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Towards the Use of Geothermal Resources Available in Oil and Gas Sedimentary Basins in Colombia

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ABSTRACT

The electrical energy generation in oil and gas fields from co-production waters is possible by using binary or Organic Rankine Cycle (ORC) plants with the aim of converting heat into electricity. The better efficiencies of ORC plants facilitate the use of low-temperature water that has been determined unfeasible both technically and economically in a previous study carried out for petroleum-producing sedimentary basins in Colombia. From reports and studies, it was estimated that about 10-12 million barrels of water are co-produced daily from oil and gas wells with temperatures varying between 42-179 °C. We show that from the co-production waters with temperatures of 80 °C, in the sedimentary basins Eastern Llanos, Eastern Cordillera, Caguán-Putumayo, Catatumbo, Cesar Ranchería and Middle Magdalena Valley, about 170 MW_e of electric power could be installed. The Eastern Llanos basin would contribute the largest amount with about 81%. It also presents the oil and gas fields with potential for geothermal development from co-production fluids.

Additionally, we analyse two particular cases oil and gas fields located in the Eastern Llanos basin, with water temperatures of 82 °C and 88 °C, mass flows of 61 kg/s and 99 kg/s, and with a temperature differential of the water outlet of 10 °C for both cases. The electric power is modeled and calculated based on four working fluids: R123, R245fa, R134a and Isopentane. The outcomes show powers of 200 kW_e for the first case and 320 kW_e for the second. Isopentane is the working fluid that provides better results in terms of power, and by using the lowest possible values of evaporation pressure and mass flows.

Finally, the financial feasibility assessment allows us to conclude that it is possible to implement the ORC binary plant technology for electrical energy generation using co-produced waters in Colombia from oil and gas sedimentary basins. This assessment is carried out having the local energy market as a constraint. The outcomes indicate that the ORC plants with generation capacity of 200 kW_e and 320 kW_e are profitable with project paybacks of 7 years and 9 years, respectively.

1. INTRODUCTION

The geothermal resources used today are essentially high-temperature resources, where wells of moderate depth (1000-2000 m) are drilled into aquifers and produce steam or a mixture of steam and water. These resources are used with steam turbines (e.g., geysers) or in single and double flashing plants (e.g., Wairakei and Imperial Valley). Since most of the high temperature aqueous resources have been utilized, the next expansion of geothermal power plants will necessarily be with lower temperature resources where water can surface as a liquid at temperatures in the 90-150 °C range. Binary geothermal systems, which use a secondary fluid as a refrigerant or a hydrocarbon, are typically used for the development and exploitation of these resources (Davis and Michaelides, 2009).

All sedimentary basins have potential for the development of geothermal energy due to the existence of deep aquifers that have high temperatures and high production capacity. Advances in the commercial development of Organic Rankine Cycles (ORC) and other heat-energy conversion technologies, make geothermal power generation economical with water temperatures as low as 90 °C and flow rates of 55.2 l/s (30,000 BPD) (Gosnold, et al., 2010). When hydrocarbons are produced from deep rock formations, water is also extracted. This water is known as co-production water. Treatment of the water produced from the oil fields is a direct cost to the well operator and costs more than all other services combined. Once the cost of managing and disposing of the water exceeds the profits from oil production, the well is shut down. Oil and gas companies design fields and operations to limit the amount of water produced. Some well fields produce enough water at high enough temperatures to produce electricity using an Organic Rankine Cycle (ORC) or a binary power plant. Adding this type of electricity generation could generate additional revenue for operators (or reduce operating expenses), increase the useful life of the well field and decrease the carbon footprint of the field (Augustine and Falkenstern, 2012).

In Colombia, according to the annual reports of the National Hydrocarbons Agency (ANH by its Spanish acronym), and the Colombian Petroleum Association (ACP by its Spanish acronym), between 2013 and 2019 the amount of water co-produced during oil and gas production is between 10 and 12 million barrels (bbl) per day (ACP, 2015; Colombia, 2019). The study carried out by Cuadrado et al., (2015), showed that the generation of energy for a 280 kW_e ORC plant in the Eastern Llanos basin in Colombia, is feasible from co-production waters with temperatures above 93 °C and mass flow of 63 kg/s, with a cycle efficiency of 6.6%, where its generation cost is 0.102 USD/kWh. Other studies presented by Bennett et al., (2012) and Gosnold et al., (2019), show that the cost of generating electricity in ORC plants with co-production fluids is 0.080 USD/kWh and 0.0878 USD/kWh, respectively.

This study shows that the sedimentary basins of the Eastern Llanos, Eastern Cordillera, Caguán-Putumayo, Catatumbo, Cesar Ranchería and Middle Magdalena Valley, could generate around 170 MW of electrical energy with co-production water co-with temperatures around 80 °C, The Eastern Llanos basin would contribute up to 81% of the total energy with approximately 137 MW. The energy calculation was estimated from the Exergy and MIT Model methods, described in MIT (2006), and Augustine and Falkenstern, (2012). Additionally, a list of oil and gas fields with potential for geothermal exploitation and co-production fluid rates greater than 36,000 barrels per day is presented. These rates correspond to the Cesar Ranchería, Caguan-Putumayo, Middle Magdalena Valley, and Eastern Llanos basins. The results obtained when analyzing the generation of electrical energy from ORC plants, in two oil and gas fields located in the Eastern Llanos basin, show the viability of obtaining electrical power from 200 kW_e with co-production water temperatures of 82 °C and mass flow of 61 kg/s, and using Isopentane as the working fluid.

2. METHODOLOGY

The present study calculates the electrical power that could be available in the sedimentary basins where geothermal anomalies have been identified by the Colombian Geological Survey (SGC by its Spanish acronym) (Alfaro et al., 2009; Alfaro et al., 2009a; Alfaro et al., 2010). Subsequently, the electrical power in two areas of the Eastern Llanos basin with co-production waters at certain temperatures and flows is calculated. The procedure used is as follow:

1. Estimation of the production crude and co-production water rates in Colombia.

2. Identification of the sedimentary basins with the highest geothermal gradient.

3. Calculation of the amount of electrical power available in the sedimentary basins, with different temperatures of co-production waters.

4. Estimation of the electrical power generated in two specific areas of the Eastern Llanos basin with established temperatures and flow rates.

2.1 Colombian oil and water production

Based on information presented by the National Hydrocarbons Agency (ANH by its Spanish acronym), since 2013 Colombia has maintained an oil production close to one million barrels per day, with a notable decrease in the last 4 years (Figure 1). According to the Environmental Performance Report 2015 (IDA by its Spanish acronym), published by the Colombian Petroleum Association (ACP by its Spanish acronym), in Colombia for each barrel of crude produced, 12.02 barrels of water are generated, for a water cut of 92.3% (Colombia, 2019). For the years after 2015, the IDA was not published and the amount of water produced in the oil fields was not reported, however, its volume was calculated from the volume of oil produced with a water cut of 92.3%. In general, it is observed that the production of water is higher than ten million barrels per day.

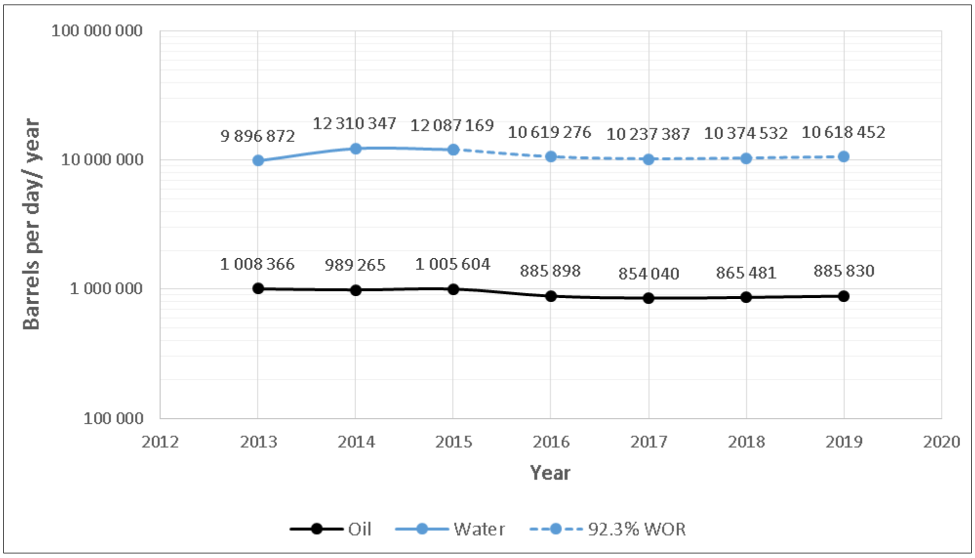

Figure 1: Oil and water production in Colombia 2013-2019 (Colombia, 2019).

2.2 Geothermal gradients

The map presented by the Colombian Geological Survey (SGC by its Spanish acronym) contains information on temperature data from 4400 wells drilled in the oil and gas industry (Figure 2), where the temperature range ranges from 42-179 °C at depths between 515-6273 m. The highest temperature, corresponding to 179 °C, was recorded in the Cumaral 1AX well in the Eastern Llanos basin, at a depth of 5319 m. The apparent geothermal gradients range between 8-59 °C/km, with a mean value of 28.8 °C/km. The SGC identified five main anomalies located in the Eastern Llanos, Eastern Cordillera, Caguan-Putumayo, Catatumbo and Cesar Ranchería basins, with apparent geothermal gradients greater than 40 °C/km (Alfaro et al. 2009; Alfaro et al. 2009a; Alfaro et al. 2010). It is important to highlight that the geothermal gradient map does not include the geothermal gradient of 140 °C/km corresponding to the

Nereidas-1 well, 1356 m deep, which was drilled on the western flank of the Nevado del Ruiz volcano (Alfaro et al. 2009; Alfaro et al. 2015).

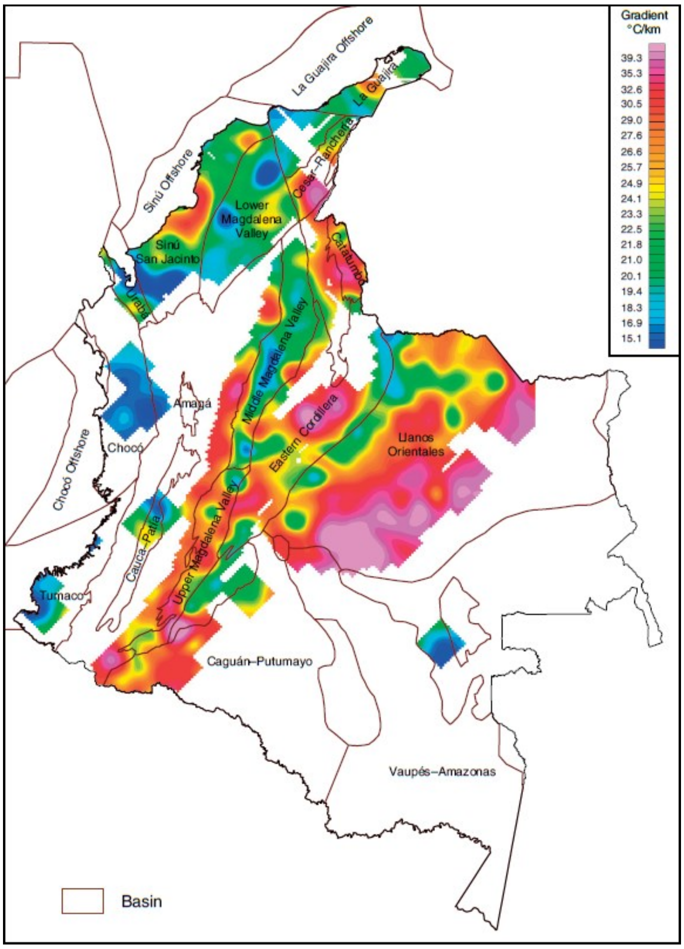

Figure 2: Geothermal gradient map (Alfaro et al., 2020)

For the basins with the main geothermal gradient anomalies, adding the Middle Magdalena Valley basin due to its high volumes of co-production water, the volume of oil between 2013-2019, and co-production waters for the year 2019 were determined (Figure 3). With these inputs, the amount of electrical power that could be generated in each basin is estimated. These basins contribute 94% of the volume of nationally co-produced water, with the Eastern Llanos basin having the highest percentage with 74% of the national production.

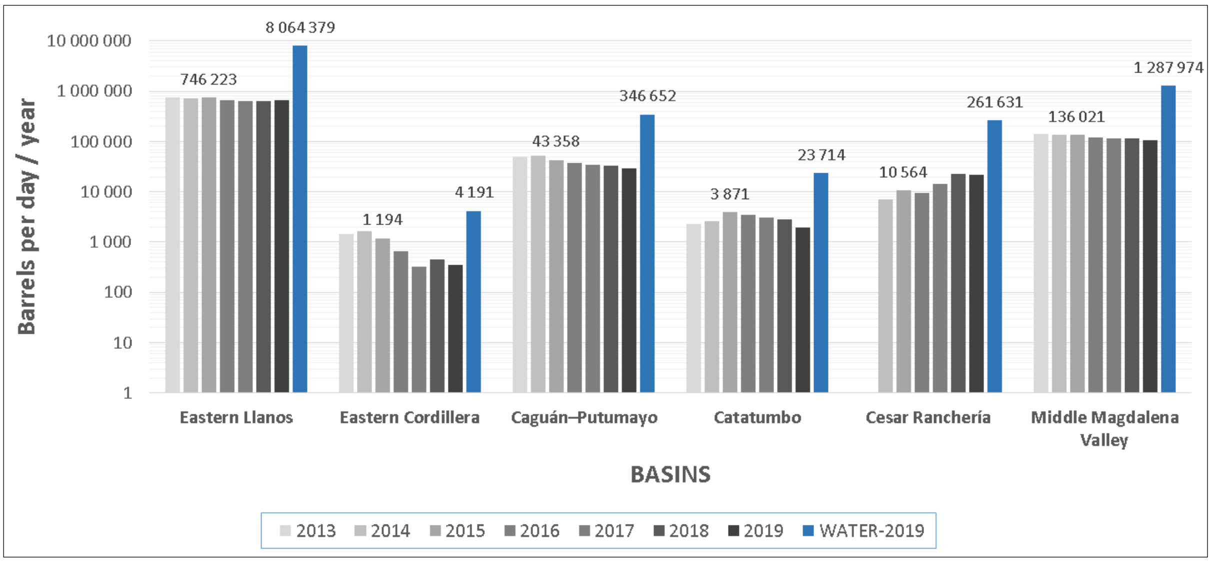

Figure 3: Oil and water production per basins in Colombia 2013-2019 (Colombia, 2019).

Table 1 shows the Colombian oil and gas fields with potential for geothermal exploitation of co-production waters. These fields have a crude production of more than 3,000 bpd, and co-production waters exceeding 36,000 bpd, equivalent to a water cut of 92.3% (ACP, 2015; Colombia, 2019).

Table 1: Colombian oil and gas fields with potential for geothermal exploitation.

Basin	Oil and Gas Field	Field Operator
Cesar Ranchería	Acordionero	Gran Tierra Energy Colombia LTD.
Caguán - Putumayo	Moqueta, Platanillo, Cohembi, Costayaco	Gran Tierra Energy Colombia LTD., Amerisur Exploración Colombia LTD., Vetra Exploración y Producción Colombia S.A.S.
Middle Magdalena Valley	Casabe, Palagua, Jazmin, Moriche, Infantas, La Cira, Llanito Unificado, Yariguí-Cantagallo.	Ecopetrol S.A., Mansorovar Energy Colombia LTD.
Eastern Llanos	Chipirón, Caño Limón, Caño Yarumal, Finn, Rex NE, Caricare, Andina, Cupiagua, Chiricoca, Tigana, Tua, Jacana, Bacano, Floreña, Floreña Mirador, Pautosur, Akacias, Castilla Norte, Chichimene, Indico, Mariposa, Ceibo, Castilla, Chichimene SW, Cañosur Este, Rubiales, Quifa, Ocelote, Apiay, Suria	Occidental de Colombia LLC., Parex Resources Colombia LTD. Sucursal, Ecopetrol S.A., Geopark Colombia S.A.S., Equion Energía Limited, ONGC Videsh Limited Sucursal Colombiana, Frontera Energy Colombia Corp Sucursal Colombia, Hocol S.A.

2.3 Electricity Generation Estimate

To estimate the amount of energy that could be produced in the oil fields with the co-production waters, the Exergy and MIT model methods were used, both described in Augustine and Falkenstern, (2012).

2.3.1 Exergy (theoretical maximum power potential):

The exergy (E) is the theoretical maximum amount of work that can be extracted from the co-production waters. This calculation gives an upper limit potential. The theoretical maximum power that could be extracted from a fluid relative to the ambient or dead state is defined as:

$$\dot{E} = \dot{m}\left[\left(H(T_{in}) - H(T_{ambient})\right) - T_{ambient}\left(S(T_{in}) - S(T_{ambient})\right)\right] \tag{1}$$

Where $\dot{m}$ is the mass flow rate, T_{in} is the plant inlet temperature, $H(T)$ is enthalpy, and $S(T)$ is entropy. In this case, it is assumed that the co-production resource is pure water, where the enthalpy and entropy are only a function of temperature, since the effects of pressure are ignored. For the Eastern Cordillera basin, an ambient temperature $T_{ambient}$ of 15 °C was assumed. For the rest of the basins, 30 °C temperature is chosen.

2.3.1 MIT model:

The MIT model suggested by MIT (2006), allows estimating the potential of the co-produced resource from existing oil and gas operations.In this model it is also assumed that the co-production fluid is pure water and that the pressure effects are ignored. It implies that the enthalpy is a function of temperature only. Additionally, the plant outlet temperature of 37 °C is assumed. The rate of heat input to the binary plant is calculated from the change in enthalpy of the co-production waters between the inlet and the outlet:

$$\dot{Q} = \dot{m}\left[H(T_{in}) - H(T_{out})\right] \tag{2}$$

Where T_{out} is the plant outlet temperature. For the calculation of the thermal efficiency η_{th} , which is defined as the ratio of the net output work $\dot{W}$ and input heat rates $\dot{Q}$ of the binary plant, the following correlation is used:

$$\eta_{th} = 0.0935 * T(°C) - 2.3266 \tag{3}$$

This correlation was derived from data from binary plants in operation with temperatures between 100 - 200 °C (Augustine and Falkenstern, 2012). Finally, the net work-out rate $\dot{W}$ is calculated with the following equation:

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}} \tag{4}$$

2.4 Eastern Llanos – Case Studies

Based on temperature and flow rate data from two oil fields located in the Eastern Llanos Basin (called Case 1 and Case 2), the net power is calculated by taking advantage of the thermal energy with binary plants. In Case 1, a mass flow of 61 kg/s and inlet water temperature of 82 °C were used. For Case 2, the mass flow is 99 kg/s and the water inlet temperature is 88 °C. In both cases the condenser temperature is 37 °C. In addition, the difference between the water inlet and outlet temperature is 10 °C, based on the case of the binary plant installed in the NPR-3 oil field in Wyoming - USA (Reinhardt, et al., 2011). In both cases, R123, R245fa, R134a and Isopentane were used as working fluids (Xin, et al., 2012). The calculations were performed in EES software licensed from LaGeo S.A. de C.V (EES, 2015). The thermodynamic equations were taken from DiPippo, (2015).

3. RESULTS

The electrical energy potential obtained by the exergy and the MIT model methods is shown in Table 2. Considering a minimum temperature of 80 °C of co-production water, the exergy method indicates an energy potential of 287 MW for the six Colombian basins chosen. Additionally, using the MIT model method, the energy potential of these basins could be around 170 MW. In both methods, the Eastern Llanos basin would provide the highest amount of electrical energy equivalent to 81% of the total. It is important to note that these six basins correspond to 94% of the total volume of co-production waters generated in Colombia.

Table 2: Power potential per basin of co-produced water.

Resource Temperature [°C]	Power Potential (kWe) per bbl/day Co-Produced Water Flow per Basin											
	Eastern Llanos (8 064 379 bbl/day = 14 838 kg/s)		Eastern Cordillera (4 194 bbl/day = 7.7 kg/s)		Caguán–Putumayo (346 652 bbl/day = 638 kg/s)		Catatumbo (23 714 bbl/day = 44 kg/s)		Cesar Ranchería (261 631 bbl/day = 481 kg/s)		Middle Magdalena Valley (1 287 974 bbl/day = 2 370 kg/s)	
	Exergy	MIT Model	Exergy	MIT Model	Exergy	MIT Model	Exergy	MIT Model	Exergy	MIT Model	Exergy	MIT Model
80	231 657	137 601	207	72	9 958	5 915	681	405	7 516	4 464	36 998	21 977
100	438 519	275 231	341	143	18 850	11 831	1 289	809	14 227	8 929	70 037	43 958
120	701 900	460 267	503	239	30 172	19 785	2 064	1 353	22 772	14 932	112 101	73 510
140	1 017 951	693 466	692	360	43 757	29 809	2 993	2 039	33 025	22 498	162 579	110 754
160	1 384 214	975 864	906	507	59 501	41 948	4 070	2 870	44 908	31 660	221 075	155 857
180	1 799 449	1 308 862	1 144	680	77 350	56 262	5 291	3 849	58 379	42 463	287 393	209 040

For Case 1 and Case 2, Figure 4 shows the water outlet temperature versus the vaporization pressure for four different working fluids: R123, R245fa, R134a and Isopentane. The geothermal water outlet temperature corresponds to 72 °C and 78 °C for Case 1 and Case 2, respectively. It is important to appreciate that for the required water outlet temperature, the pressure of the R134a fluid must be higher than 22 bars for Case 1 and 26 bars for Case 2. It can also be observed that the Isopentane and R123 fluids present a similar behavior with vaporization pressure values close to 4 bars for Case 1 and close to 5 bars for Case 2. For the working fluid R245fa, in both cases the vaporization pressure of 8 bars is not exceeded.

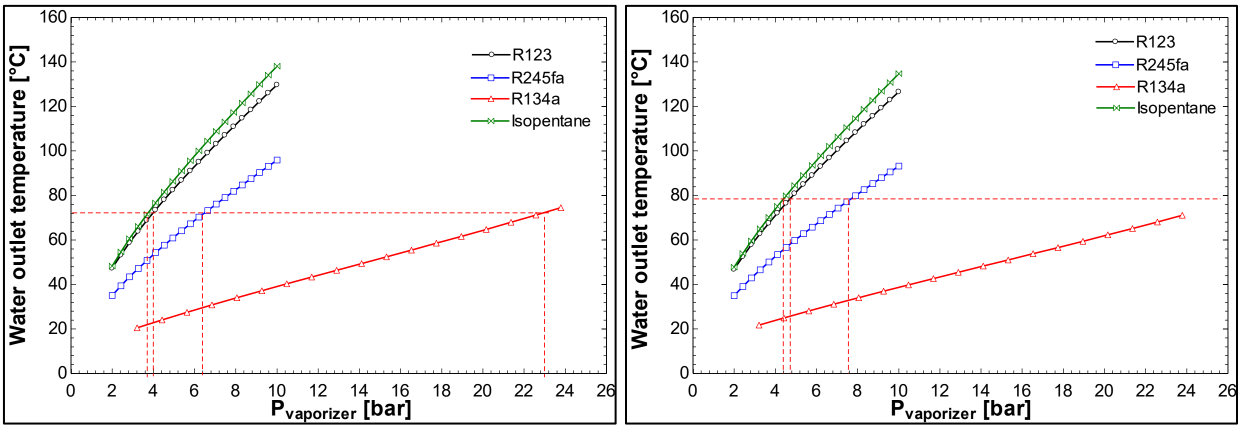

Figure 4: Vaporization pressure for different working fluids based on the water outlet temperature. Left) Case 1 and right) Case 2

In Figure 5, the turbine power outputs are determined for the vaporization pressure values calculated above. The outcomes are 177-200 kW for Case 1 and 315-355 KW for Case 2. In Case 1, the power obtained for R245fa and Isopentane are similar, as for the working fluids R123 and R134a. In Case 2, similar power values are observed for the working fluids R123 and Isopentane with 315 and 320 kW, respectively. In this case, the R245fa fluid has the highest turbine power of about 355 kW. The power of the R134a fluid is around 320 kW approximately.

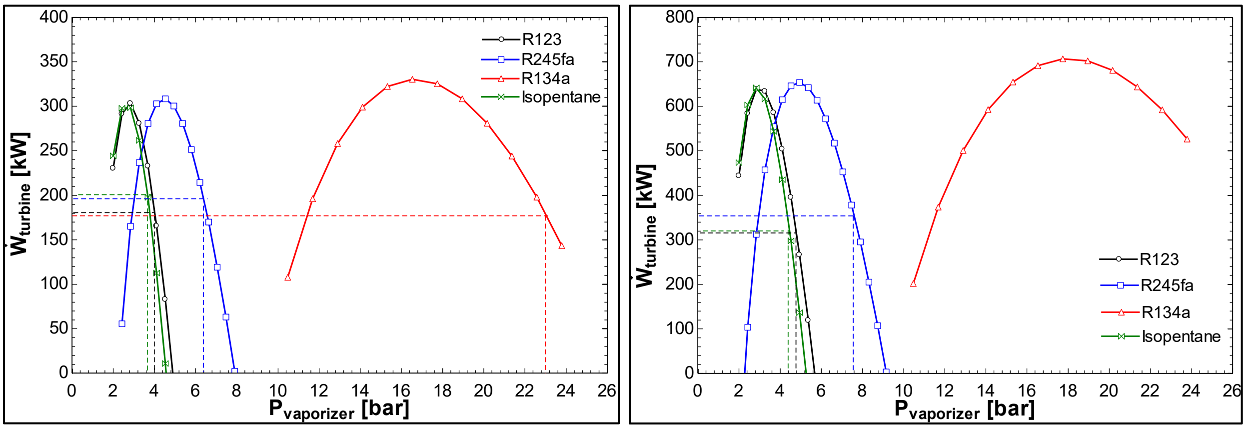

Figure 5: Turbine power as a function of vaporization pressure for different working fluids. Left) Case 1 and right) Case 2

Figure 6 shows the estimation of the working fluid flow as a function of the water outlet temperature. The mass flow values of the R123 and R134a fluids are very similar and around 13.7 kg/s and 22.1 kg/s for Cases 1 and Case 2, respectively. In addition, for Isopentane the fluid rate is about 6.8 kg/s for Case 1 and 10.9 kg/s for Case 2. Finally, Table 3 summarizes the values of vaporization pressure, net turbine power and mass flow for each working fluid.

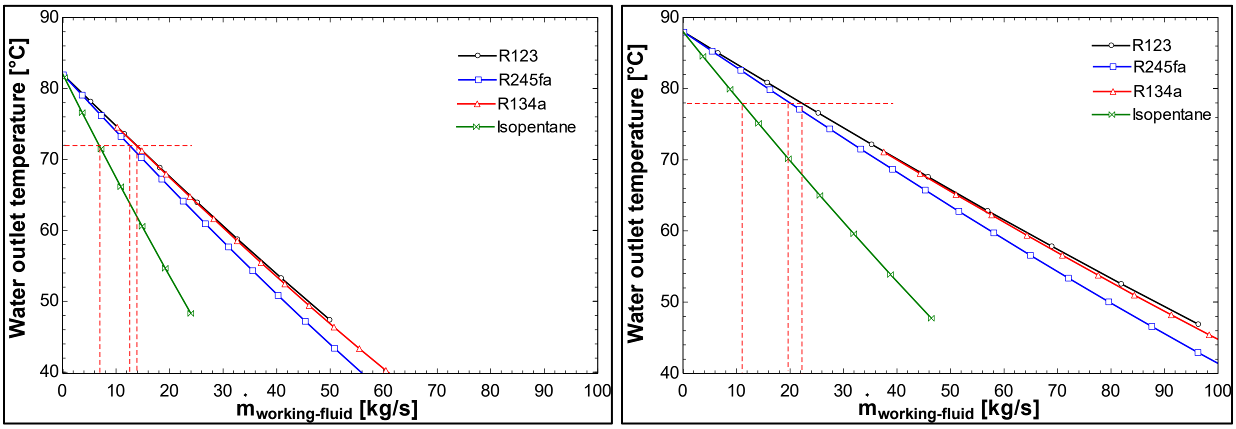

Figure 6: Mass flow for each working fluid as a function of the geothermal water outlet temperature. Left) Case 1 and right) Case 2.

Table 3: Values of vaporization pressure, net turbine work and mass flow for different working fluids.

Working fluid	Case 1*			Case 2**		
	Pvaporizer [bar]	Wturbine [kW]	$\dot{m}$ working fluid [kg/s]	Pvaporizer [bar]	Wturbine [kW]	$\dot{m}$ working fluid [kg/s]
Isopentane	3.7	200	6.8	4.4	320	10.9
R245fa	6.4	195	12.4	7.6	355	20
R123	4	180	13.8	4.8	315	22.1
R134a	23	177	13.7	26-27	-	-

*Case 1: $\dot{m}$=61 kg/s; Water outlet temperature=72°C. **Case 2: $\dot{m}$=99 kg/s; Water outlet temperature=78°C

3.1 Financial Assessment

The financial feasibility assessment for the startup of two ORC power plants of 200 kW and 320 kW is carried out. The aim is to estimate financial parameters such as the net present value (NPV) and the internal rate of return (IRR). This evaluation considers the influence of the domestic financial market of Colombia on the investment and operation costs. The project financial assessment includes estimations of the initial investment (equity and debt), tax incentives, productivity, operation and maintenance costs, cash flows, and profitability.

The cost breakdown is detailed in Table 4, with a total cost estimate of 2942.5 US per kilowatt (US$/kW) and 2625.0 US$/kW for the 200 kW and 320 kW, respectively. The cost estimate, as recommended by Association for the Advancement of Cost Engineering (AACE International), can be classified as Class 4. Class 4 is related to a number of purposes; in this paper, we are looking for the confirmation of technical and economic feasibility (AACE International, 2019).

Table 4: Project cost breakdown for ORC plants of 200 kW and 320 kW.

N	Development Capacity	200 kW	320 kW
1	**Supervision, contracting fee, commissioning**	$45,000.00	$67,500.00
2	**Gathering system, pipelines.**		
	Pipes lines from well to binary unit	$37,500.00	$37,500.00
	Pipes lines from binary unit to reinjection well	$37,500.00	$37,500.00
3	**Civil works**		
	Pad	$6,000.00	$10,000.00
4	**Transmission lines**	$12,500.00	$12,500.00
5	**ORC Plant**		
	2 Units of 125 kW	$450,000.00	
	3 Units of 125 kW		$675,000.00
	Best Estimated Total	**$588,500.00**	**$840,000.00**
	USD/kW	**$2,942.50**	**$2,625.00**

With regards to the domestic market conditions, Colombia has implemented crucial legal and regulatory actions to promote the use of sustainable energy. For instance, the Law 1715 of 2014 and the National Development Plan 2018-2022 of Colombia have established the following four main incentives to grant energy generation from non-conventional energy sources including geothermal (Colombia, 2019a):

- 15 years to deduct 50% of investments from the companies' income tax
- Exemption of the national value added tax of 19% for equipment and services
- Exemption of import duty for equipment not produced locally
- Up to 20% of accelerated depreciation per year for the investment

Related to the price of electricity, the Mining and Energy Planning Unit of Colombia (UPME by its Spanish acronym) projects that the price of electric power generation in Colombia will have an expected growth of 13% for the next 10 years (UPME, 2015). Based on this, the financial assessment is carried out with an electricity price increment of 1.3% per year (Table 5).

Table 5: Financial input parameters for ORC plants of 200 kW and 320 kW.

Plant size	kW	200	320
CAPEX - Investment	US$	588500.00	840000.00
Plant capacity factor	%	93.00	
Electricity generation per year	MWh/year	1629.00	
Equity - Cost of equity - *Ke*	%	7.60	
Equity share	%	53.00	
Debt: Average cost of debt - *Kd*	%	6.00	
Debt share	%	47.00	
Debt maturity period	years	15.00	
Debt grace period	years	2.00	
Corporate tax	%	33.00	
Tax Exemption	years	10.00	
WACC after tax	%	5.60	
Depreciation	years	20.00	
Operation and maintenance	US$/MWh	8.00	
General cost: Insurance, sales	US$/MWh	3.90	
Transmission cost	US$/MWh	0.00	
Resource decline	%	0.00	
Inflation	%	2.00	
Construction period	years	2.00	
Energy price	US$/kWh	0.07	
Energy price increase per year	%	1.30	
Life of the project	years	30.00	

The parameters are explained below:

- **Financial structure:** The capital structure for the ORC plants is assumed to be 53% equity and 47% debt.
- **Interest rate:** The nominal interest rate on the debt is set at 6.0% over 20 years.
- **Taxes, incentives, fees:** Only the corporate tax of 33% was considered for the cash flow calculations, which will be paid to the government after the tenth year. By this time 50% of the investments will have already been deducted from the income tax, according to the incentives offered by the Law 1715 of 2014.
- **Project timeline/financing needs:** The project is set with a 30 years outlook for generating revenue. Additionally, 4 years of construction is assumed. The debt maturity period is 15 years with a grace period of 2 years.
- **Operation and maintenance:** Estimated for the 30 years lifetime of the project.
- **Inflation:** It corresponds to an average annual inflation rate in the United States of around 2% as the financial modelling is carried out in US$.
- **Depreciation:** It relates to the main equipment of the power plant. 20 years are chosen as the benefit of the Law 1715 of 2014 related to the income tax exceeding the 20% of accelerated depreciation per year.
- **Energy revenues:** The energy price and sales are based on the wholesale spot market of Colombia at US$70/MWh when operation starts, with an annual increment of 1.3% (UPME, 2015).
- **Weighted Average Cost of Capital (WACC):** The calculation of *WACC* for the project considered the equity cost *Ke* and the debt cost *Kd*. This is calculated as follows:

$$WACC = We * Ke + Wd * Kd * (1 - Tc)$$

In the above calculation, *We* is the equity share, *Ke* is the cost of equity, *Wd* is the debt share, *Kd* is cost of debt and *Tc* is the corporation tax or law tax that must be paid for the gross income of the project. *Kd* is based on the current interest rates on the financial market of Colombia for this type of project (Central Bank of Colombia, 2019). The calculation of *Ke* is based on the Capital Asset Pricing Model, CAPM, with the following data:

- **Risk free rate**: US Treasury bond rate for 30 years equal to 2.58% (United States Department of the Treasury, 2019).
- **Equity risk premium**: 5.93%.
- **Beta, unlevered beta and other risk measures:** The industry is power with an unlevered beta of 0.3 (Damodaran, 2019).
- **Country risk rate:** For Colombia the country risk premium is equal to 3.0%.
- **Company size premium rate:** A rate of 1.2% is added to *Ke*

The valuation modelling is based on discounted cash flow. The Free Cash Flow (FCF) is used for the financial valuation of the entire project, with *WACC* as the discount rate. For investors, the model uses the Equity Cash Flow (ECF) discounted with the equity cost of capital *Ke*. The financial ratios or indicators included in the model are the Net Present Value (NPV), the Internal Rate of Return (IRR), the Levelized Cost of Energy (LCOE), the Debt Service Coverage Ratio (DSCR) and the Payback.

NPVs for 200 kW and 320 kW generation capacity of ORC plants are shown in Figure 7. The additional financial outcomes are presented in Table 6. The results indicate that both units are profitable with project paybacks of 7 years and 9 years for the 200 kW and 320 kW ORC plants, respectively. The LCOE obtained of 0.047USD/kWh and 0.062USD/kWh contrast significantly with the estimation carried out by Cuadrado et al., (2015) of 0.102 USD/kWh suggesting that the recent tax incentives of the Law 1715 of 2014 are improving the financial conditions to these types of geothermal plants.

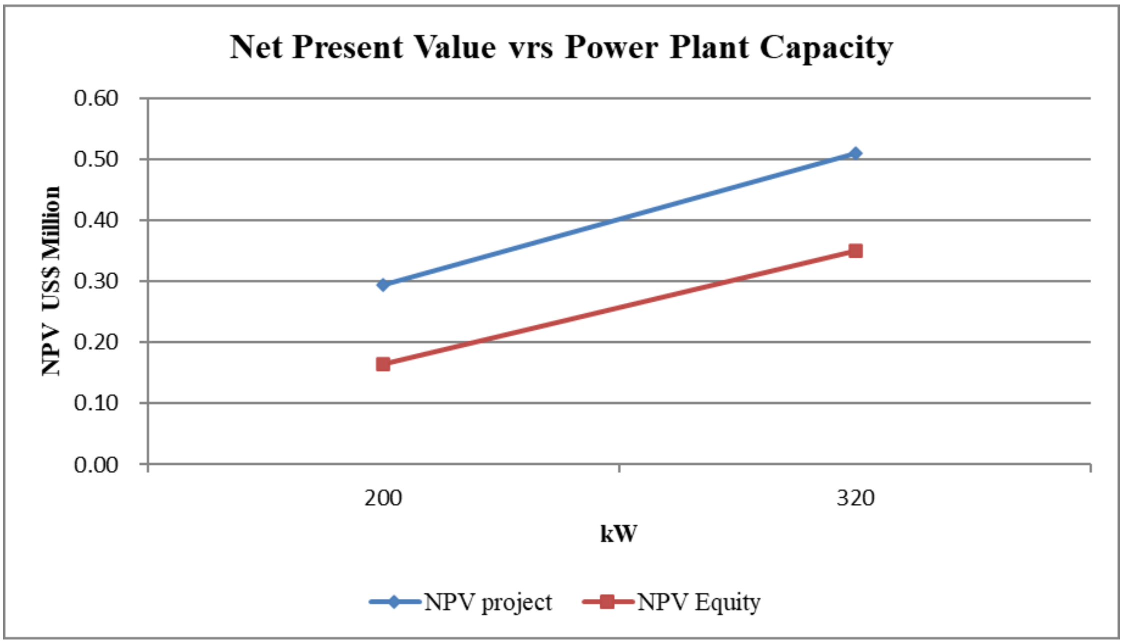

Figure 7: NPV versus generation capacity for ORC plants of 200 kW and 320 kW.

Table 6: Financial results of the Project and the Equity for ORC plants of 200 kW and 320 kW.

Results	**kW**	**200**	**320**
Project IRR	%	12.51	8.65
Equity IRR	%	15.73	10.50
LCOE	US$/kWh	0.047	0.062
DSCR	Average	3.80	2.7
Project Payback	years	7.00	9.00
Equity Payback	years	5.00	8.00

4. CONCLUSIONS

In Colombia, the sedimentary basins of Eastern Llanos, Eastern Cordillera, Caguán-Putumayo, Catatumbo, Cesar Ranchería and Middle Magdalena Valley, have a potential of about 170 MW by using medium-enthalpy geothermal resources. The Eastern Llanos basin would contribute the largest amount with about 81% of this potential.

Using ORC plants for taking advantage of this potential, four different working fluids with lower boiling temperature than water, were analyzed in this study: Isopentane, R123, R134a and R245fa. This was applied to two different oil fields from the Eastern Llanos basin named Case 1 and Case 2.

For case 1, the values of vaporization pressure, turbine power and mass flow of the working fluids range between 3.7-23 bars, 177-200 kW and 6.8-13.8 kg/s, respectively. However, the working fluid R134a is discarded because its vaporization pressure is 23 bar. The working fluid with the best characteristics is Isopentane, with vaporization pressure values of 3.7 bar, turbine power of 200 kW and mass flow of 6.8 kg/s.

For case 2, the values of vaporization pressure, turbine power and mass flow of the working fluids range between 4.4-27 bars, 315-355 kW and 10.9-22.1 kg/s, respectively. For this case, the working fluid R134a is also discarded because its vaporization pressure is approximately 27 bars. Once again, the working fluid with the best characteristics is Isopentane, with vaporization pressure values of 4.4 bars, turbine power of 320 kW and mass flow of 10.9 kg/s.

Additionally, this study included a financial feasibility assessment for the powers obtained for ORC plants using Isopentane as the working fluid. For this aim, the local financial market of Colombia is analyzed. It shows that public policies and the recent growing interest in Colombia for the development of geothermal projects is creating a convenient atmosphere that could facilitate the installation of ORC plants for oil and gas fields from sedimentary basins in this country. The results of the financial assessment indicate the profitability of installing 200 kW and 320 kW in the two case studies located in the Eastern Llanos sedimentary basin. This profitability has improved when compared with studies carried out before the Law 1715 of 2014 was established. However, the financial assessment also suggests a review of tax incentives and regulatory framework to improve the profitability of these projects. For instance, the income tax of Law 1715 of 2014 showed that, in the first 10 out of 15 years, 50% of the investments had already been deducted from the project incomes assuming a depreciation for 20 years. In addition, the use of power purchase agreement (PPA) type contracts is recommended to reduce the risk of energy sales.

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NOMENCLATURE

$\dot{E}$ = exergy, kJ/s

$\dot{m}$ = mass flow rate of co-production resource (water from well), or working fluid (a refrigerant or a hydrocarbon) , kg/s

$H(T)$ = specific enthalpy of fluid at temperature T, kJ/kg

$S(T)$ = specific entropy of fluid at temperature T, kJ/(kg-°C)

T_{in} = plant inlet temperature, °C

T_{out} = plant outlet temperature, °C

$T_{ambient}$ = ambient temperature, °C

$\dot{Q}$ = rate of net heat input to power plant, kWth

η_{th} = thermal efficiency, %

W = net power output from power plant, kWe

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