

ENCIT-2018-0549

ECONOMIC EVALUATION OF EGS IN THE BRAZILIAN ENERGY MARKET: FOCUS ON THE NORTHEASTERN REGION.

Francisco Tarcísio Guedes Lima Verde Neto

Daniel Albiero

Universidade Federal do Ceará, Campus do Pici - Bloco 714 - CEP 60455-760 - Fortaleza - CE

tarcisiolv@gmail.com, daniel.albiero@gmail.com

Abstract. *The purpose of this paper is to evaluate the economic viability of establishing an Enhanced Geothermal System in the Brazilian Northeast Region. The paper consists on a comparison between the LCOE (Levelized Cost of Energy) between different energy sources such as coal, nuclear, biomass and geothermal energy in the form of EGS (Enhanced Geothermal System). At first, some concepts vital to the comprehension of EGS are presented, such as the concepts of Geothermal Resource Base and the Recoverable Resource Base. Thus, there are some estimates obtained from public data from the Brazilian EPE (Empresa de Pesquisa Energética) and the US Department of Energy are used, as long as geological data from several sites along the Northeast Region of Brazil. A comparison is made, placing geothermal energy amongst the energy sources across Brazil. A cost analysis is made and an objective criteria is stated to highlight potential sites to place a Geothermal Power Plant. The main conclusions are that the Geothermal Energy can be a competitive source of energy in Brazil, especially if considered that this source is renewable and not dependent of climate conditions. The scenario of the Northeast Region and the EGS technological similarities with the Oil and Gas production industry are analyzed, stating a possible technology exchange and opportunity.*

Keywords: *Geothermal, Renewable, Energy, Economic Evaluation.*

1. INTRODUCTION

Renewable energy technologies are alternatives to the use of fossil fuels, and they are considered highly responsive to overall energy policy guidelines and environmental and social goals such as diversifying energy carriers and improving access to more clean energy, as long as reducing pollution and dependence of fossil fuels and imported fuels (Turkenburg et al., 2000). Among these alternatives, there is the use of geothermal energy, an abundant source that originates from the high temperatures lying beneath Earth's Crust. There is a challenge associated to using geothermal energy: the conversion of heat from high subsurface temperatures in electrical energy. The most direct way of obtaining this conversion is through the vapor provided from high temperature energy sources, such as geysers. However, its occurrence around the world is small, thus excluding it as an alternative for large-scale production. That said, some alternatives as EGS (Enhanced Geothermal Systems) arise. It consists on injecting fluids at low temperature, making the same flow through high temperature regions on the Earth's Crust. This fluid is produced in another point, and used as a source of heat for the most diverse applications, such as binary cycles for Energy Production. The U.S. Department of Energy has broadly defined Enhanced (or engineered) Geothermal Systems (EGS) as engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources (Tester et al., 2006). A schematic of an EGS is shown in Fig. (1).

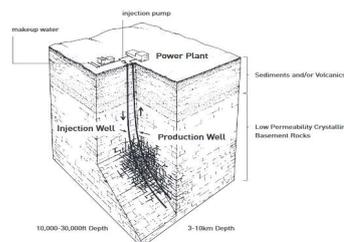


Figure 1 - Schematic of a conceptual two-well Enhanced Geothermal System in hot rock in a Low-permeability crystalline basement formation. (Tester et al., 2006).

For the full comprehension of this work, some definitions are necessary, such as Geothermal Resource Base and the fraction of it that's recoverable, the Recoverable Geothermal Resource. The definition of Geothermal Resource Base can be found at Eq. (1) (Vieira et al, 2015):

$$Q_{RB(i)} = \rho_i c_{pi} A_i d_i (T_i - T_o) \quad (1)$$

Where:

- $Q_{RB(i)}$ is the geothermal resource base of a defined layer (i) of the subsurface.
- ρ_i is the specific mass of layer i.
- c_{pi} is the specific heat capacity of layer i.
- A_i is the section area of layer i.
- d_i is the thickness of layer i.
- T_i is the mean temperature of layer i.
- T_o is the surface temperature.

That is all the heat capacity that can be found on a defined layer of subsurface.

Through algebraic work and some different definitions, we can relate the Recoverable Geothermal Resource as the fraction of the Heat that is associated with fluids, as we can see on Eq. (2) (Vieira et al, 2015):

$$Q = [\phi C_f + (1 - \phi) C_r] (T_r - T_o) Ah \quad (2)$$

- Q is the geothermal resource base.
- ϕ is the mean porosity.
- C_f is the heat capacity of fluids.
- C_r is the heat capacity of rock.
- T_r is the temperature.
- T_o is the surface temperature.
- A is the resource area.
- h is the resource thickness.

That said, we can use some definitions as the geothermal gradient, on Eq. (3) (Vieira et al, 2015):

$$(T_r - T_o) = gz \quad (3)$$

Where:

- T_r is the temperature.
- T_o is the surface temperature.
- g is the geothermal gradient.
- z is the depth.

To complete the geothermal characterization of the resource, we have to assess the specific heat flow, i.e. the amount of heat energy that flows through a specific area of the resource.

Made the definitions, we need, in order to assess the economic viability of an EGS project, to compare it with other energy sources, such as wind, solar, fossil fuels, nuclear and biomass. The comparison will take place by comparing the Levelized Cost of Energy (LCOE) for many different Energy Sources. The definition of LCOE (Tolmasquim, 2016) is the sum of all the costs to implement and operate a powerplant divided by the generated power, considering time effects like the lifespan and others. We can see the formulation for LCOE on Eq. (4):

$$\frac{\sum_i^n (I_i + O\&M_i + F_i + D_i) * (1 + tx)^t}{\sum_i^n (E_i) * (1 + tx)^{-t}} \quad (4)$$

Where:

- I is the investment.
- $O\&M$ is operation and maintenance cost.
- F is the fuel cost.
- D is the decommissioning cost.

- E is the energy produced.
- tx is the discount rate.
- i represents a year.
- n is the lifespan of the project.

2. METHODOLOGY

The analysis consists on a comparison between LCOE (Levelized Cost of Energy) for many different Energy Sources. The data for Enhanced Geothermal Systems is obtained from GETEM (Geothermal Electric Technology Evaluation Model), a free software available on (DOE, 2016), and it consists on stating 3 basic information: Resource Temperature, Resource Depth and the Method of Extraction (Hydrothermal or EGS). GETEM comes with a description: “This model estimates the Levelized-Cost-of-Electricity (LCOE) for a User defined geothermal resource type, temperature and depth. With this information, GETEM estimates a generation cost using a set of default inputs that are based upon several resource scenarios that the DOE Geothermal Technologies Office (GTO) has defined and evaluated. The costs, performance and LCOE based on those default input are displayed in the model as the 'Default Scenario'. A GETEM User can develop an alternative scenario by revising selected default inputs (up to ~109 total) for the power plant, well field, exploration, confirmation, operation and maintenance, geothermal pumping, reservoir performance, and economic parameters used. The model displays the values used in the default scenario. Those values can be retained for the scenario evaluation, or can be revised. As inputs are revised, the LCOE for the revised scenario (shown at top of page) will change.” (DOE, 2016).

Figure (2) show the main screen of GETEM used on this work, as seen on the sheet “Start Here”:

The screenshot displays the GETEM software interface. At the top, it shows 'Revised Scenario' with a value of 10,01 ¢/kWh and 30.000 kW, and 'GETEM Default' with a value of 10,01 ¢/kWh and 30.000 kW. Below this is a yellow warning box: 'The cells with the yellow background are input cells. Some have dropdown lists - select from that list, or leave blank to use the default value. The units have dropdown lists as well. If units are changed, the default values should change to be displayed in the units selected.' The main input area includes: 'Do you wish to evaluate a Hydrothermal or EGS resource?' with a dropdown set to 'Hydrothermal'; 'What is the resource temperature?' with a dropdown set to '175' and unit 'C'; 'What is the resource depth?' with a dropdown set to '1.500,0' and unit 'meter'. Below these is a section for 'Type of Conversion System to Be Used' with a dropdown set to 'Binary'. A red button labeled 'DONE - Resource Definition' is visible. To the right, there are explanatory text blocks: 'GETEM determines the input used for the Default scenario based upon the resource type selected, and the resource temperature and depth that are specified. The LCOE for the GETEM default scenario is based on these 3 inputs' and 'The default conversion system is based on the resource temperature provided. If you elect to change the conversion system, the type selected will be used for both the Default and the Revised Scenarios - if blank the default will be used. Recommended that Binary not be used above 200C and Flash not below 150C'. At the bottom, a note states: 'If GETEM defaults to Binary, or if a Binary conversion system is selected - run the optimize macro for default scenario by clicking on button to the right. This must be done to obtain a LCOE estimate. The macro does not come to the same solution for the default and revised scenarios. As a consequence the plant costs, total flow, number of wells, pumping power, and well field costs will vary slightly when the default inputs are used for the revised scenario. One can go to sheet Binary A1, and enter the same level of performance for both scenarios and the costs, flows, and well count will be the same.'

Figure 2. Main Screen of GETEM (DOE, 2016)

The geothermal data source is found on (Carneiro et al, 2017), and we took basic statistical characterization (mean, minimum and maximum), to infer the influence of resource depth and geothermal gradient on LCOE.

Table 1. Geological Data for 89 sites Across the Northeastern Region (Carneiro et al, 2017)

Geological data for 89 sites Across the Northeastern Region	Geothermal Gradient (°C/km)
Minimum	7,0
Mean	31,3
Maximum	123,0

Therefore, data for Geothermal Gradient will be used in 11 different values, varying from 20 °C/km to 110 °C/km, on 3 different depths, going from 1500 m to 3000 m, considering soil temperature as 25 °C. The inputs on GETEM are shown on Tab. 2.

Table 2. Temperature Inputs on GETEM for the Gradient x Depth Analysis.

Geothermal Gradient (°C/km)	Depth (m)		
	1500	2000	2500
20	55	65	75
30	70	85	100
40	85	105	125
50	100	125	150
60	115	145	175
70	130	165	200
80	145	185	225
90	160	205	250
100	175	225	275
110	190	245	300
120	205	265	325

Additionally, we put on comparison eight sites that are eminent by its high geothermal gradient, as shown in Tab. 3, and put on comparison for different depths, going from 1000m to 3000m:

Table 3. Geological Data for Eminent Locations across the Northeastern Region (Carneiro et al, 2017)

Site	State	Geothermal Gradient (°C/km)	Specific Heat Flow (mW/m ²)
ANT. NAVARRO	PB	65,0	195
CAMINDE	CE	76,2	229
PARAMOTI	CE	79,1	237
QUIXADA	CE	82,7	248
CRATEUS	CE	86,2	259
FORTALEZA	CE	99,8	299
CARIDADE	CE	99,9	300
BRE. M. DEUS	PE	123,0	370

The inputs on GETEM are shown on Tab. 4:

Table 4. Temperature Inputs on GETEM for Depth Analysis for specific sites.

Site	Depth (m)				
	1000	1500	2000	2500	3000
ANT. NAVARRO	90,0	122,5	155,0	187,5	220,0
CAMINDE	101,2	139,3	177,4	215,5	253,6
PARAMOTI	104,1	143,7	183,2	222,8	262,3
QUIXADA	107,7	149,1	190,4	231,8	273,1
CRATEUS	111,2	154,3	197,4	240,5	283,6
FORTALEZA	124,8	174,7	224,6	274,5	324,4
CARIADA	124,9	174,9	224,8	274,8	324,7
BRE. M. DEUS	148,0	209,5	271,0	332,5	394,0*

(*) The geothermal gradient approach for this site would reach a temperature greater than the critical temperature for the water (374,15°C), so we did not have this data on calculations.

Figure (3) shows isogradient lines for the eastern part of the Brazilian Northeast Region, that are useful to represent geographically the data seen in this paper.

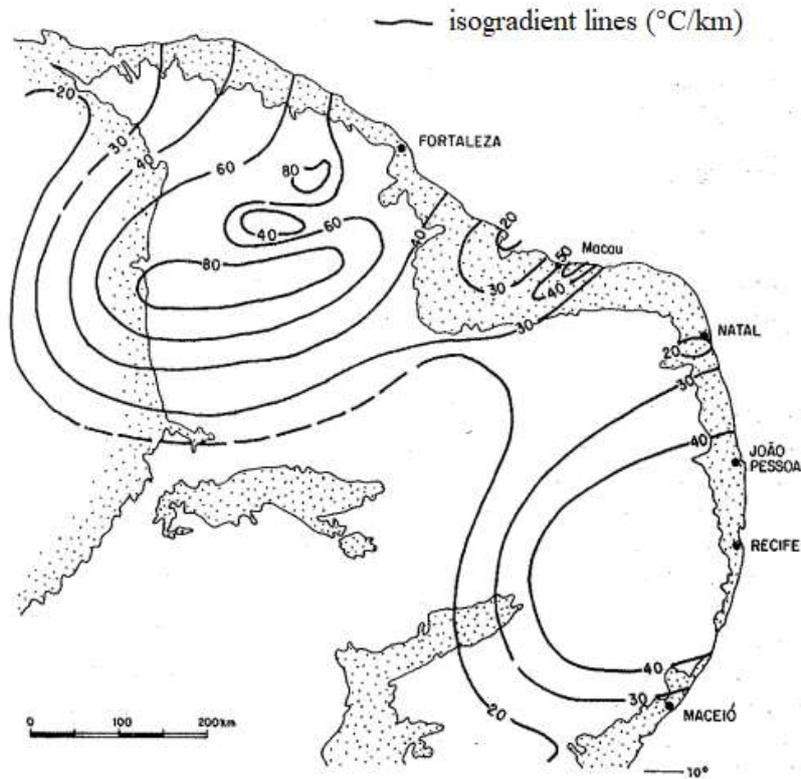


Figure 3 – Geothermal Gradient Map of Northeast Brazil (Adapted from Carneiro et al, 2017)

The data from Brazilian Energy Sources is found on (Tolmasquim, 2016), in two studies for the EPE (Empresa de Pesquisa Energética) that consolidates data for thermoelectric energy and renewable energy across Brazil. Gathering information across the studies, we have the data shown on Tab. 5:

Table 5. Levelized Cost of Energy for different Energy Sources. (Tolmasquim, 2016)

Source	Levelized Cost of Energy (US\$/MWh)
Biomass	11-75
Coal	82,8-111,3
Heliothermal	200-356
Hydroelectric	40-103
Nuclear	69,6-110,8
Photovoltaic	71-103
Tides	214-270
Waves	340-425
Wind	27-50 ¹

(1) Converted from R\$

3. RESULTS

In the first analysis, we went through the inputs established on Tab.2, with the combinations of GETEM simulations, selecting only the binary power plant option, despite the technical recommendation that for temperatures above 200°C, the best option would be flash power plants. The results are shown on Tab. 6, and plotted on Figure (4).

This technical recommendation is due to the mechanism of Binary Power Plants, mainly dependant on the water phase diagram to operate. In higher temperatures, water would emerge to surface with high enthalpy and there would be a great amount of energy to be extracted from steam, and Flash Power Plants would make more sense than Binary Power Plants.

Table 6. Results for GETEM simulations on data from Tab. 2, taking Binary Cycle as default.

Geothermal Gradient (°C/km)	Depth (m)		
	1500	2000	2500
20	27132,2	3587,9	2258,6
30	2258,3	1219,6	787,4
40	1055,8	581,6	391,4
50	590,1	339,7	252,7
60	369,2	233,5	186,4
70	267,7	188,9	149,2
80	202,9	148,5	120
90	171,3	123,3	112,1
100	140,4	104,6	112,6
110	123,2	98,9	136,7
120	107,2	96,8	173,2

In possession of this data, we can see that, for some values (Geothermal gradient greater than 100°C/km), the LCOE begins to grow as we gain specific gradient. This phenomenon can be explained because of the efficiency parameters of the binary cycle, and are coherent to the technical recommendation of GETEM, if we take into account that for Geothermal Gradients above 90 on Tab. 2, Resource Temperatures would be above 200 °C.

Figure (4) shows the influence of Geothermal Gradient on the LCOE, for different established depths of the resource. This information is especially useful because, when searching for opportunities to start a geothermal power plant, one can establish an objective criteria to start exploratory research based on this criteria. As shown on Figure (4) and Table (1), if we analyze only the mean geothermal gradient for the northeastern region of Brazil, we would find prohibitive LCOE data comparing to Tab. 5, discouraging any investment or research. However, if we take as a criteria the Geothermal Gradient as greater than 60°C/km, as per the sites chosen in Tab. 4, we find that Geothermal energy can start getting on the same order of magnitude of other renewable energy sources around Brazil. Data for lower Geothermal Gradient and lower depth were omitted because it wouldn't reason on any evaluation.

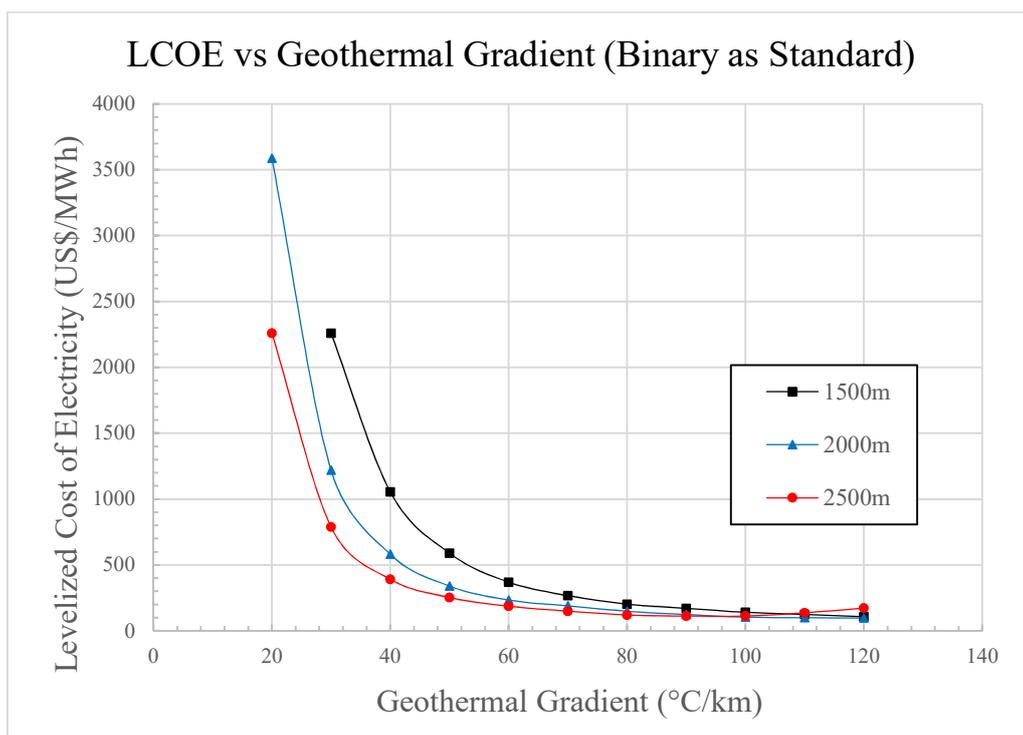


Figure 4 . LCOE variation according to Geothermal Gradient for Binary Power Plants.

On a second moment, we took GETEM simulations using GETEM standards, i.e., taking binary power plants for resources below 200 °C and flash power plants for resources with temperatures greater than 200 °C. Results are shown on Tab. 7, and plotted on Figure (5). As we can observe, the decrease on LCOE has a change of behavior especially when the conversion technology changes, indicating a difference between the costs of operating a Flash Power Plant and a Binary Power Plant. We can also observe that, for some cases (2500 m – Gradient greater than 80°C/km), LCOE values are lower for Binary Power Plants than they are for Flash Power Plants.

It is important to notice that GETEM is a tool for a preliminary study, and the technical matter of the recommendation of using Flash Power Plants instead of Binary Power Plants resides on the phase diagram of the brine, and other factors. This study is mainly focused on finding EGS energy as an alternative to other energy sources, so this difference, despite noticeable, does not influence the main conclusions of this study.

Table 7. Results for GETEM simulations on data from Tab. 2, taking software's default.

Geothermal Gradient (°C/km)	Depth (m)		
	1500	2000	2500
20	27132,2	3587,9	2258,6
30	2258,3	1219,6	787,4
40	1055,8	581,6	391,4
50	590,1	339,7	252,7
60	369,2	233,5	186,4
70	267,7	188,9	149,2
80	202,9	148,5	144,4
90	171,3	123,3	118,2
100	140,4	104,6	103,3
110	123,2	98,9	92
120	107,2	96,6	82,6

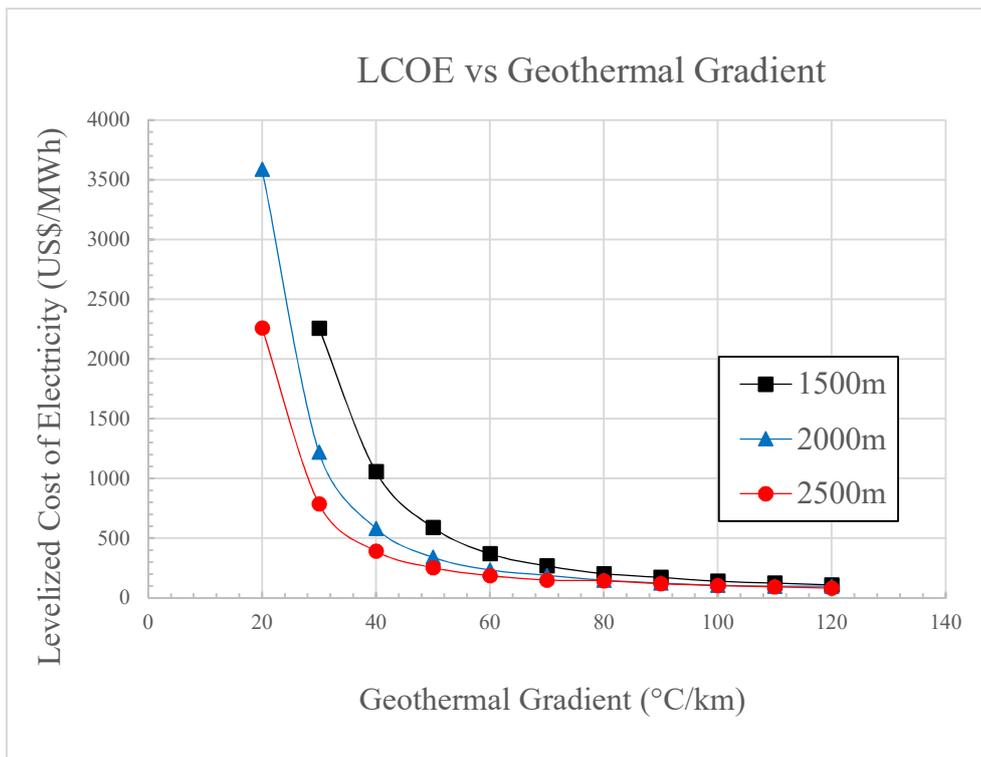


Figure 5. LCOE variation according to Geothermal Gradient.

Now, in possession of this data, we can take into consideration the examples of Tab. 4, as they are the ones who meet the criteria of Geothermal Gradient greater than 60 °C. Taking it into account, we can have the results seen on Tab. 8 and Figure (6).

It is important to clarify that the definition of the criteria 60°C/km. If we look at Figure (5) and data on Tab. 7 and Tab. 5 we see that for every depth simulated, the Geothermal Gradients greater than 60°C/ km provide LCOE lower than sources that are operating on Brazil today. So, it is reasonable to assume that this “breaking point” can be established as the opportunity point to start, for example, an exploratory campaign to find a geothermal resource.

Table 8. Results for GETEM simulations on data from Tab. 4, taking software’s default.

LCOE (US\$/MWh)								
Depth (m)	ANT. NAVARRO	CAMINDE	PARAMOTI	QUIXADA	CRATEUS	FORTALEZA	CARIDADE	BRE. M. DEUS
1000	736,3	488,2	445,0	392,8	354,5	255,8	255,3	169,6
1500	310,0	230,8	206,4	192,5	181,5	150,0	149,8	129,2
2000	207,9	158,6	150,9	141,7	132,6	127,8	127,6	93,6
2500	167,6	155,4	146,7	137,7	130,1	103,6	103,4	79,9
3000	171,0	131,4	125,2	118,1	112,1	92,9	92,8	

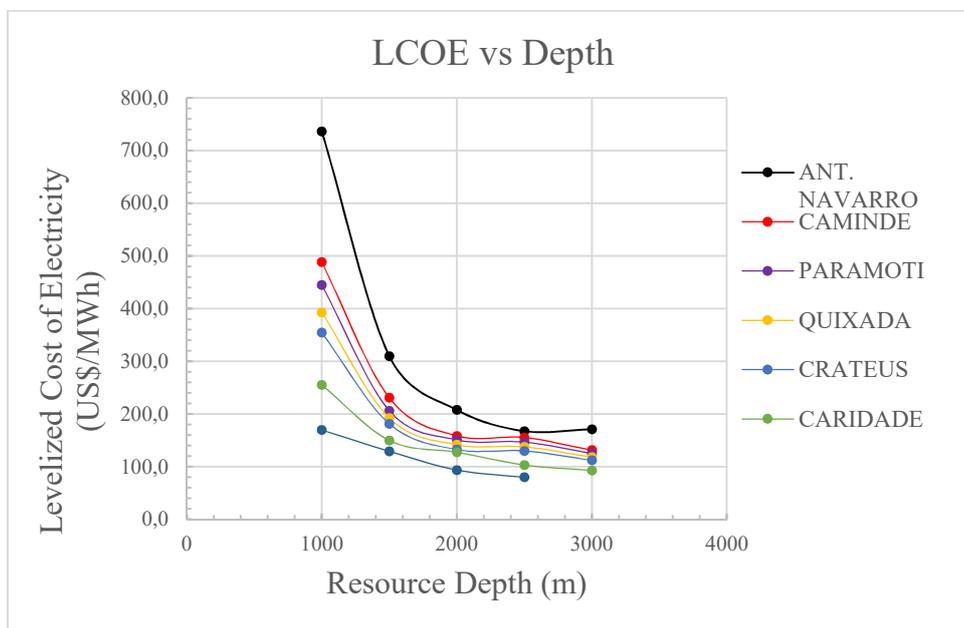


Figure 6. LCOE variation for different sites.

Finally, in possession of this data, we can assess the comparison of LCOE between geothermal energy and other energy sources. This comparison can be seen on Figure (7).

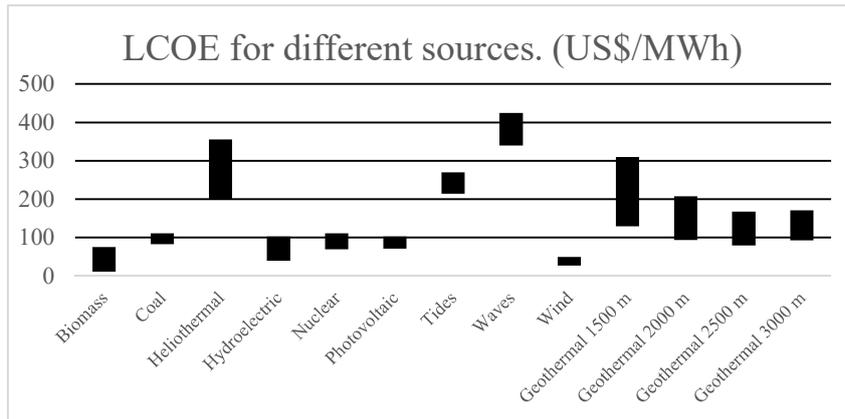


Figure 7. LCOE for different energy sources.

The data of levelized cost of energy for different sources, if displayed this way, makes it possible to compare the economic viability of energy. However, the Levelized Cost of Energy should not be the only criteria because it doesn't capture all the benefits and costs originated from the use of each technology (Tolmasquim, 2016). This is illustrated in Tab. 5 (adapted from Long, 2009), where we can see a qualitative analysis of different renewable energy methods and its main characteristics, that can be used to support a more strategic analysis, if regarded State and R&D issues.

Table 5 – Qualitative comparison between renewable energy sources.

Energy Source	Capacity Factor (%)	Reliability	Environmental Impact	Main Use
Geothermal	86 - 95	Reliable and Continuous	Minimum Use of Soil	Electrical Energy
Biomass	83	Reliable	Use of Fertile Lands	Transportation, Heat, Electrical Energy
Hydroelectric	30-35	Weather Related	Dam Construction	Electrical Energy
Wind	25-40	Weather Related	Large Occupation	Electrical Energy
Solar	24-33	Weather Related	Large Occupation	Electrical Energy

Adapted from (Long, 2009).

Also, it is very important to clarify that, if we look through GETEM other sheets, we can see a better description of costs, like seen on Figure (8). This image shows that, for Enhanced Geothermal Systems, Well Field Capital and Exploratory costs are nearly one third of all costs impacting on LCOE. This data is extremely important because, if we consult ANP website, we can see the overall production for every oil and gas well onshore on the Northeast Region, and there are approximately 3800 wells that did not produce neither oil nor gas, from a total of about 10500 wells (ANP, 2018). That being said, we can state that a great opportunity of exchange is eminent between the oil and gas industry and an eventual Geothermal Energy Power Plant, using the EGS technology, which implies heavily on Well Construction costs and technology.

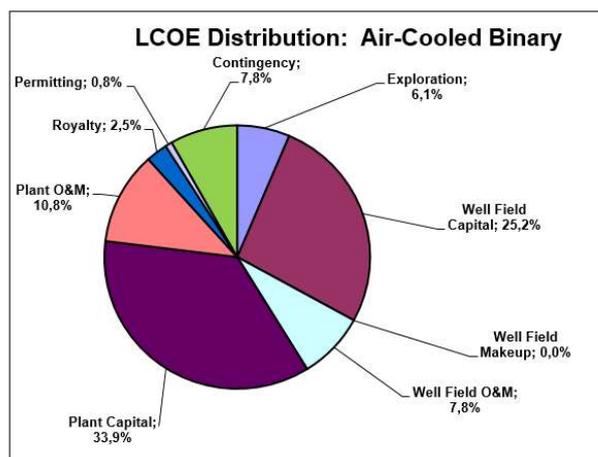


Figure 8 – LCOE composition on GETEM – CARIDADE1500m scenario (DOE, 2016)

4. CONCLUSIONS

As we look into the data we analyzed, we can conclude that Geothermal Energy, in the form of Enhanced Geothermal Systems (EGS), is a competitive energy source, if compared to other sources, especially if taken into account other factors aside the strictly economic. Geothermal Energy is a renewable, reliable and with minimum use of soil, characteristics that make it a strategic opportunity for the Northeastern Region.

Also, when we look at the geological characteristics and the economic opportunities stated on this article, we can see very clearly that there is a large area, especially on the State of Ceará, with a Geothermal Gradient greater than 60°C/km, a criteria defined on this article as an opportunity definer to consider the possibility of developing Geothermal Energy fields, applying EGS technology.

Finally, when confronting the fact that there are a great number of oil and gas wells, an opportunity emerges to assess, in future work, the possibility of a technology exchange and perhaps a great economy of resources, making the EGS technology even more competitive as an opportunity for the Brazilian Energy Matrix.

5. REFERENCES

- ANP, 2018. *Dados Estatísticos*. Brazilian Petroleum National Agency 22 Ago. 2018. <<http://www.anp.gov.br/dados-estatisticos>>.
- Carneiro, C. D. R., Hamza, V. M., & de Almeida, F. F. M., 2017. “Ativação Tectônica, Fluxo Geotérmico e Sismicidade no Nordeste Oriental Brasileiro”. *Revista Brasileira de Geociências*, Brazil.
- DOE, 2016. *Geothermal Electricity Technology Evaluation Model*. US Department of Energy. 15 Apr. 2018 <<https://www.energy.gov/eere/geothermal/geothermal-electricity-technology-evaluation-model>>.
- Long, A. (2009). “Improving the economics of geothermal development through an oil and gas industry approach”. 11 Dec. 2017 <http://www.slb.com/media/services/consulting/business/thermal_dev.pdf>.
- Tester, J. W. et al., 2006. “The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century.” Massachusetts Institute of Technology, v. 209.
- Tolmasquim, M. T., 2016. “Energia Renovável: hidráulica, biomassa, eólica, solar, oceânica.” EPE: Rio de Janeiro, Brazil.
- Tolmasquim, M. T., 2016. “Energia Termelétrica: Gás Natural, Biomassa, Carvão, Nuclear.” EPE: Rio de Janeiro, Brazil.
- Turkenburg, W. C., Beurskens, J., Faaij, A., Fraenkel, P., Fridleifsson, I., Lysen, E., ... & Sinke, W. C., 2000. “Renewable energy technologies. World energy assessment: Energy and the challenge of sustainability”, 219-272.
- Vieira, F. P., Guimarães, S. N., & Hamza, V. M., 2015. Updated assessment of geothermal resources in Brazil. In Proceedings, World Geothermal Congress, Melbourne, Australia.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.