen mature oil and gas reservoirs for a profitable conversion to a geothermal power source. A quantitative analysis conducted based on the Villafortuna-trecate oil field in Italy revealed that a 500 kW power plant could be sustainably serviced, with the capacity to generate a total of 25 GWh of electrical power in 10 years. Chmielowska et al. [12] surveyed the world trend on the utilization of oil wells as geothermal energy sources and reiterated that it is increasingly being implemented in reality, particularly with the use of borehole heat exchangers. Duggal et al. [13] identified the conversion technology choice, transient ambient conditions, and fluid handling system among the issues that should be handled well for maximum benefits from geothermal power production from an oil well. Also, Oyekale and Emagbetere [14] discussed some steps that could be taken for a quick feasibility assessment of geothermal power production from abandoned oil and gas wells. Kaplanoglu et al. [15] reported that the use of downhole heat exchangers can facilitate the conversion of abandoned oil wells to geothermal sources in Southeastern Turkey for an improved economy of the region. Gong et al. [16] employed the technical features of the LB reservoir from the Huabei oil field (China) to simulate numerically the effects of mass flow rate and temperature of the injected water on the reservoir temperature. They identified the limits of the injection mass flow rate and temperature at which geothermal energy can be co-produced efficiently in a reservoir. Mehmood et al. [17] reported that abandoned oil wells can not only be repurposed for geothermal power production in China but also the power can be generated at a competitive price relative to other energy sources. Naseer et al [18] demonstrated the possibility of improving the sustainability of repurposing abandoned oil and gas wells by a coproduction of electricity and power, with additional potential for direct H_2S and CO_2 capture. Gharibi et al. [19] studied the feasibility of using a U-tube heat exchanger to extract geothermal energy from abandoned oil wells based on the real data of such a well in Southern Iran. They reported that the U-tube heat exchanger is adequate for the extraction both for direct use of the geothermal energy and for power conversion. Wight and Bennett [20] demonstrated the advantages of using water as the wellbore fluid in conjunction with a closed well, for the generation of electrical power from abandoned oil wells using binary power plants. Based on the well log data for over 2500 wells in Texas (USA), the authors obtained the possibility of net power generation in the range of 190 kW – 630 kW. Similarly, Milliken [21] estimated the power producible from the Naval Petroleum Reserve 3 (NPR-3) at about 300 kW based on the available technologies in the early 2000s, although thermal energy equivalent to about 22 MW power was estimated to be lost daily. Sanyal and Butler [22] discussed the basic technological and cost requirements for geothermal energy production from abandoned oil wells, those still in use but with high water cuts, and geo-pressured brine wells with dissolved gas. Case histories were also presented for the estimation of available power capacity in a well or a group of wells. Harris et al. [23] investigated the potential of directionally drilled wells in maximizing geothermal power production from abandoned oil wells. Based on 2 vertically drilled wells each 4000 m deep and a horizontally drilled well 4800 m, the authors estimated the production of 2 MW of thermal energy which could be converted to about 200 kW of electrical power using an ORC plant. Noorollahi et al. [24] estimated from a numerical simulation that about 138 kW and 364 kW of electrical power can be generated respectively from the AZ-II and DQ-II wells in the Ahwaz oil field in Southern Iran. Patihk et al. [25] obtained that about 4.4 GWe can be produced from 6 wells in the Forest Reserve Field in Trinidad over 25 years of operation, at an $0.05 electricity cost, saving about 50 Mtons of CO_2 cumulatively. Singh [26] also reported a survey of Indian oil fields with their potential for geothermal power production either with the use of a downhole heat exchanger or by in-situ combustion of hydrocarbons in the wells that are hard to exploit.

The foregoing literature review is a testament to the global interest in geothermal energy production from oil and gas wells with high water cuts which is particularly common with abandoned wells. Also, ORC can be identified as a viable power conversion technology for the exploitation of geothermal energy from oil and gas wells. However, the majority of the literature studies on this subject focused hitherto on feasibility assessments with little or no detail on the effects of ORC thermodynamic characteristics on performance. Additionally, no specific technical feasibility studies exist for power generation from abandoned oil and gas wells in Nigeria, despite ranking the largest oil producer in Africa and the 12th largest in the world as of 2016 [27]. Thus, this study investigates for the first time the power production potential of ORC plants utilizing geothermal energy from an abandoned oil well in Nigeria. Moreover, emphasis is placed on the impacts of ORC configurations and working fluids on the performance, thereby closing an existing gap in the field as aforementioned. The specific objectives of the study are:

- To quantify the geothermal electrical power producible from a typical abandoned oil well in Nigeria using thermodynamically optimized ORC plants with different working fluids;
- To assess the technical impacts of incorporating an internal heat recuperator on the ORC performance for the intended heat source;
- To assess the impacts of adopting a supercritical configuration on the ORC performance for the oil well based geothermal energy source;
- To investigate the sensitivities of the optimal ORC parameters to a change in the condensation temperature of the cycle.

2. Materials and Methods

2.1 System Configuration

The heat source comprises a coaxial borehole heat exchanger (BHE) exploiting the thermal contents of an abandoned oil well in form of geothermal energy. The numerical analysis presented in [28] was adopted in this study using the geometrical parameters of a typical abandoned oil well in the Niger Delta region of Nigeria [29]. The main features of the abandoned well and the BHE are highlighted in Table 1. The main interest in this study for the COMSOL simulation of the BHE [28] is the temperature of the geothermal fluid (brine) that could be generated from the abandoned well, for the production of electrical power using the ORC system.

Four ORC configurations were analyzed for the same abandoned oil well turned geothermal energy heat source. The first ORC configuration is a subcritical ORC configuration without a recuperator, dubbed SBC in this study. The highest cycle pressure of a subcritical ORC plant is below the critical pressure of the working fluid, while an ORC plant having no recuperator connotes that the working fluid leaving the turbine condensed directly without recouping/re-using its heat within the cycle. The second ORC configuration analyzed in this study assumes a subcritical type still, but a recuperator is added, dubbed here as SBC-R. Here, the recuperator utilizes the thermal energy content of the organic working fluid exiting the turbine to pre-heat the liquid working fluid leaving the pump before the geothermal heat source is applied in the evaporator/pre-heater. The third configuration considered is a supercritical ORC type with no recuperator, dubbed SPC in this study. By definition, supercritical/transcritical ORC plants have the minimum cycle pressure to be less than the working fluid critical pressure but the maximum cycle pressure (evaporation pressure) to be greater. Lastly, the fourth ORC configuration analyzed in this study assumes a supercritical ORC type with a recuperator, dubbed here as SPC-R. For each of the four ORC configurations, the organic working fluids R115, R236fa, and R1234yf were analyzed. These working fluids were selected based on their good acceptance as suitable working fluids in real ORC plants [30], [31], [32]. Air is considered the heat sink for all the ORC configurations considering the scarcity of water in most West African countries. Moreover, brine is considered the heat transfer mechanism from the geothermal well to the ORC plant, as aforementioned. Figures 1a and 1b illustrate the ORC configuration with and without a recuperator, respectively. Again, the figures could suffice for both the subcritical and supercritical configurations depending on the state properties employed during ORC design.

2.2 Design Modeling of the ORC Configurations

Zero-dimensional models based on the First Law of Thermodynamics were employed for the design modeling of the ORC plants for the different configurations investigated in this study. Specifically, each component of the ORC plant was modeled to satisfy the general mass and energy balance equations defined in (1) and (2), respectively. The actual models that apply for the ORC configurations with and without a recuperator are discussed hereunder.

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

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

The symbols $\dot{m}$, h, $\dot{Q}$, and $\dot{W}$ denote respectively the mass flow rate, state enthalpy, heat energy inlet, and work output. The subscripts 'i' and 'o' signify inlet and outlet flow for a given component.

2.2.1 ORC Plant Without a Recuperator

The ORC unit interacts with the heat source (marine engine exhaust gas heat) through the evaporator and the preheater. Referring to Fig. 1a, the total heat supplied to the ORC externally is given by:

$$\dot{Q}_{HS} = \dot{m}_{HTF} c_p (HTF\_T_i - HTF_{T,o}) = \dot{m}_{OF}(h_{OF,4} - h_{OF,2}) \tag{3}$$

where *HTF_T,i* and *HTF_T,o* represent respectively the inlet and the exit temperatures of the heat source, and the subscripts '*HS*' and '*OF*' represent respectively the heat source and the ORC working fluid.

The expander power output is given by:

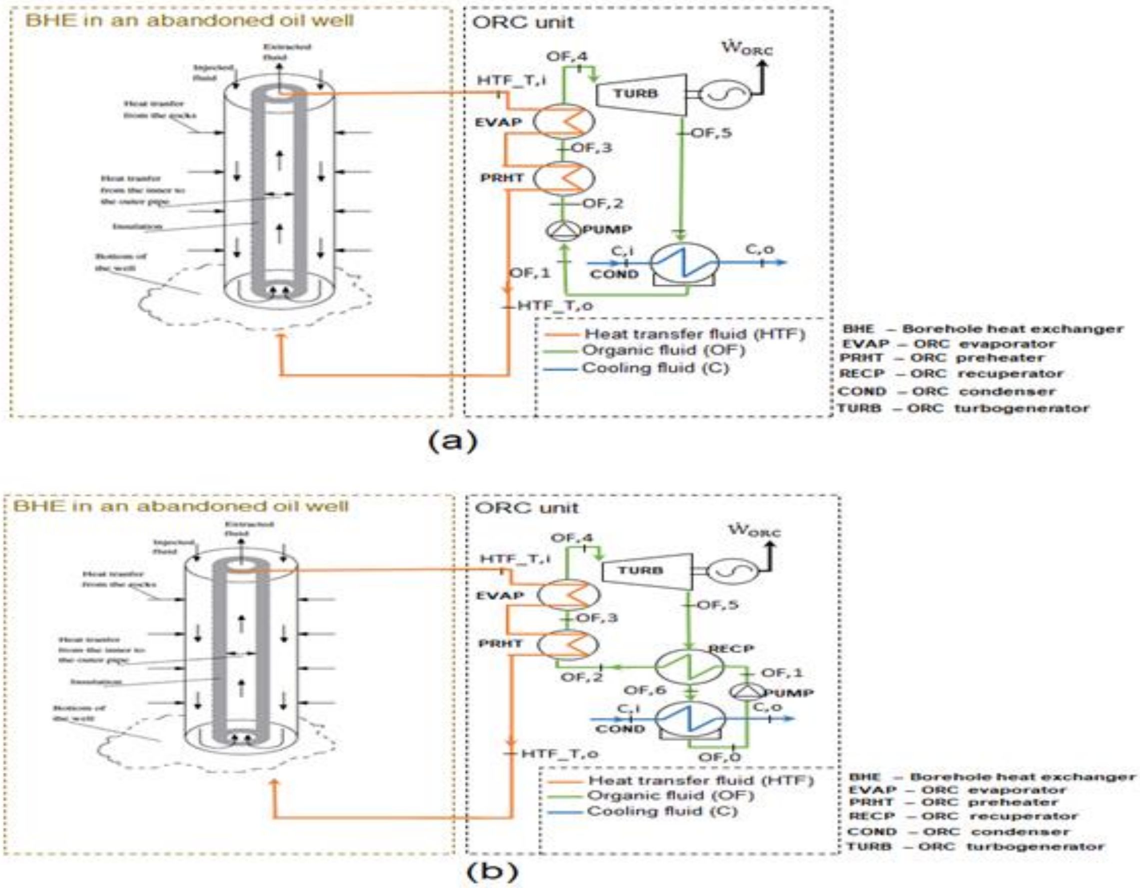

Fig. 1. *Interaction of the geothermal energy from an abandoned oil well with the ORC unit*

$$\dot{W}_{TURB} = \dot{m}_{OF}(h_{OF,4} - h_{OF,5}) = \dot{m}_{OF}(h_{OF,4} - h_{OF,5s})\eta_{s,T} \quad (4)$$

where $\eta_{s,T}$ is the turbine isentropic efficiency. The heat rejected by the condenser is given by

$$\dot{Q}_{COND} = \dot{m}_{OF}(h_{OF,5} - h_{OF,1}) = \dot{m}_C(h_{C,o} - h_{C,i}) \quad (5)$$

where the subscript 'c' represect the coolog fluid taken as air in this study.

The power consumed by the pump is given by:

$$\dot{W}_{PUMP} = \dot{m}_{OF}(h_{OF,2} - h_{OF,1}) = \dot{m}_{OF}\frac{(h_{OF,2s} - h_{OF,1})}{\eta_{s,P}} \quad (6)$$

where $\eta_{s,P}$ is the pump isentropic efficiency.

The net power output is given by:

$$\dot{W}_{NET} = \dot{W}_{TURB} - \dot{W}_{PUMP} - \dot{W}_C \quad (7)$$

where $\dot{W}_C$ is the power expended to drive the cooling air through the condenser.

The ORC thermal efficiency (η_{th}) is given by:

$$\eta_{th} = \frac{\dot{W}_{NET}}{\dot{Q}_{HS}} \quad (8)$$

2.2.2 ORC plant with a recuperator

The same principle applies to modeling the ORC configuration with a recuperator as illustrated in Fig. 1b. The heat supplied to the ORC unit and the turbine work output has the same models as defined in eq. 3 and eq. 4, respectively. The heat rejected by the condenser is slightly adjusted with the introduction of thermal recuperation within the system, given in this case by:

$$\dot{Q}_{COND} = \dot{m}_{OF}(h_{OF,6} - h_{OF,0}) = \dot{m}_C(h_{C,o} - h_{C,i}) \quad (9)$$

The pump power consumption is given by:

$$\dot{W}_{PUMP} = \dot{m}_{OF}(h_{OF,1} - h_{OF,0}) = \dot{m}_{OF}\frac{(h_{OF,1s} - h_{OF,0})}{\eta_{s,P}} \quad (10)$$

The internal heat recuperated within the system is given by

$$\dot{Q}_{RECP} = \dot{m}_{OF}(h_{OF,5} - h_{OF,6}) = \dot{m}_{OF}(h_{OF,2} - h_{OF,1}) \quad (11)$$

The net power output and the ORC thermal efficiency for this configuration also have the same models as defined respectively by eq. 7 and eq. 8. The design modeling and simulation were implemented in MATLAB for all the configurations examined.

2.2.3 Optimization approach of the ORC systems

The optimization models which were also programmed in MATLAB defined the maximization of the net power output of the ORC plant as the objective function. For each of the ORC configurations considered, the optimization tools require the following input parameters:

- The temperature of the HTF (heat source) at the ORC exit;
- The minimum cycle (condensation) temperature; and
- HTF mass flow rate at the ORC inlet.

Additionally, other cycle parameters were fixed in the optimization tools as independent variables, as follows:

- Pinch point temperatures of the heat exchangers (evaporator; pre-heater; condenser; and recuperator in the case of the SBC-R and SPC-R);
- Isentropic and electromechanical efficiencies of the pump;
- Isentropic and electric generator efficiencies of the turbine; and
- Mechanical efficiency of the fan.

The values assigned to these fixed variables are highlighted in Table 1.

The decision variables optimized by the tool to maximize net output power are as follows:

- Maximum pressure and temperature of the ORC;
- ORC working fluid mass flow rate;
- Degree of superheat; and
- Minimum cycle pressure.

2.4 Sensitivity analysis

The sensitivity of the objective function (net output power) to the condensation temperature of the HTF heated by the engine exhaust gas was also investigated in the study. This was considered necessary to take into account the transient operation of the ORC system in which case a change in ambient conditions would vary thermodynamic properties during condensation, with a consequence on the overall system performance. Additionally, ORC thermal efficiency that corresponds to each output power was also computed during the sensitivity analysis for all the ORC configurations. Suffice it to mention that the optimization models were used for the sensitivity analysis, such that the results obtained remain the optimal choices for each of the working fluids and ORC configurations.

Table 1 Characteristics of the heat source and the ORC plant

Abandoned oil well and BHE		**ORC unit**	
Well head	4500 m	Working fluid	R115, R236fa, and R1234yf
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 ^oC	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 ^oC

3. Results and Discussion

3.1 Thermodynamic optimization results for the different ORC configurations for utilizing geothermal energy from an abandoned oil well

The most significant thermodynamic optimization results are reported in this section for the ORC schemes and working fluids analyzed in this study.

3.1.1 Subcritical ORC without a recuperator (SBC)

Table 2 reports the main results of thermodynamic optimization for the SBC configuration, for the 3 working media examined in this study. As can be seen, electrical power of between about 273 kW and 875 kW can be produced from the referenced abandoned oil well when converted to a geothermal energy source, using the SBC. Specifically, using R236fa as the ORC working fluid for utilizing geothermal energy from the abandoned oil well would yield the highest net power, about 44% and 220% above what is obtainable using the fluids R1234yf and R115, respectively. Similarly, the SRC with working fluid R236fa would convert the geothermal energy to power at a thermal efficiency of about 7.19%, more efficient than using R1234yf and R115 by around 2.7 percentage points, and 5.2 percentage points, respectively. Furthermore, it is noteworthy that using R115 would mean that about 786 kW of the total power production would be expended as an auxiliary energy, instead of about 752 kW for R1234yf and 713 kW for R236fa. The cycle auxiliary energy is very high for all the fluids due to the use of air as the heat sink, requiring substantial electrical power to drive the fan.

3.1.2 Subcritical ORC with recuperator (SBC-R)

The basic thermodynamic optimization results for the SBC-R are highlighted in Table 3, referencing the 3 working fluids investigated in this study. Again, the fluid R236fa was obtained with the highest net power of about 992 kW for the SBC-R utilizing geothermal energy from the abandoned oil well. Additionally, for the SBC-R, the fluid R1234yf yielded net power about 180 kW below R236fa and about 247 kW beyond R115. It suffices to report explicitly here that a switch from the SBC to the SBC-R would yield a more thermodynamically efficient system irrespective of working fluid. Specifically, a comparative analysis of the SBC and the SBC-R reveals that net power would increase by around 13% for R236fa, 33% for R1234yf, and 107% for R115, while thermal efficiency would increase by about 1 percentage point for R236fa, 3.3 percentage points for R1234yf, and 3.8 percentage points for R115. It thus means that the introduction of a recuperator is less significant with increasing net power and thermal efficiency facilitated by the choice of an optimal ORC working fluid.

Table 2 Thermodynamic optimization results for the subcritical ORC plant without a recuperator

Parameter	R115	R236fa	R1234yf
Net Work (kW)	272.8	874.8	609.3
Pump Work (kW)	201.2	223.2	192.4
Fan Work (kW)	585.0	490.1	560.0
Max Pressure (MPa)	2.82	2.88	3.04
Max Temperature (°C)	106.87	120.69	108.13
Min Pressure (MPa)	1.31	0.44	1.02
Min Temperature (°C)	40	40	40
Superheat Degrees (°C)	31.96	1	18.72
ORC mass flow rate (kg/s)	107.1	73.0	75.9
Thermal Efficiency (%)	1.99	7.19	4.53

Table 3 Thermodynamic optimization results for the subcritical ORC plant with a recuperator

Parameter	R115	R236fa	R1234yf
Net Work (kW)	564.5	991.6	811.4
Pump Work (kW)	183.3	223.2	166.4
Fan Work (kW)	303.4	370.9	318.7
Max Pressure (MPa)	2.82	2.88	3.04
Max Temperature (°C)	122.29	120.69	121.6
Min Pressure (MPa)	1.31	0.44	1.02
Min Temperature (°C)	40	40	40
Superheat Degrees (°C)	47.39	1	32.20
ORC mass flow rate (kg/s)	97.6	73.0	65.7
Thermal Efficiency (%)	5.83	8.15	7.82

3.1.3 Supercritical ORC without recuperator (SPC)

Table 4 summarizes the optimal thermodynamic parameters for the SPC, for all the working fluids analyzed in this study. It can be seen that the fluid R236fa would extend its optimal performance to this case study, yielding a net power of around 906 kW; about 15 kW more than what obtains with R1234yf, and around 218 kW above the net power produced with R115. Similarly, the SPC with the working fluid R236fa yielded a thermal efficiency of about 7%, only around 0.1 Percentage points beyond what obtains with R1234yf, and about 1.5 percentage points more than R115. Furthermore, results showed that the use of a supercritical configuration would improve the performance of the ORC plant for all the working fluids. Specifically, comparing the results of SBC with those of SPC shows that the net power would increase by about 3.6% for R236fa, 46% for R1234yf, and 152% for R115. However, results showed that the thermal efficiency could be negatively impacted by using the supercritical configuration. Specifically, a lower thermal efficiency of 7.03% was recorded for the SPC with R236fa, relative to 7.19% with the SBC. The other working fluids showed increased thermal efficiency with a switch from SBC to SPC.

3.1.4 Supercritical ORC with recuperator (SPC-R)

The optimal thermodynamic performance parameters of the SPC-R are highlighted in Table 5, for all the working fluids assessed in this study. For this case study, the highest net power output of 1043 kW was obtained with R1234yf as the working fluid; about 12 kW more than what obtains with R236fa, and around 143 kW beyond that with R115. It is important to emphasize the observation here that the fluid R1234yf performed better in terms of net power production than R236fa which had hitherto yielded the highest net power in all the other ORC configurations. Additionally, the working fluid R115 was obtained with the highest thermal efficiency for the SPC-R, rated at about 9.5%; about 0.4 percentage points more than R1234yf and about 1.6 percentage points above R236fa. Furthermore, a comparative assessment of SPC and SPC-R reinforces the submission earlier that incorporating a recuperator would improve performance for all the working fluids considered. The same can be said for a switch from a subcritical ORC configuration to a supercritical one in terms of net power output with all the working fluids studied. It can however be observed that the fluid R236fa reduced the ORC thermal efficiency for the switch from the subcritical to the supercritical configuration, from 8.15% in SBC-R to 7.91% in SPC-R.

Table 4 Thermodynamic optimization results for the supercritical ORC plant without a recuperator

Parameter	R115	R236fa	R1234yf
Net Work (kW)	688.2	906.4	891.1
Pump Work (kW)	613.9	292.7	450.4
Fan Work (kW)	509.0	519.8	519.2
Max Pressure (MPa)	6.64	3.28	5.84
Max Temperature (ºC)	146.72	126.85	136.85
Min Pressure (MPa)	1.31	0.44	1.02
Min Temperature (ºC)	40	40	40
Superheat Degrees (ºC)	66.77	1.93	42.15
ORC mass flow rate (kg/s)	92.19	82.36	74.68
Thermal Efficiency (%)	5.52	7.03	6.95

Table 5 Thermodynamic optimization results for the supercritical ORC plant with a recuperator

Parameter	R115	R236fa	R1234yf
Net Work (kW)	900.4	1,031.1	1,043.2
Pump Work (kW)	521.9	300.5	394.8
Fan Work (kW)	283.9	398.3	349.7
Max Pressure (MPa)	6.06	3.29	5.48
Max Temperature (ºC)	147.44	126.85	136.85
Min Pressure (MPa)	1.31	4.37	1.02
Min Temperature (ºC)	40	40	40
Superheat Degrees (ºC)	67.49	1.93	42.15
ORC mass flow rate (kg/s)	88.0	84.3	70.8
Thermal Efficiency (%)	9.47	7.91	9.03

3.2 Sensitivity of the optimal ORC performance to waste heat temperatures

This section reports the sensitivities of the optimized power output and conversion efficiency for the various ORC schemes and working fluids considered in the study. These sensitivities are shown illustrated in Fig. 2 for the SBC utilizing geothermal energy from an abandoned oil well. As can be seen, lowering the condensation pressure favors both the net power produced and the thermal efficiency linearly for all the working fluids considered. Also, the order of performance of the working fluids is preserved throughout the range of condensation temperatures investigated; R236fa>R1234yf>R115 for both the net power output and the thermal efficiency. It can however be seen also that the margins between the net power produced between the fluid R236fa and R1234yf close up narrowly with decreasing condensation temperature, while that between R1234yf and R115 widens very slightly at lower condensation temperatures. The implication is that adopting a lower condensation temperature would be slightly more favorable with some working fluids (R1234yf) than others.

The sensitivity analysis results for the SBC-R are plotted in Fig. 3, showing some sorts of correlations with what obtains with the SBC, but with slight distinctions. The distinctions are more pronounced with the variations in thermal efficiency; the fluid R115 closes up drastically with R1234yf and R236fa as the condensation temperature drops. For instance, while the thermal efficiency of R1234yf exceeds that of R115 by about 5.6 percentage points at a condensation temperature of 50 ºC, it has reduced to only about 0.4 percentage points at 30 ºC. The reverse is the case between R236fa and R1234yf; the margin of the improved thermal efficiency recorded with R236fa reduces as the condensation temperature increase, both generating power at almost the same thermal efficiency at 50 ºC

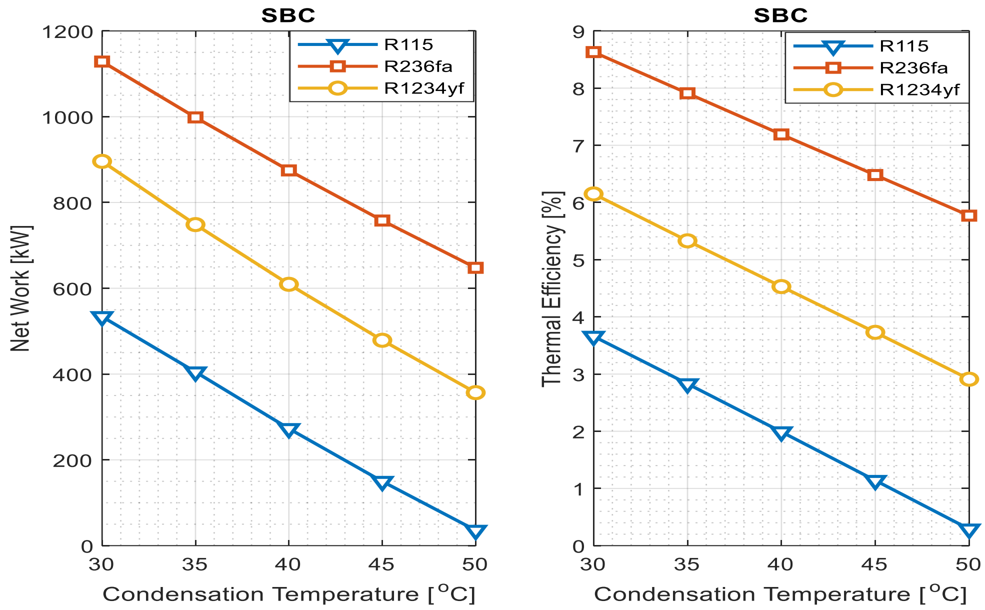

Fig. 2. *Sensitivities of net power and thermal efficiency to the condensation temperature for the subcritical ORC without a recuperator*

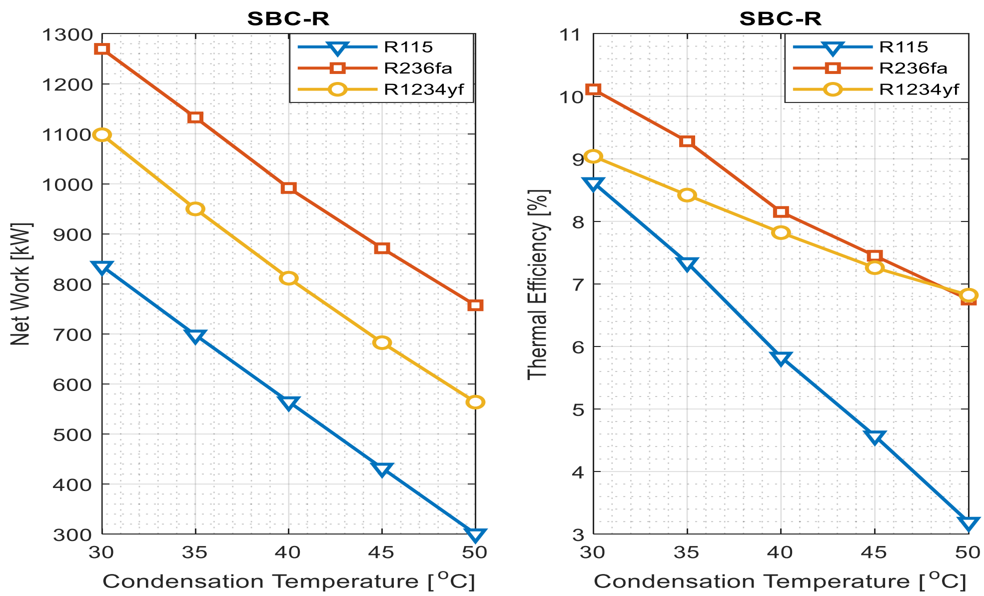

Fig. 3. *Sensitivities of net power and thermal efficiency to the condensation temperature for the subcritical ORC with a recuperato*

Furthermore, the variations of the net power and thermal efficiency with condensation temperature are shown in Fig. 4 for the SPC. It should be reiterated here that a switch to the supercritical ORC configuration not only improves net power for all the fluids considered; the fluid R1234yf exhibited a closely matched performance with R236fa, with only very slight margins for both the net power and thermal efficiency. The fluid R1234yf produces net power increasingly lower than R236fa with decreasing condensation temperature but at a closer thermal efficiency. The two fluids produced power at about the same thermal efficiency at 30 ºC.

Finally, the variations of net power and thermal efficiency are illustrated in Fig. 5 for the SPC-R, for all the working fluids considered. It is worth noting here again that the two fluids R236fa and R1234yf produced almost the same net power at lower condensation temperatures, say between 30 ºC and 38 ºC. Even at higher condensation temperatures up to 50ºC, the difference in net power produced by the two fluids is only marginal. However, the conversion thermal efficiency of the ORC is observed much lower with the fluid R236fa for all the range of condensation temperatures examined, contrary to what obtains with the other ORC configurations discussed earlier. The fluid R115 showed much better conversion efficiency throughout the condensation temperatures examined for the SPC-R, contrary to what would be expected. It thus shows that the performance of working fluids clearly differs for different ORC configurations, and an optimal selection should only be made after thorough computations.

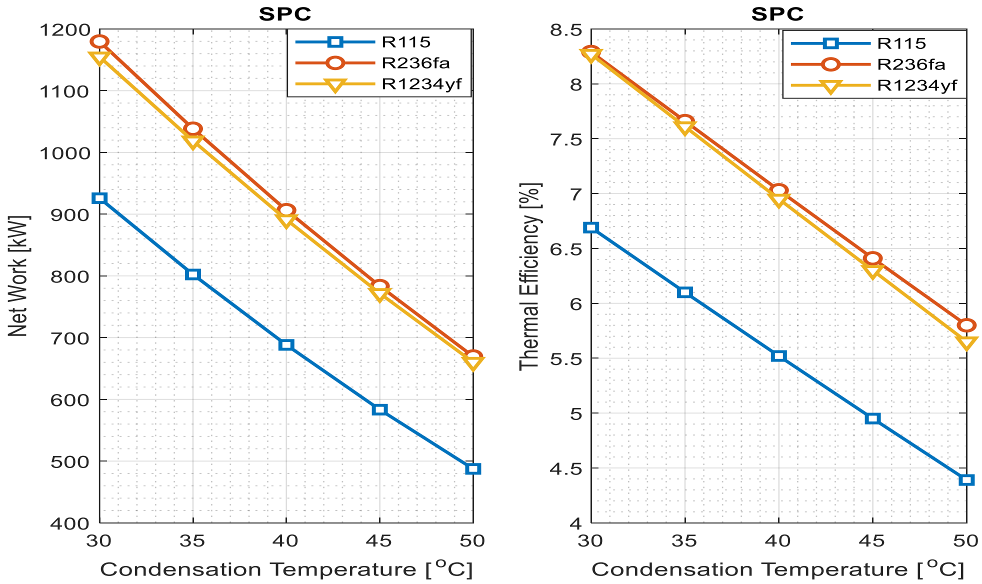

***Fig. 4**. Sensitivities of net power and thermal efficiency to the condensation temperature for the supercritical ORC without a recuperator.*

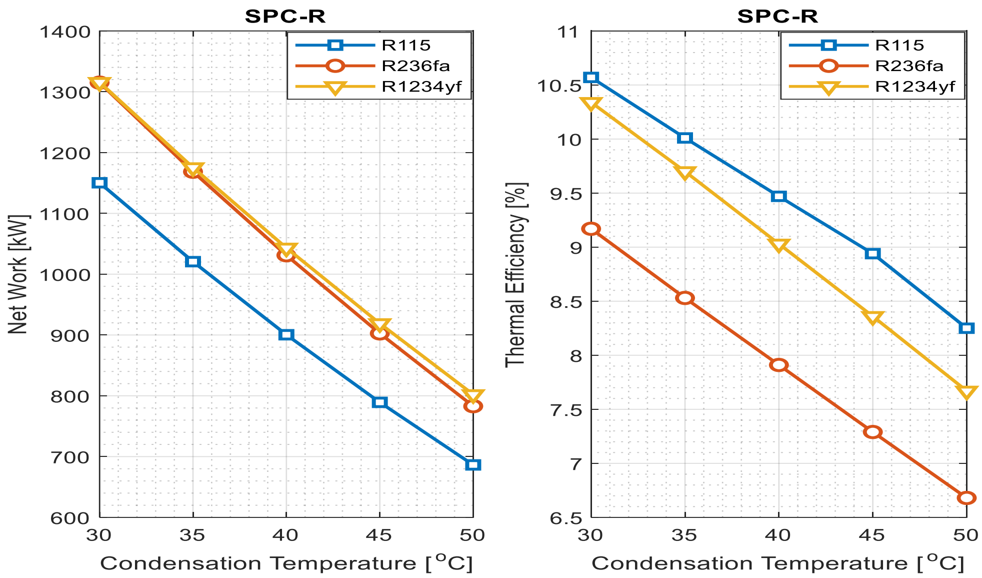

***Fig. 5** - Sensitivities of net power and thermal efficiency to the condensation temperature for the supercritical ORC with recuperator.*

4. Conclusions

Optimal geothermal power producible from an abandoned oil well in Nigeria has been compared in this study for different ORC configurations and working fluids. Four ORC configurations were assessed, designated as subcritical without a regenerator (SBC), subcritical with a regenerator (SBC-R), supercritical without a regenerator (SPC), and supercritical with a regenerator (SPC-R). The geological characteristics of an abandoned oil well in the Niger Delta region of Nigeria were employed to numerically simulate the ORC heat source parameters. Additionally, zero-dimensional ORC design and optimization models were implemented in MATLAB to satisfy the mass and energy balance equations defined by the First Law of Thermodynamics. This study is the first attempt at the technical quantification of electrical power production from an oil well in Nigeria, to the authors' best knowledge. Additionally, previous studies on this subject haven't given adequate consideration to the effects of design configurations and working fluids on ORC performance for the exploitation of geothermal energy from abandoned oil wells, which further highlights the contribution to knowledge intended by this study. The main results obtained from the study are:

➢ The most basic ORC configuration employed can produce between 272 kW and 875 kW of electrical power; about 273 kW with the working fluid R115, about 609 kW with R1234yf, and about 875 kW with R236fa;

- The introduction of a recuperator would increase ORC performance for all working fluids. For instance, a switch from the SBC to the SBC-R would increase net power by around 13% for R236fa, 33% for R1234yf, and 107% for R115, while thermal efficiency would increase by about 1 percentage point for R236fa, 3.3 percentage points for R1234yf, and 3.8 percentage points for R115;
- The use of a supercritical ORC configuration would increase net power irrespective of the choice of the working fluid. Specifically, results showed that a switch from the SBC to the SPC would increase the net power by about 3.6% for R236fa, 46% for R1234yf, and 152% for R115;
- Decreasing the condensation pressure would result in a linear increase in both the net power and thermal efficiency for all the working fluids. Also, the order of the performance of the working fluids is preserved throughout the range of condensation temperatures investigated; R236fa>R1234yf>R115 for both the net power output and the thermal efficiency.

Future studies should give attention to improvement opportunities available in each of the ORC components for the different cycle configurations, using the technical and economic methods defined by the Second Law of Thermodynamics.

Author Contribution

Data curation – Joseph Oyekale (JO); Formal analysis - JO; investigation – Oluwaseun Adetona (OA); Experimental Performance - JO; Data Collection - OA; Processing – JO and OA; Literature review - JO; Writing - JO; review and editing - OA.

Declaration of Competing Interest

The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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References

[1] He, Y., Wang, S., & Lai, K. K. (2010). Global economic activity and crude oil prices: A cointegration analysis. *Energy Economics*, *32*(4), 868–876. https://doi.org/10.1016/j.eneco.2009.12.005

[2] Lukawski, M. Z., Anderson, B. J., Augustine, C., Capuano, L. E., Beckers, K. F., Livesay, B., & Tester, J. W. (2014). Cost analysis of oil, gas, and geothermal well drilling. *Journal of Petroleum Science and Engineering*, *118*, 1–14. https://doi.org/10.1016/j.petrol.2014.03.012

[3] Owen, N. A., Inderwildi, O. R., & King, D. A. (2010). The status of conventional world oil reserves-Hype or cause for concern? *Energy Policy*, *38*(8), 4743–4749. https://doi.org/10.1016/j.enpol.2010.02.026

[4] Burdon, D., Barnard, S., Boyes, S. J., & Elliott, M. (2018). Oil and gas infrastructure decommissioning in marine protected areas: System complexity, analysis and challenges. *Marine Pollution Bulletin*, *135*(February), 739–758. https://doi.org/10.1016/j.marpolbul.2018.07.077

[5] Raimi, D., Krupnick, A. J., Shah, J.-S., & Thompson, A. (2021). Decommissioning Orphaned and Abandoned Oil and Gas Wells: New Estimates and Cost Drivers. *Environmental Science & Technology*, *55*(15), 10224–10230. https://doi.org/10.1021/acs.est.1c02234

[6] Alboiu, V., & Walker, T. R. (2019). Pollution, management, and mitigation of idle and orphaned oil and gas wells in Alberta, Canada. *Environmental Monitoring and Assessment*, *191*(10). https://doi.org/10.1007/s10661-019-7780-x

[7] D'Alesio, P., Caramanico, L., Angelucci, E., Scalzitti, L., Jamot, N., & Sorhabil, J. (2019, March 27). Well Ageing Studies for the Safe Extension of Wells Life. *Offshore Mediterranean Conference and Exhibition*.

[8] D'Alesio, P., Caramanico, L., Angelucci, E., & Scalzitti, L. (2019, October 13). Wells Life Extension Through a Risk-Based Well Ageing Study. *SPE Kuwait Oil & Gas Show and Conference*. https://doi.org/10.2118/198162-MS

[9] Nezamian, A., & Altmann, J. (2013, June 9). An Oil Field Structural Integrity Assessment for Re-Qualification and Life Extension. https://doi.org/10.1115/OMAE2013-10968

[10] Nian, Y. Le, & Cheng, W. L. (2018). Insights into geothermal utilization of abandoned oil and gas wells. *Renewable and Sustainable Energy Reviews*, *87*(November 2017), 44–60. https://doi.org/10.1016/j.rser.2018.02.004

[11] Liu, X., Falcone, G., & Alimonti, C. (2018). A systematic study of harnessing low-temperature geothermal energy from oil and gas reservoirs. *Energy*, *142*, 346–355. https://doi.org/10.1016/j.energy.2017.10.058

[12] Chmielowska, A., Tomaszewska, B., & Sowizdza, A. (2020). The Utilization of Abandoned Petroleum Wells in Geothermal Energy Sector. Worldwide Trends and Experience. *E3S Web of Conferences*, *154*. https://doi.org/10.1051/e3sconf/202015405004

[13] Duggal, R., Rayudu, R., Hinkley, J., Burnell, J., & Ward, S. (2021). Identifying issues in geothermal energy production from petroleum fields. *IEEE Region 10 Annual International Conference, Proceedings/TENCON*, *2021-Decem*, 254–259. https://doi.org/10.1109/TENCON54134.2021.9707342

[14] Oyekale, J., & Emagbetere, E. (2022). 19 - Pragmatic steps to the revitalization of abandoned oil and gas wells for geothermal applications. In Y. Noorollahi, M. N. Naseer, & M. M. B. T.-U. of T. P. of A. W. Siddiqi (Eds.), (pp. 389–403). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-323-90616-6.00019-1

[15] Kaplanoğlu, M. A., Baba, A., & Gokcen Akkurt, G. (2020). Use of abandoned oil wells in geothermal systems in Turkey. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, *6*(1). https://doi.org/10.1007/s40948-019-00125-0

[16] Gong, B., Liang, H., Xin, S., & Li, K. (2011). Effect of Water Injection on Reservoir Temperature During Power Generation in Oil Fields. In *Thirty-sixth Workshop on*

Geothermal Reservoir Engineering Stanford University. Stanford, California.

[17] Mehmood, A., Yao, J., Fan, D., Bongole, K., Liu, J., & Zhang, X. (2019). Potential for heat production by retrofitting abandoned gas wells into geothermal wells. *PLoS ONE*, *14*(8), 1–19. https://doi.org/10.1371/journal.pone.0220128

[18] Naseer, M. N., Noorollahi, Y., Zaidi, A. A., Wahab, Y. A., Johan, M. R., & Badruddin, I. A. (2022). Abandoned wells multigeneration system: promising zero CO2 emission geothermal energy system. *International Journal of Energy and Environmental Engineering*, (0123456789). https://doi.org/10.1007/s40095-022-00496-3

[19] Gharibi, S., Mortezazadeh, E., Jalaledin, S., Aghcheh, H., & Vatani, A. (2018). Feasibility study of geothermal heat extraction from abandoned oil wells using a U-tube heat exchanger. *Energy*, *153*, 554–567. https://doi.org/10.1016/j.energy.2018.04.003

[20] Wight, N. M., & Bennett, N. S. (2015). Geothermal energy from abandoned oil and gas wells using water in combination with a closed wellbore. *Applied Thermal Engineering*, *89*, 908–915. https://doi.org/10.1016/j.applthermaleng.2015.06.030

[21] Milliken, M. (2007). Geothermal resources at naval petroleum Reserve-3 (NPR-3), Wyoming. *Thirty-Second Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 22-24, 2007 SGP-TR-183*, *3*(Figure 1), 9.

[22] Sanyal, S. K., & Butler, S. J. (2010). Geothermal Power Capacity from Petroleum Wells – Some Case Histories of Assessment. *World Geothermal Congress*, (April), 25–29.

[23] Harris, B. E., Lightstone, M. F., & Reitsma, S. (2021). A numerical investigation into the use of directionally drilled wells for the extraction of geothermal energy from abandoned oil and gas wells. *Geothermics*, *90*(November 2020), 101994. https://doi.org/10.1016/j.geothermics.2020.101994

[24] Noorollahi, Y., Pourarshad, M., Jalilinasrabady, S., & Yousefi, H. (2015). Numerical simulation of power production from abandoned oil wells in Ahwaz oil field in southern Iran. *Geothermics*, *55*, 16–23. https://doi.org/10.1016/j.geothermics.2015.01.008

[25] Patihk, J., Warner-Lall, D., Alexander, D., Maharaj, R., & Boodlal, D. (2022). The optimization of a potential geothermal reservoir using abandoned wells: a case study for the forest reserve field in Trinidad. *Journal of Petroleum Exploration and Production Technology*, *12*(1), 239–255. https://doi.org/10.1007/s13202-021-01322-y

[26] Singh, H. K. (2020). Geothermal energy potential of Indian oilfields. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, *6*(1), 1–9. https://doi.org/10.1007/s40948-020-00148-y

[27] Akinyetun, T. (2016). Nigeria and Oil Production : Lessons for Future. *International Journal of Multidisciplinary Research and Development*, *3*(5), 19–24.

[28] Hu, X., Banks, J., Wu, L., & Victor, W. (2020). Numerical modeling of a coaxial borehole heat exchanger to exploit geothermal energy from abandoned petroleum wells in Hinton , Alberta. *Renewable Energy*, *148*, 1110–1123. https://doi.org/10.1016/j.renene.2019.09.141

[29] Idialu, P., Ainodion, J., & Alabi, L. (2004, March 29). Restoration and Remediation of Abandoned Petroleum Drill Sites - A Nigerian Case Study. *SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production*. https://doi.org/10.2118/86796-MS

[30] García-Pabón, J. J., Méndez-Méndez, D., Belman-Flores, J. M., Barroso-Maldonado, J. M., & Khosravi, A. (2021). A review of recent research on the use of r1234yf as an environmentally friendly fluid in the organic rankine cycle. *Sustainability (Switzerland)*, *13*(11). https://doi.org/10.3390/su13115864

[31] Lazzaretto, A., & Manente, G. (2014). A new criterion to optimize ORC design performance using efficiency correlations for axial and radial turbines. *International Journal of Thermodynamics*, *17*(3), 173–181. https://doi.org/10.5541/ijot.562

[32] Borsukiewicz-gozdur, A., & Nowak, W. (2010). Geothermal Power Station with Supercritical Organic Cycle Principles of operations of a power. *World Geothermal Congress*, (April), 25–29.