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Geothermal Heat Recovery from Matured Oil and Gas Fields in Nigeria – Well Integrity Considerations and Profitable Outlook

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ABSTRACT

The quest for a sustainable energy future, increasing economic demand for stable electricity and high cost of Oil and Gas field abandonment has led to strong consideration of the possibility of extracting Geothermal energy from High Temperature Mature Oil and Gas fields in Nigeria. Nigeria, as endowed as the country is with oil and natural resources, still battling with an acute shortage of power supply for both domestic and industrial consumptions. It is therefore imperative that additional energy be generated and added to the present energy capacity in order to cater for Nigeria impending energy crisis which leaves many industries running at high cost and keeps many private homes in blackout.

Mature fields are mostly characterized by large water cut and thus increase the cost of wastewater disposal (OPEX). To increase this field profitability, heat extraction from this medium temperature field generates electricity thus reducing the energy requirement of the field while also generating capital. The geothermal gradient in Niger Delta ranges from 1.3 to 5.5°C/100 m and could be as high as 7.6°C/100m in Sokoto Basin. Literature reported that the Amenan-Npono Oil and Gas field discovered in 1990 with reservoir depth between 3400 to 4700 m, has a porosity of 15%, permeability of several hundred millidarcy, the reservoir pressure is between 350 to 500 bar and temperature in the range of 130 to 150°C. In analyzing the produced fluid, an integrated investigation is being employed to model the fluid flow from reservoir to the surface facilities by using MBAL, PROSPER and GAP to predict tubing, pipeline hydraulics and temperature of the well.

This paper discusses the potentials of generating additional energy through the conversion of depleting oil and gas wells to a geothermal energy plant in order to meet the energy demand of Nigerian populace, and analysis of possible well integrity issues that these fields could encounter which might result to lost production or induce significant maintenance costs. The well integrity risk assessment associated with the existing well design and operations most especially casing and cement failures arising from temperature and thermal effects some of the potential matured fields was investigated.

An analysis of potential energy capacities from the produced fluids (water and gas) and design of the efficient energy conversion system are also discussed. This study was carried out using an open-source data from the internet and all judgments were based on its accuracy. The benefits accrued to this research work when fully implemented, will not only be seen in improving the electricity generation in Nigeria but also in the areas of employment opportunities, economy boost for the Government, development of Indigenous research sector, and near-zero carbon emissions by reducing gas flaring operation. The energy generated can offset the cost of day-to-day energy consumption of the field while the excess can be sold to the neighboring community or added to the National grid. Economic analysis of a similar project in Italy yielded a reasonable payback time of less than four years with an investment of just over a million euros while generating approximately 400GWh of electricity.

1. INTRODUCTION

The concept of harnessing energy from a low-temperature mature oil & gas field in Nigeria has several underlining advantages. The modern universal quest for green and sustainable energy is a key factor considered when researching on this project having in mind that Nigeria's electricity generation and distribution is less than 7500 MW for an astonishing population of over 190 million people. The need for ingenious ways of generating electricity for the host communities where over 90% of Nigeria earnings comes from cannot be overemphasized.

This concept of low-temperature energy recovery has thus been practiced in several regions of the world where there is considerably high surface temperature and pressure of the reservoir fluid, the water cut is over 60% and proximity of communities in the near that can utilize this energy. This candidature made the Niger-Delta Nigeria is a very good environment to develop this type of exciting technology. A good number of oil wells and fields in the Niger Delta have been producing for a long time and have achieved water cut of well over 60%. Given that the temperature gradient in this region is in the order of 3° C /100 m and heat flow average of slightly over

50 mWm^{-2}, one can safely predict reservoir temperature of wells to be over 145.2 °C at 6000 m depth where most of the oil and as deposit are in this depth zone.

There are numerous mature oil and gas fields in this region with high water cut since water in the predominate carrier of this heat, a well producing over 50% water cut will be a good candidate provided the exit temperature and pressure are also favorable. The reservoir temperature for most of the wells in this area practically less than 160 °C and the well head temperature varies widely with the type of completion for this wells and energy loss in transit. With increased researches into the usage of waste heat, Organic Rankine Cycle (ORC) serves as a low enthalpy energy converter into electricity.

This concept has been adopted in various region of the world like the hot water spring in Alaska where a two 200 kW ORC power plant was installed to generate a staggering 400 kW of electricity from an initially waste heat of with surface temperature of less than 75 °C spring. In a project between Ormat Nevada, Inc. and the Department of Energy (DOE) between the year 2007 to 2010 in Wyoming, a 250 kW ORC was installed and was designed to use about 40000 bpd 77 °C produced water using isopentane as the working fluid. This system generated about 180 kW of electricity (Johnson et al.,2010). In Huabei oilfield in China, a 400 kW of power generator was installed with a binary screw expander system. Within the first nine month of usage, this system has generated around 31 x 104 kWh of electricity (Zhu et al. 2015)

In 2014, Alimonti et al. presented a preliminary assessment on the possibility of generating power from the Villafortuna-Trecate Oil field. The project was also based on a single well system and through an Organic Rankine Cycle (ORC) plant. The result suggested that approximately 25 GWh of electric power can be generated over a 10 years period. The technological improvement has thus made it a lot more efficient to generate electricity from a low-temperature heat source via a binary power plant. The procedure of generating this electrical power is quite similar to the traditional power generation mechanism employed in the Clausius-Rankine Cycle. The major difference between these processes is the usage of organic substance in the ORC while water (steam) is used as the working fluid in the CRC system. The working fluid in ORC has a lower boiling point thus a higher vapor pressure than steam. This made the ORC possible to take-in heat from a low enthalpy environment to generate electricity. The working fluid employed is mainly based on the properties of the intended heat source in other to achieve a high efficiency in the primary cycle and the expander. The ORC system consists of the following critical components: The Turbine, The Heat Exchanger, the Condenser and the Feed Pump.

The well integrity management and risk assessment life cycle of most of the potential wells were also examined. This entails how the best practice integrity management principles and risk management processes as a function barrier construction and monitoring within oil and gas industry can be applied for assurance of well integrity within some of the potential mature fields for geothermal development.

2. OIL AND GAS PARADIGM IN NIGER-DELTA NIGERIA

Since the inception of hydrocarbon exploration and production in Nigeria in the early 1950 to early 1960, a reasonable number of wells/fields have been producing and are now generally nearing their end. A good number of this wells depending on their drive mechanism now account for over 50% water cut. As the water cut increases, the IOC are tasked with the challenges of water management which invariably increase the OPEX of these projects while the revenue decreases. Conversely, the heat content of this wastewater can be converted to electric power and stem the challenge of the progressive cost of disposal (treatment /injection). In the Niger Delta region, the geothermal gradient increases towards the North and lower in the south. The high thermal environment is attributed to a low sedimentary thickness and vice versa with temperature ranging from 65 to 150 °C at the prime location of the deposited hydrocarbon, (Omokenu and Nwosu, 2016).

3. GEOLOGY OF THE NIGER DELTA AND THE GEOTHERMAL POTENTIALS

The geology of this region is comprehensively documented and recognized as the youngest sedimentary basin in the Benue Trough system of formation. The growth of this region sprouted at the end of the Eocene tectonic phase. It is on record that well over 12 km of deltaic and shallow marine deposits is made up in this formation. There are three major lithostratigraphic units identified in this location named: The basal Akata, Agbada and the Benin formations. River Niger and Benue are the chief depositors of this sediments.

Akata Formation is a marine prodelta shale deposit compacted and contains abnormal high-pressure siltstone formation. This formation is the main source rock for the Delta and the rudimentary unit of the Cenozoic complex. It is overlaid by paralic sand /shale deposit of the Agbada Formation. The Benin Formation is the uppermost limit of the Delta with a thickness of 3000 m and spread to over 9000 m out of the Bonny beach. The majority of the hydrocarbon deposit in this region is located in the sandstone of Agbada formation (Emujakporue and Ekine, 2014; Akpabio et al., 2013).

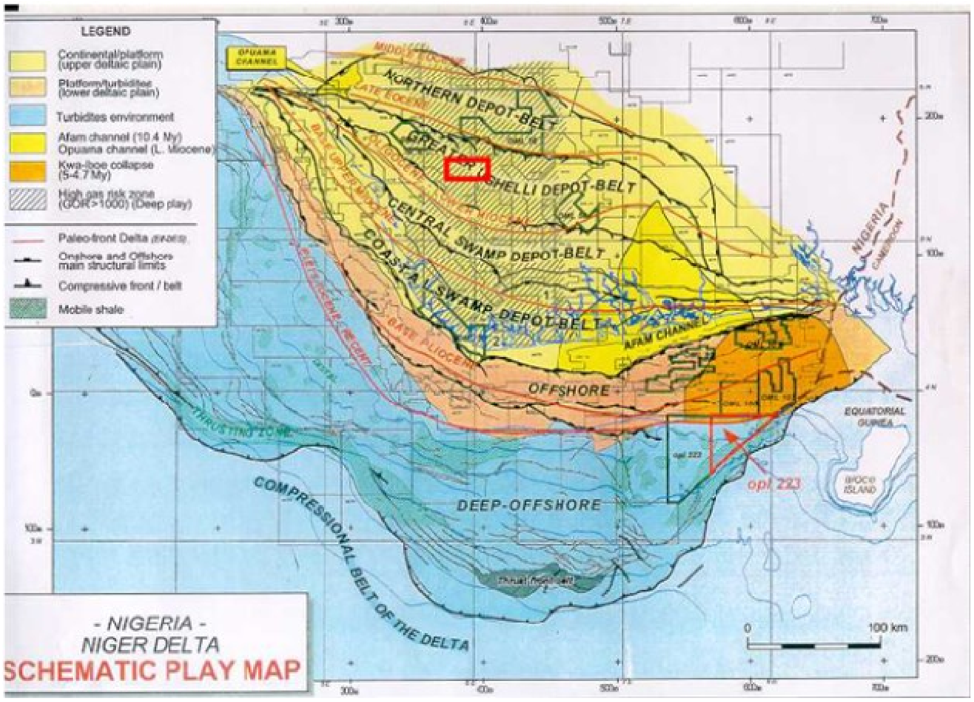

Figure 1: Geological Formation of the Niger-Delta (Izuchukwu andObiadi, 2016)

4. ENERGY SITUATION IN NIGERIA

Nigeria is a developing nation with an estimated population of over 190 million people. It is estimated that less than half of this growing population have access to electricity. According to the International Energy Agency (IEA), the total primary supply of energy in Nigeria is approximately 118.325 Kilotonne of Oil equivalent (ktoe). Thermal and hydro powers are the main sources of generating electricity. The primary supply of electricity in Nigeria is through the Fossil fuel (Gas-fired power plants).

In total, Nigeria produces on the average 5000 MW which is extremely low from what is needed by her huge population. This void provides a great incentive to this type of project and if properly harnessed, could provide electricity for the host communities at the minimum. With daily focus now on sustainable and environmentally friendly energy production, harvesting the wasted energy from our ageing oil field is expedient and of ultimate urgency.

5. CONCEPT OF LOW-TEMPERATURE ENERGY RECOVERY

With vastly huge low-temperature energy generation in Nigeria, exploring the geothermal nature of our marginal field will be a game-changer. This will not only cut down on the OPEX of both our national and IOC but also give them a sense of corporate social responsibility (CSR) for their host communities. Different studies and insider report have given the Niger Delta region to have an estimated geothermal gradient of around 3°C/100m which implies that wellhead temperatures could widely range below 150°C which is a base candidate for low-enthalpy energy recovery.

The co-produced fluid water which is the primary carrier of heat is a by-product in Oil and Gas production. The quality of the usage is dependent on the wellhead temperature, pressure and water quality.

6. WASTE HEAT RECOVERY

Today, over 50 % of fuel has been wasted to produce power in conventional power plants. This huge amount of energy is wasted due to limited processes that are available for power conversion. Waste heat recovery is the economic method to increase the efficiency of the plant and lowers the demand for fuel. Heat to power units or Waste heat recovery units could recover the waste heat and transform it into electricity by using Organic Rankine Cycle (ORC). Figure 2 shows the mechanism of this system.

Some of the benefits of Waste Heat Recovery are:

- Save natural resources by decreasing fuel demand.
- Reduce the CO_2 emission
- Reduce demand for primary energy

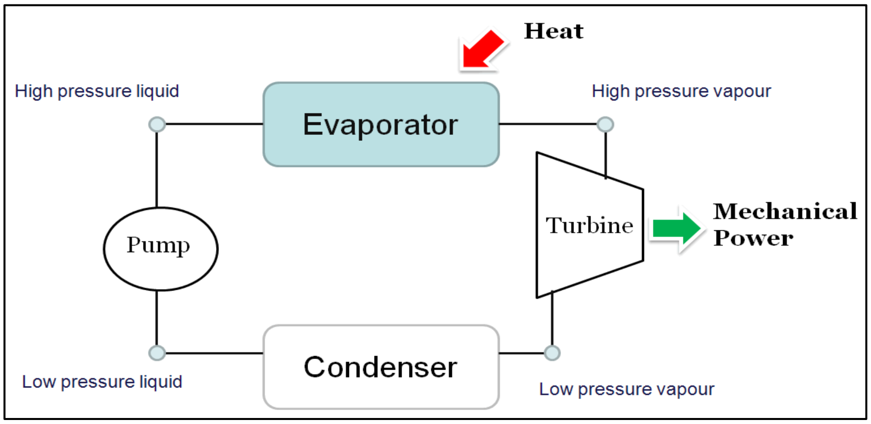

Figure 2: Working Method of ORC

The fluid is pumped to an evaporator (Boiler), acquire heat from a heat source, this then evaporate the working fluid which is chosen based of other prevailing criterial. The evaporated fluid is then passed through a turbine where mechanical power is generated and then to a condenser (Heat exchanger) where condensation takes place and the fluid re-circulated.

7. HEAT EXTRACTION MODELS

This research work would analyse three basic scenarios:

- Recovery from low-temperature co-produced water from a hydrocarbon reservoir
- Heat recovery from re-circulation of the steam-flooded heavy-oil reservoir (Not applicable in Niger Delta but in the Bituminous accumulation in other parts of the country)
- Pre-heating the produced water using the usually flared gas co-produced with oil and water

These listed scenarios above can be adequately proven for economic calculation to know the best possible scenario adoptable at the various field and well locations in the Niger Delta and the environs. The Nigeria technological space does not have enough data to make a proper estimation of the feasibility of this project, but inferences can be made from previously executed geothermal projects from other parts of the world with comparable properties. The workflow for this research work is documented below.

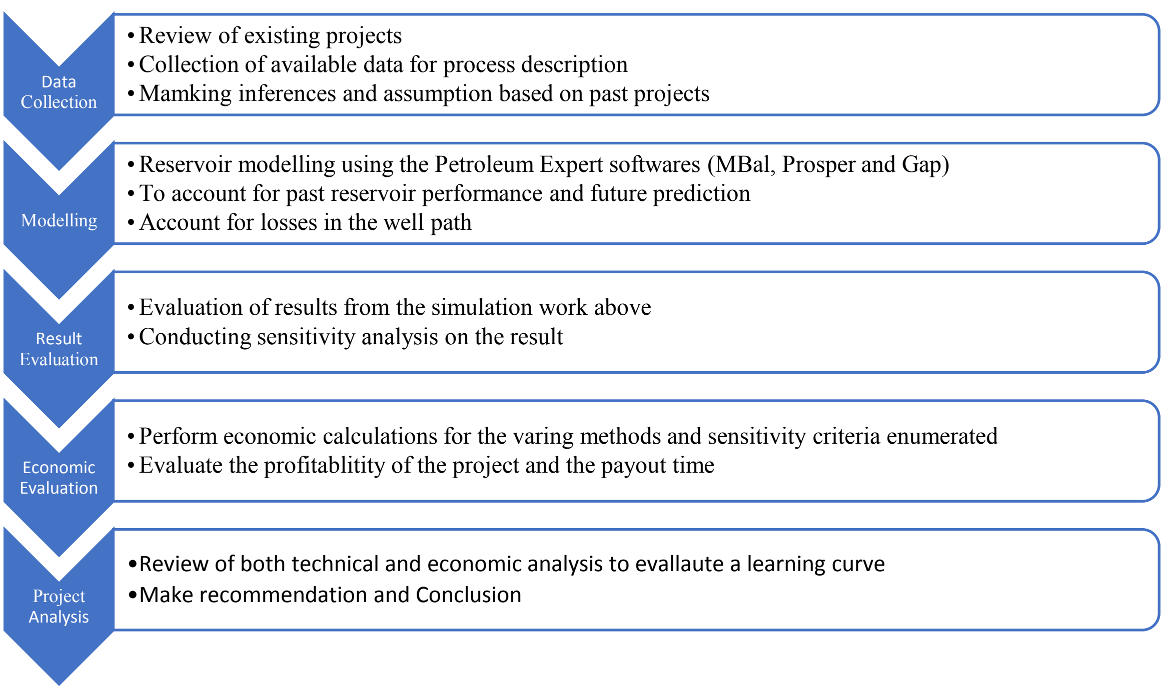

Figure 3: Conceptual Project Workflow

The heat extraction technology for this research is the traditional doublet (co-produced water and re-injection) governed by this heat flow equation:

$$Q = c_p.\rho.q.(T_i - T_o) \quad (1)$$

$$Q = c_p.m.(T_i - T_o)\eta \quad (2)$$

Where c_p is the specific heat capacity of the fluid, (W/kg K); ρ is the fluid density, (kg/m^3); q is the fluid flow rate (m^3/s), Ti is the fluid temperature at the wellhead, (°C), To is the fluid exit temperature; m is the mass flow rate and ŋ is the thermal efficiency (Soldo and Alimonti, 2015).

7.1 Recovery from Low-Temperature Co-Produced Water from Hydrocarbon Reservoir

The concept adopted in this research work is heat annexation using an ORC. The Petroleum Expert simulation will indicate the wellhead temperature for the year in consideration and the multiphase flow situation. In most cases, Oil flows out of the well simultaneously with water and Gas. Thus, the thermal energy for all three phases needs to be calculated. The mass flow of the oil phase is known; hence the specific capacity is needed to obtain the heat flow. Since the specific heat capacity of crude depends on the oil temperature and grade of API, the equation below would be used to calculate the specific heat capacity of crude oil dynamically (equation 3).

$$c_p = (-1.39 * 10^{-6} * T + 1.847 * 10^{-3}) * °API + (6.312 * 10^{-4}) * T + 0.352 \quad (3)$$

Specific heat capacity of crude oil [btu/lbm/°F] depending on temperature and °API. With correct data, the heat flow would be estimated considering the multiphase nature of the fluid.

7.2 Pre-Heating the Produced Pater before Pumping into ORC System

In most cases, the optimal temperature for ORC intake temperature is above 70 °C. The Niger Delta wells we are considering could have wellhead temperature as low as 35 °C in some cases. It is, however, a good practice to preheat the water immediately after separation to condition it to the intake condition from the ORC system as shown below. The fluid from the wellhead is sent to the separator where the gas stream collected is used to preheat the liquid in other to compensate for the lower temperature of the water for the wellhead. The effluent from this pre-processing can then be sent for cleaning and treatment. The oil center in this case represents the treatment plant.

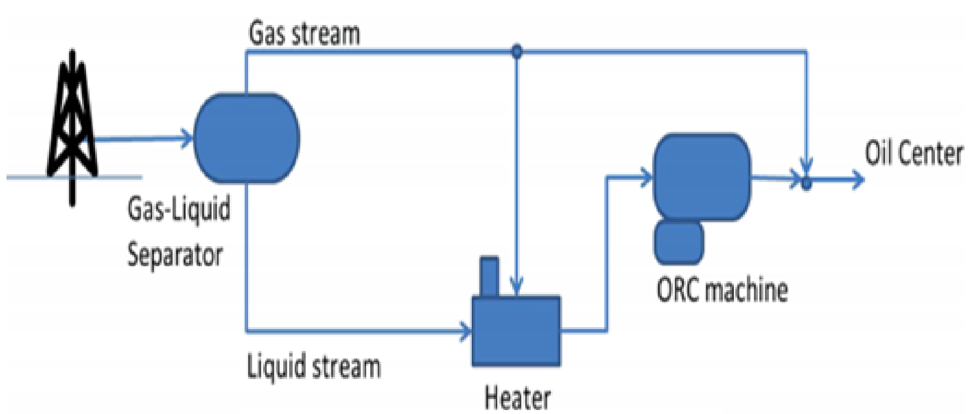

Figure 4: Proposed Process Schematics (Alimonti and Gnoni, 2014)

7.3 Inference from the Villafortuna-Trecate Oil Field

This oil field is located in Northern Italy and shares some similarities with most of the field in the Niger Delta. With temperatures of around 166 °C and under 850 bars. Using a single well as the base case scenario and employing the petroleum expert to generate the dynamic well performance, a completion design was implemented taking into consideration the high-water production (water cut >50%). As expected, oil production declined with years while water production increases which account for the technical viability of the project provided temperature is constant. Given the data in appendix 1, a typical choke performance is shown in Figure 4. The opening of this choke is important because of Joule Thompson effect.

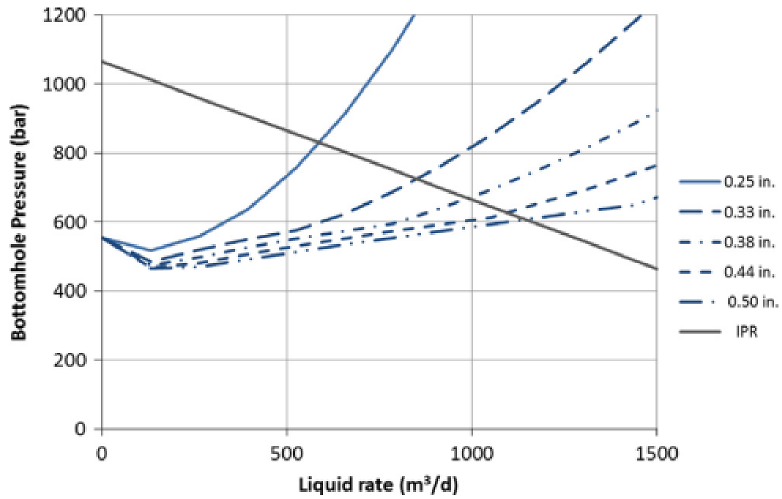

Figure 5: Well vs Choke Performance (Alimonti and Gnoni, 2014)

The recoverable thermal power under the prevailing condition is then calculated by equation (4):

$$Q = (c_{pw}\rho_w q_w + c_{po}\rho_o q_o)((T_i - T_o)) \tag{4}$$

Figure 5 below shows comparable properties of different working fluids. For this analysis, R245fa was used because of the following reasons:

- First, at temperatures encountered for production of geo-fluid this refrigerant has the highest efficiency.
- Although R245fa has a high global warming factor (950 times the global warming effect of CO2), it presents no ozone ozone-depleting effect and it is non-toxic *(Honeywell, HFC-245fa Product Stewardship Summary, December 2007)*.

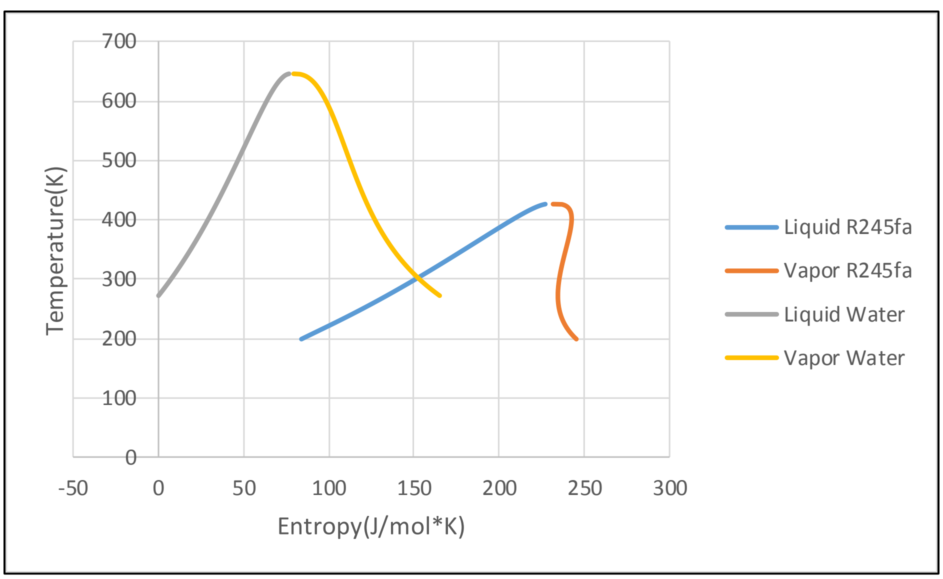

Figure 6: T-S diagram showing R245fa vs Water. (NIST, U.S. Secretary of Commerce, Thermophysical Properties of Fluid Systems)

Table 1: Thermodynamic properties of some candidate working fluids for binary plants

Fluid	Formula	T_c °C	T_c °F	P_c MPa	P_c lbf/in^2	P_s @ 300 K MPa	P_s @ 400 K MPa
Propane	C_3H_8	96.95	206.5	4.236	614.4	0.9935	n.a.
i-Butane	i-C_4H_{10}	135.92	276.7	3.685	534.4	0.3727	3.204
n-Butane	C_4H_{10}	150.8	303.4	3.718	539.2	0.2559	2.488
i-Pentane	i-C_5H_{12}	187.8	370.1	3.409	494.4	0.09759	1.238
n-Pentane	C_5H_{12}	193.9	380.9	3.240	469.9	0.07376	1.036
Ammonia	NH_3	133.65	272.57	11.627	1686.3	1.061	10.3
Water	H_2O	374.14	705.45	22.089	3203.6	0.003536	0.24559

After the general analysis of this process and different basic scenarios, presents the assumptions for the technical data of the considered systems, based on literature reviews and own calculations and assumptions. The table below shows the achievable generation of electrical energy, based on the net assumptions for efficiencies.

Table 2: Technical data of the considered binary systems

	ORC R245fa	*ORC Dual Pressure*	*Kalina*	*Multiple ORC R245fa*	*Large Scale Kalina*
Thermal Efficiency of Power Plant [%]	9.1%	10.7%	10.6%	9.1%	8.7%
Reference for Efficiency	(Brasz, 2004)	(Guzovic, 2014)	(Fallah, 2016)	(Brasz, 2004)	(Fallah, 2016)
Number of Supplying Wells	1	1	1	5	5
Number of Power Plants	1	1	1	5	1
Power Plant Capacity [kW]	250	290	290	1230	680
Temperature Inlet [°C]	101.9	101.9	101.9	101.9	90.4
Specific Invest Costs [€/kW]	2,521	3,176	1,992	2,521	1,824
Specific O&M costs [€/kWh]	0.0176	0.0219	0.0138	0.0173	0.0095
Recooling	Air	Air	Air	Air	Air
Heat Exchanger Efficiency [%]	85%	85%	85%	85%	85%
Internal electricity consumption power plant [%]	12%	12%	12%	12%	12%
Max. Electrical Power at Wellhead [kW]	246	289	287	1231	692
Max. Electrical Power at Separator [kW]	242	285	282	1212	682

8. PROFITABILITY ANALYSIS

To assess the respective monetary impact for each system, the specific investment costs have been acquired via pieces of literature review. The table below shows the evaluation of the specific investment costs per type of system. Since the oil production facilities and necessary auxiliary devices are already in place, the specific investment costs are assumed to be on the lower limit of the possible costs found during the literature review.

Table 3: Specific investment costs for the ORC and Kalina systems

	Specific Invest Costs [USD/kW] (USD 2010)		Reference	Averaged Specific Costs [USD/kW] (USD 2010)	Averaged Specific Costs [€/kW]	Estimated Specific Costs [€/kW]	Total Specific Costs [€/kW]
Technology	Min.	Max.					
ORC	3,400	4,240	(World Bank, 2006)	3,820	2,884	-	**2,521**
ORC	3,040	6,283	(EPRI, 1996)	4,662	3,520	-	
ORC	2,481	3,848	(EPRI, 2010)	3,165	2,389	-	
ORC	-	-	(Valdimarsson, 2003)	-	2,289	-	
ORC dual pressure	-	-	(Shokati, 2015)	-	-	3,176	**3,176**
Kalina	-	-	(Valdimarsson, 2003)	-	1,824	-	**1,992**
Kalina	-	-	(Kalina Power Limited, 2015)	-	2,080	-	
Kalina	-	-	(Modi, 2015)	-	2,072	-	

The total O & M (Operation and Maintenance) costs per year are calculated as a percentage of the total investment for the power plant. In all cases, it is assumed to be 5% of the total investment. The specific O & M costs can be obtained by calculating the total O & M costs over 9.5 years and divide the amount by the amount of generated electrical energy in kWh.

Table 4: Technical parameters with O&M costs

	ORC R245fa	***ORC Dual Pressure***	***Kalina***	***Multiple ORC R245fa***	***Large Scale Kalina***
Thermal Efficiency of Power Plant [%]	9.1%	10.7%	10.6%	9.1%	8.7%
Reference for Efficiency	(Brasz, 2004)	(Guzovic, 2014)	(Fallah, 2016)	(Brasz, 2004)	(Fallah, 2016)
Number of Supplying Wells	1	1	1	5	5
Number of Power Plants	1	1	1	5	1
Power Plant Capacity [kW]	0	0	0	0	690
Total Generated Electrical Energy [GWh]	20.4	24.0	23.8	102.1	74.7
Temperature Inlet [°C]	101.9	101.9	101.9	101.9	90.4
Recooling	Air	Air	Air	Air	Air
Heat Exchanger Efficiency [%]	85%	85%	85%	85%	85%
Internal electricity consumption power plant [%]	12%	12%	12%	12%	12%
Max. Electrical Power at Wellhead [kW]	246	289	286	1229	692
Max. Electrical Power at Separator [kW]	242	285	282	1210	681
Heat Exchange at	Wellhead	Wellhead	Wellhead	Wellhead	Separator

Using an electricity price in Italy, the profitability table below can be generated.

Table 5: Results of profitability analyses for all systems

	ORC R245fa	***ORC Dual Pressure***	***Kalina***	***Multiple ORC R245fa***	***Large Scale Kalina***
Lifetime [a]	9.5	9.5	9.5	9.5	9.5
Specific Power Plant Costs [€/kW]	2,521	3,176	1,992	2,521	1,824
Completed Plant Costs [€]	630,207	921,110	577,692	3,100,617	1,240,320
Financed Invest Costs [€]	630,207	921,110	577,692	3,100,617	1,240,320
Discount Rate NPV 3%	3.0%	3.0%	3.0%	3.0%	3.0%
Discount Rate NPV 5%	5.0%	5.0%	5.0%	5.0%	5.0%
Annuity Factor 3%	0.123	0.123	0.123	0.123	0.123
Annuity Factor 5%	0.135	0.135	0.135	0.135	0.135
Dept Service 3% [€/a]	77,223	112,869	70,788	379,935	151,983
Dept Service 5% [€/a]	84,950	124,164	77,872	417,956	167,192
Specific O&M costs [€/kWh]	0.018	0.022	0.014	0.017	0.009
Total O&M costs over 9.5 Years [€]	359,218	525,033	329,284	1,767,352	706,982
Installed Power [kW]	250	290	290	1230	680
Capacity Factor [%]	10	10	10	10	10
Total Generated Electrical Energy [GWh]	20.4	24.0	23.8	102.1	74.7
Electricity Price [€/MWh]	157	157	157	157	157
Revenue [€/a]	296,984	349,201	345,937	1,484,919	1,086,835
Revised Revenue [€/a]	259,171	293,934	311,276	1,298,882	1,012,416
Exposure 3% [€]	620,961	907,597	569,216	3,055,129	1,222,124
Payback period 3% [a]	**3.5**	**5.1**	**2.4**	**3.4**	**1.4**
Payback period 5% [a]	**3.6**	**5.4**	**2.5**	**3.5**	**1.5**
NPV 3% [€]	**1,557,390**	**1,562,937**	**2,047,074**	**7,862,050**	**7,287,289**
NPV 5% [€]	**1,338,004**	**1,316,071**	**1,781,893**	**6,762,016**	**6,418,773**
DPIR 3% [-]	**2.5**	**1.7**	**3.6**	**2.6**	**6.0**
DPIR 5% [-]	**2.2**	**1.5**	**3.2**	**2.2**	**5.3**

As geothermal energy market size is forecast to exceed $57 billion by 2024, the implementation and installation of geothermal power projects in Nigeria will spike the electricity generation across the nation by producing geothermal power from matured or abandoned wells. Presently, Kenya has the most installed geothermal capacity in the entire region of Africa. Furthermore, leveraging geothermal energy frameworks and technologies from countries like the United States, Indonesia, Turkey, Italy, Japan New Zealand, Portugal, the Netherlands, Germany will foster geothermal growing investment, accelerate development, deployment and increase electricity stability in Nigeria. The ability to offer reliable, stable, base-load power and environment-friendly will attract industry penetration.

9. POSSIBLE WELL INTEGRITY ISSUES AND REMEDIAL ACTIONS

Well integrity concerns create challenges for maintaining the production of geothermal wells. Due to the high chloride content and pressene of Cabron dioxide in some of the geothermal fluids in comination with the intrinsic elevated temeperatures of the application. Issues regarding well integrity are mainly associated during the operation phase whether production and injection operations (Marbun, 2019) and likely to occur if the potentials wells for geothermal exploration are designed according to oil and gas standards without considering the extreme geothermal temperature condition. Different failures might occur in this stage affecting different parts of the well caused by different well problem issues. This section will discuss the possible well integrity issues related to the casing, tubing, cementing and completion that can be encountered during geothermal drilling development in Nigeria, with possible remedial actions to mitigate them.

9.1 Downhole Tubulars - Casing and Tubing Integrity

Casing and tubing are both one of the major well integrity concern during geothermal exploitation due to the initial heating up the well, temperature variations during the operational life and formation environment (e.g. presence of corrosive fluids. Failure of downhole tubulars can lead to problems to the stability of the well and allowing cross-communication between the wellbore and the surrounded formation. Casing engineers should achieve certain goals while designing the casing string and they are mainly related to the integrity of the well. Improper design and material selection for the casing, tubing, and connection pose a great threat to the integrity of the well most especially the temperature change, hence impacting the tubular material characteristics and its stress state

Geothermal wells require casing and tubing material with higher yield strength with any further decrease in material yield strength will lead to the reductions of casing load ratings. Failure of the casing can lead to sever leak in the system and negatively affects the well production and on the other hand, it can harm the environment by polluting the freshwater aquifer.

Another major challenge is the casing and tubing corrosion when exposed to geothermal fluid elements comprising of dissolved carbon dioxide (CO_2), hydrogen sulfide (H_2S) and chloride ions impacting the completion and long life production of material used for geothermal wells. The following corrosion types such as uniform corrosion; pitting corrosion; cracking corrosion; stress corrosion cracking; sulfur stress corrosion cracking (SSC); intergranular corrosion; galvanic corrosion; erosion-corrosion; and decomposition of alloy structure can transpire as result of dissolved geothermal fluid elements like H_2S, CO_2, and high salt concentration in many geothermal wells.

In order to keep the well flowing in a safe manner and applying remedial actions to the damaged casing or tubing after identifying the root cause of the problem. Tubular should be fixed as soon as it is identified to prevent any farther problems. Possible remedial action can be done in order to fix the damaged interval of the casing and they are listed below:

i. Casing patch is one of the most effective solutions in order to fix a damaged interval of the casing.
ii. Using of expendables pipes to be expanded against the damaged casing.
iii. Performing a squeeze cementing job to cover casing leaks.
iv. Replacement of the damaged tubing and casing in case the casing is in shallow depths and not cemented.
v. Injecting chemicals which work as a sealant, to fix small casing leaks and joint leak.
vi. Sidetracking and plugging the damaged well.

For corrosion related issues mitigation, it is advised to opt for appropriate metallic materials to minimize corrosion risks. According to Richter (2015), Nickel Institute suggested corrosion-resistance alloys with high nickel content as the best functioning material that alleviates the corrosion issues in the geothermal industry. For cases of chloride corrosion, the casing designer might need to use a corrosion-resistant alloy with Titanium alloy like Ti grades 12, 29 or Ruthenium for geothermal production well casing.

It has been reported that one of the technologies that may undoubtedly revitalize the global geothermal market in the very near future is the use of composite materials for casing, liner and drill pipes in production as well as injection wells. Composites are non-metallic anisotropic materials, that enable pipe constructions with different strength and physical properties depending on the direction of consideration (Figure 7). One of the biggest advantages of composite pipes is their high chemical resistance and complete exclusion of corrosion and scale deposits development on the casing wall, enabling safe production of highly saline geothermal waters and the use of various types of chemicals being applied in the drilling industry (Hanson, 2019). The additional benefit of composites is their high ductility, and lighter weight (around 6 times) compared to the conventional steel casing. The relatively low weight of the pipes enables the use of drilling rigs with a much lower hoisting capacity, which significantly reduces the investment costs of the geothermal project. Pipes currently available on the market are able to operate at a downhole temperature not exceeding 105°C, however, research is underway to use composite materials under temperatures from 150 to 170°C in geothermal wells deeper than 3500 m. In the future, the enhancement of composite materials capable of operating in high enthalpy boreholes with temperatures of up to 300°C and depths of up to 5500 m is being investigated.

Figure 7: Example of a Composite Casing (akiet.com)

9.2 Cement Integrity

Cementing is considered to be one of the most important barriers in the well and it provides the integrity of the well during the life of the well since it fixes the casing into the wellbore. As cement plays a vital role in both oil and gas, and geothermal well exploration ranging from the isolation of porous formation from the producing zone, isolate the produced fluid from the subsurface undesirable fluids, protect the casing from the corrosive environment and to seal off abnormal pressure formations. However, the failure of cement to seal the annulus and avert fluid migration can endanger the safety of the crew and environment (Thai, et al., 2019).

According to Wilcox et al. 2016, it was mentioned that casing eccentricity is one of the factors that attribute to the cement failure to seal the annular space. Casing eccentricity describes how the casing is off-centered in the open hole. In the field, one of the reasons for high casing eccentricity is the hole angle. In high casing eccentricity, the fluid in the annulus prefers to flow in the wide side as a substitute of the narrow side, causing a skew distribution of drilling fluid and later spacer. Inadequate mud displacement process results in inefficient mud removal in the narrow side of the annulus. Non-uniformly placed cement creates voids that might be invaded later by drilling, completion and formation fluid.

Cement could fail due to several possible reasons after the completion of the cementing job and while the production phase with their consequences regarding well integrity, they are listed below:

i. Insufficient number of casing centralizers used while running the casing string which could lead to mud channeling in the annulus which impact cross-communication between formation fluids and casing.
ii. Bad quality of cementing job or wrong cement type, which cannot hold the pressure or temperature of the surrounding environment causing the cement to crack and fail to perform its objectives.
iii. Mechanical stresses resulted from the formation causing cracks to the cement.
iv. Cement fatigue after a long time of operation which is increased in case of high pressure and temperature resulting in a loss in structural integrity.
v. High pressure applied on the cement at casing shoe could lead to casing shoe failure and possible leak.

There are possible remedial actions to be done in order to mitigate the failure of the cement. Squeeze cementing is the most popular remedial action done to solve problems of cement failures whether to fix the certain problems during the production period or the increase the quality of the cement job directly after a bad cement job The possibility of a successful squeeze cementing job is considered to be low which is estimated to be around 50%. Moreover, it could collapse the casing in some cases where the pressure behind the casing exceeds the collapse pressure of the casing. Top job cementing could be a solution in the case where the casing is not cemented to the surface and there is a possibility of casing failure due to instability of the formation or corrosive formation surrounding the casing.

In providing long term zonal isolation, it is advised to cement geothermal wells all the way to the surface to prevent the long term effect of annular pressure build-up. Based on ISO 10427-2 2004, the standoff ratio is recommended to be preserved above 67% by using centralizers along the wellbore in order to avert high eccentricity. Torres (2014) likewise suggested a rigid spiral centralizer to prevent entrapment of water in the annulus.

9.3 Completion Integrity

Well completion is carried out to get the well ready for production or injection. It defines as activities and operations for installation of tubular and equipment in a well that will be used as transport means to and from the reservoir and surface (Norsok-Standard-D10, 2013). After drilling a well to total depth, completion starts with the cleaning of the well and installation of completion equipment and ends with the suspension of the tubing hanger in the subsea wellhead or surface production tree (Norsok-Standard-D10, 2013). Some of the well integrity issues may arise from well completion if the design and construction of the well are done without proper consideration of all the anticipated activities of the wells. In selecting the materials and components for the well completion, the environmental condition of the wellbore (temperature and pressure, and the fluids i.e. hydrocarbon, water, steam and waste products such as carbon dioxide, sulfur, hydrogen sulfide, etc.) must be considered. So that appropriate components and materials that can withstand the anticipated loads and the corrosive nature of wellbore fluids will be selected.

Generally, completion can either be open or cased hole completion. The open hole completion is employed where the producing zone is strong and competent so that it does not cave in (Lyons et al., 2016). The cased hole completions are usually used where the producing zone is not strong and can fail easily while producing or as the reservoir depletes (Lyons et al., 2016).

In the completion string design, all the components are subjects to load verification. The minimum design safety factors for burst loads, collapse load, axial loads and tri-axial loads are 1.10, 1.10, 1.25, and 1.25, respectively, for both pipe body and connection wherever the combination is weaker (Norsok-Standard-D10, 2013).

9.4 Connection Integrity

Casing connection is an important issue that needs to be considered during the selection of casing connection. Connection failures are most likely to occur in the potential geothermal locations in Nigeria due to connection yielding when subjected to high compressive stress as the wellbore temperature increases to flowing conditions. As reported by Torres (2014), there are three highly common casing connection failures observed in geothermal wells: ***pin compression deformation*** (compression of the pin against the connector shoulder leading to deformation of the pin end); ***pin jump-in*** (that is, compression of the pin against the coupling shoulder leading the pin end to "jump-in" into the casing with some of the threads disengaged); and ***pin pull-out*** (ensues when a "jump-in" is subjected to further tension, thus threads are no longer engaged and a pull-out effect happens exposing some of the threads. API Buttress threaded couplings most common connection being used in the geothermal industry are vulnerable to thread jumping in compression because of the lack of positive pressure contact at the pin ends after it is torqued up.

To augment compression and torque, a load bearing area commonly referred to as the torque shoulder should ber established in the box area of proprietary connection. Proprietary connections with a positive-stop shoulder and special thread profile could alleviate the mentioned common casing connection failures, while providing an easier and faster tubular running solution. A special consideration should be taken to select connections with 100% tension and compression capacity (Merliahmad, et al., 2015).

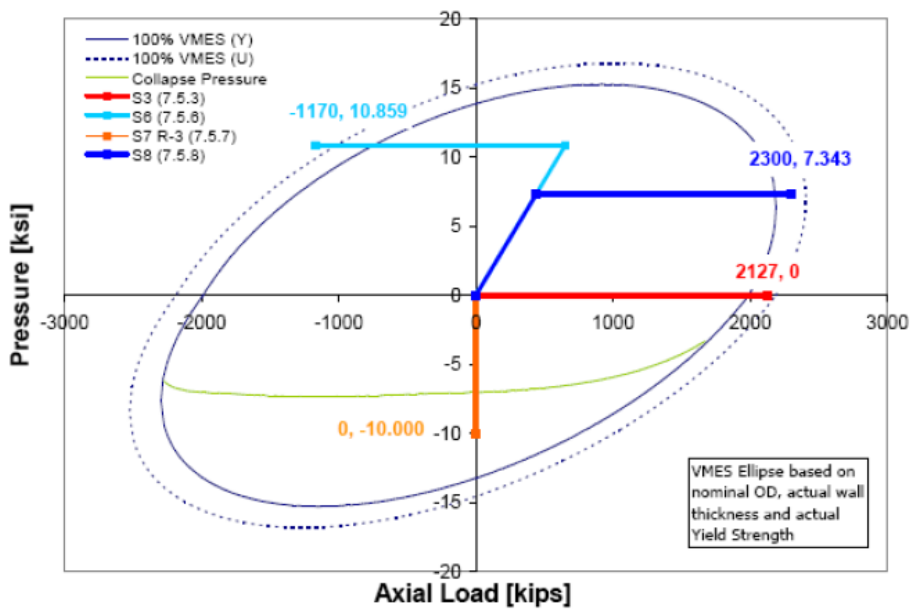

Figure 8: A representative result of a API 5C5/ ISO 13679 Failure Test (Merliahmad, et al., 2015)

Figure 8 illustates a representative result of API 5C5/ISO 13679 testing to failure, subjected to a specific combination of tension, compression, internal pressure and external pressure until it fails. These connections would be equivalent or greater than the pipe body in tensile and compressive strength,eliminating a weak point in the string with regards to these aspects. Furthermore, it highly recommended to discuss with casing and connection providers the geothermal well conditions that will aid the required testing and qualification needed in order to mitigate or have a further assurance connection failures will not happen from time to time.

CONCLUSIONS

The capability of geothermal energy to stipulate an alternative to conventional fuel for electric generation in Nigeria depends on being able to develop these resources at a cost that is at least equivalent to the alternatives available. After comprehensive consideration of the heat extraction process, with an average surface temperature of 101.8°C and liquid flowrate of 11.1Kg/s, will be able to generate around 20.4 GWh of electricity over the prediction period of 10 years and an NPV value of 1.33 M€ at 5% interest rate.

This result should, however, be attractive for any mature High-Temperature onshore fields in Nigeria and globally, as the majority of the CAPEX has already been installed. The revenue generated from this process can be used to offset a considerable part of the current expenditure on energy generation from the burning of fossil fuel. Tapping into geothermal energy exploration will pave a more realistic way of generating green energy from a natural heat source and foster Nigeria geothermal market. This concept in several countries around the would help energy companies get Tax reduction which translates to good savings.

Critical geothermal wells integrity issues are mostly related to tubulars, cement, casing connections and completions failure. An improved design and proper selection of casing as well as performing a good cement job have been the most important approaches to minimize the risk of catastrophic well failures. The need for a technical feasibility and corrosion protection strategy to minimize the impact of geothermal fluid aggressiveness should be considered.

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