Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Special Issue: Energy in Agriculture

Scientific Paper

Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43nepe20220160/2023

GEOTHERMAL ENERGY: AN ALTERNATIVE TO THE WATER–ENERGY DILEMMA IN NORTHEASTERN BRAZIL

Francisco T. G. Lima Verde Neto[1], Paulo A. C. Rocha[1], Jenyffer da S. G. Santos[2], Angel P. Garcia[2], Daniel Albiero[2*]

[2*]Corresponding author. Universidade Estadual de Campinas (UNICAMP)/Campinas - SP, Brasil.
E-mail: daniel.albiero@gmail.com | ORCID ID: https://orcid.org/0000-0001-6877-8618

KEYWORDS

renewable energies, water–energy nexus, levelized cost, engineered geothermal systems, desalination.

ABSTRACT

This paper proposes geothermal energy as an alternative solution to the water–energy dilemma in the northeastern region of Brazil (NEB). The main application of this study was to provide a theoretical basis to support a different approach to policies minimizing water scarcity and ensuring sustainability. The analysis developed in this study compares the levelized cost of electricity (LCOE) for many different energy sources. The novelty of this study is the use of geothermal energy in the context of the Brazilian Northeast, focusing on water desalination processes, which are expensive in terms of energy. Therefore, this study is highly important because it offers the potential of addressing the energy/economic barrier related to water desalination in environments with economically viable geothermal energy. This is the case in Northeast Brazil with potential for reuse of abandoned oil wells. In the form of enhanced geothermal systems (EGS), geothermal energy is a competitive energy source compared to other sources in the Brazilian Energy Matrix, especially when considering factors in addition to the economic benefits. In the form of EGS, geothermal energy is a suitable option for addressing water scarcity in the northeast region in a sustainable and low-emission manner. This is a strategic opportunity for NEB in the context of energy production and freshwater production through desalination.

INTRODUCTION

Approximately 27 million people live in the semiarid region of Brazil, most of whom live in the Northeastern Region of Brazil (NEB) (Cavalcante Júnior et al., 2019). Droughts are one of the main contributing factors to the social and economic problems and structural deficiencies of the region. Water scarcity and low rainfall in the NEB are substantial issues. This is predominantly because most of the groundwater in the region is saline, with desalination being a potential solution to the problem (Silva et al., 2018).

Most of the energy used in desalination processes is derived from fossil fuels, which are becoming increasingly depleted and emit carbon dioxide. Incorporating renewable energy sources into the desalination process can increase the sustainability of desalination (Manju & Sagar, 2017). This represents a decisive factor in terms of the lack of economic viability of current water desalination technologies because energy consumption is relatively high and unsustainable.

Renewable energy technologies are a sustainable alternative to fossil fuels. The development of these technologies has been highly responsive to general energy policy guidelines and environmental and social goals, such as diversifying energy carriers, improving access to clean energy, and reducing pollution and dependence on fossil and imported fuels (Turkenburg, 2000; Vogt et al., 2021).

Among these alternatives, enhanced geothermal systems (EGS) involve injecting fluids at low temperatures, which results in the same flow through high-temperature

[1] Universidade Federal do Ceará (UFC)/Fortaleza - CE, Brasil.
[2] Universidade Estadual de Campinas (UNICAMP)/Campinas - SP, Brasil.

Area Editor: Henrique Vieira de Mendonça
Received in: 4-18-2022
Accepted in: 12-22-2022

regions of the Earth's crust. This fluid is also produced at another point and used as a heat source for diverse applications, such as binary cycles for energy production. EGS have been developed on at least 18 sites in countries, including Australia, Germany, the USA, China, and the Philippines. Research efforts in different regions have generally focused on government efforts to develop this technology, with an expectation of supplying approximately 70 GWe of power by 2050 (Lu, 2018). Cost-effective desalination can be achieved on resources at 90 °C temperatures and can be improved if technological developments are made (Loutatidou & Arafat, 2015).

Abandoned oil and gas wells can be used to implement a desalination system that uses abandoned wells as a heat source to desalinate seawater (Noorollahi et al., 2017). Ali et al. (2018) noted that geothermal resources can be used for different desalination processes because geothermal resources are an uninterrupted source of thermal energy. In some places, geothermal water can be cost-effective, costing as low as 1 Euro/m³ (Tomaszewska et al., 2018), including in regions with water scarcity, such as the Gulf Coast, Sub Saharan, and Middle East, and North Africa (where the cost reaches 1.61–2.0 US$ /m³). It can represent a solution for providing freshwater with low emissions and a competitive cost, and it is cheaper than methods that use PV cells (Chandrasekharam et al., 2018).

Therefore, the purpose of this study was to analyze geothermal energy as a suitable option for NEB. The main contribution of this study was to examine the potential of using abandoned oil wells as geothermal energy generators to enhance water desalination systems in northeastern Brazil. The energy and economic viability of this proposal was also demonstrated.

MATERIAL AND METHODS

The analysis developed in this study was used to compare the levelized cost of electricity (LCOE) for many different energy sources. The data for EGS were obtained from the Geothermal Electric Technology Evaluation Model (GETEM) free software (DOE, 2018). It consists of three main information categories, namely, the resource temperature, resource depth, and the method of extraction (Hydrothermal or EGS).

This model can be used to estimate the leveled cost of electricity (LCOE) for a user-defined geothermal resource type, temperature, and depth. With this information, the GETEM is used to estimate the generation cost using a set of default inputs based on several resource scenarios defined and evaluated by the DOE Geothermal Technologies Office (GTO). The costs, performance, and LCOE based on these default inputs are displayed in the model as default scenarios.

A GETEM user can develop an alternative scenario by revising the 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 then displays the values used in the default scenario. These values can be retained for scenario evaluation or can be revised. As the inputs are revised, the LCOE for the revised scenario (shown at the top of the page) will change. Figure 1 shows the main screen of the GETEM used in this work, as seen on the sheet "Start Here":

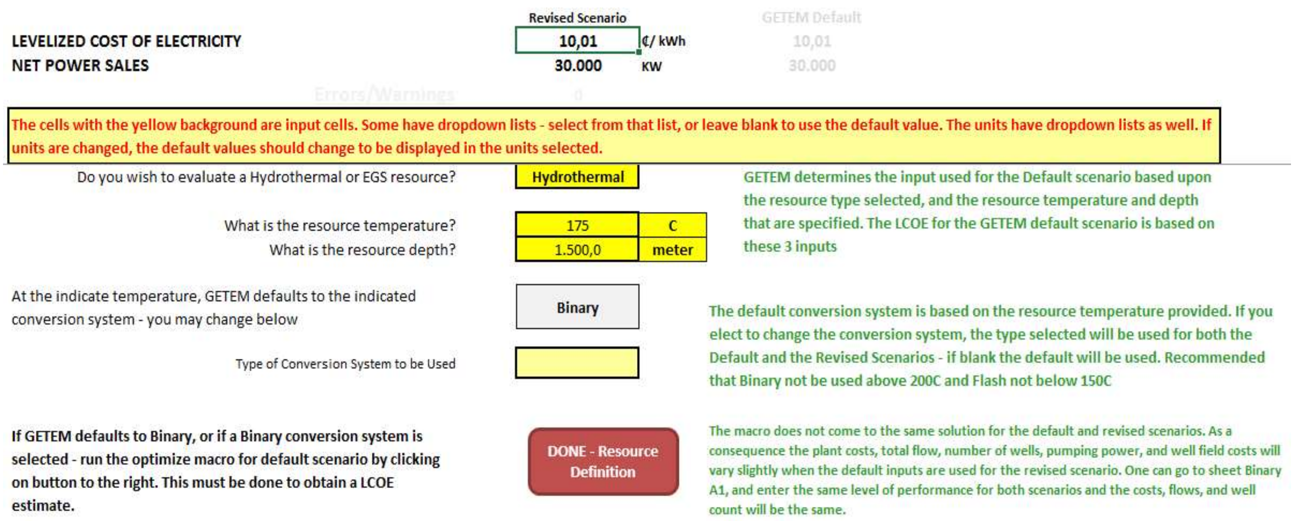

FIGURE 1. Main screen of GETEM.

The geothermal data was sourced from Carneiro et al. (2017), and we performed essential statistical characterization, namely, the mean, minimum, and maximum, as shown in Table 1, to infer the influence of resource depth and geothermal gradient on the 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 the geothermal gradient were used for 11 different values, varying from 20 °C/km to 110 °C/km at three different depths from 1500 to 3000 m, assuming a soil temperature of 25 °C. The inputs for the GETEM are listed in Table 2.

TABLE 2. Temperature inputs on GETEM for the Gradient x Depth Analysis.

	Depth (m)		
Geothermal Gradient (°C/km)	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

We compared eight sites that are well known for their high geothermal gradients, as shown in Table 3, and they were then compared at different depths from 1000 to 3000 m.

TABLE 3. Geological data for well-known locations across the northeastern Region (Carneiro et al., 2017).

Site	State	Geothermal Gradient (°C/km)	Specific Heat Flow (mW/m²)
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 in Table 4:

TABLE 4. Temperature inputs on GETEM for depth analysis for specific sites.

	Depth (m)				
Site	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
CARIADE	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 likely reach a temperature greater than the critical temperature for the water (374, 15 °C). Therefore, we excluded this data from the calculations.

RESULTS AND DISCUSSION

We initially worked through the inputs established in Table 2 with the combinations of GETEM simulations, only selecting the binary power plant option. This was despite the technical recommendation that for temperatures above 200 °C, the best option would be flash power plants. The results are presented in Table 5.

This technical recommendation is based on the mechanisms of binary power plants, which are mainly dependent on the water phase diagram. At higher temperatures, water emerges on the surface with high enthalpy, and there would be a substantial amount of energy to be extracted from the steam. Therefore, flash power plants would be more suitable for use than binary power plants.

TABLE 5. Results from the GETEM simulations (US$/MWh), taking the binary cycle as the default.

	Depth (m)		
Geothermal Gradient (°C/km)	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

For some values with a geothermal gradient more significant than 100 °C/km, the LCOE increased with a specific gradient. This observation can be explained because of the efficiency parameters for the binary cycle, and it is in line with the technical recommendation of GETEM if we consider that for geothermal gradients above 90 (in Table 2), the resource temperatures would be above 200 °C.

Figure 2 shows the influence of the geothermal gradient on the LCOE for different established resource depths. This information is especially useful because when searching for opportunities to start a geothermal power plant, an objective criterion can be established to start exploratory research based on this criterion, predominantly when focusing on energy/economic efficiency issues. These are essential for evaluating a project with a low-carbon transition perspective (Albiero et al., 2015).

The importance of geothermal energy as a player in the energy industry has increased worldwide. Countries, such as Costa Rica, El Salvador, Iceland, Kenya, and the Philippines, produce a substantial portion, comprising approximately 20% of their electricity from geothermal energy (Fridleifsson et al., 2008). Geothermal energy does not have the uncertainties associated with renewable energy, and it can be an essential source of carbon-free development in countries, such as Indonesia, where a trilemma for developing countries is present.

The need for clean, reliable, and cost-competitive energy is at the core of the Indonesian energy policy challenge. One of the solutions that has been provided by the World Bank is a loan to develop the potential of geothermal energy. LCOE is one of the many criteria that can be used to assess the decision to promote an energy source. However, if we try to monetize all the impacts, which can vary substantially for each energy source, we can have different results. This is because the criteria to monetize such effects and impacts would ignore fundamental value judgments and essential themes, such as wildlife and ecosystems. This may create an illusory method to compare that keeps policies and stakeholders outside the decision process.

The International Energy Association expects that geothermal electricity generation will grow from 87 TWh in 2017 to 277–555 TWh in 2040. Depending on the policy scenario (IEA, 2018), a 218–538% increase will occur. This places geothermal electricity generation with a faster rate than biomass and represents a strategic opportunity for the energy industry. Comparing 2017 to 2016, geothermal electricity was the only renewable energy source that had capacity growth.

We performed GETEM simulations using GETEM standards, i.e., using binary power plants for resources below 200 °C and flash power plants for resources with temperatures greater than 200 °C. The results are shown in Table 6 and Figure 2.

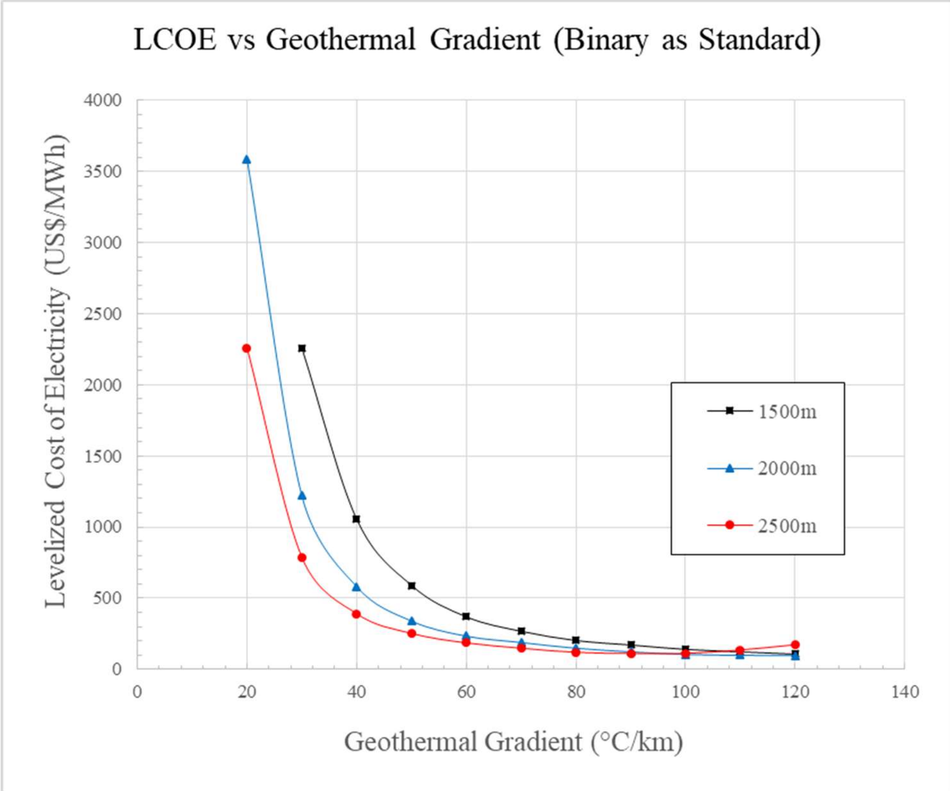

FIGURE 2. LCOE variation according to the geothermal gradient for binary power plants.

The decrease in LCOE has shown a behavioral change, especially when the conversion technology changes. This has indicated a difference between the costs of operating a flash power plant and a binary power plant. In some cases (2500 m; gradient greater than 80 °C/km), the LCOE values are lower for binary power plants than for flash power plants.

Flash power plants are a simple way of generating energy because they are used when the geofluid is produced in a mixture of steam and liquid. Binary power plants use the geofluid to heat a chosen working fluid in a closed cycle (DiPippo, 2015). In this study, the same type of power plants were analyzed to promote the use of this technology in Brazil, given that for temperatures of geofluid lower than 150 °C, it is “difficult, although not impossible, to build a flash-steam power that can efficiently and economically put such a resource to use” (DiPippo, 2015).

TABLE 6. Results for the GETEM simulations (US$/MWh), with the default software settings.

	Depth (m)		
Geothermal Gradient (°C/km)	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

The examples in Table 4 meet the criteria of having a geothermal gradient greater than 60 °C. Taking this into account, we have obtained the results shown in Table 7 and Figure 3.

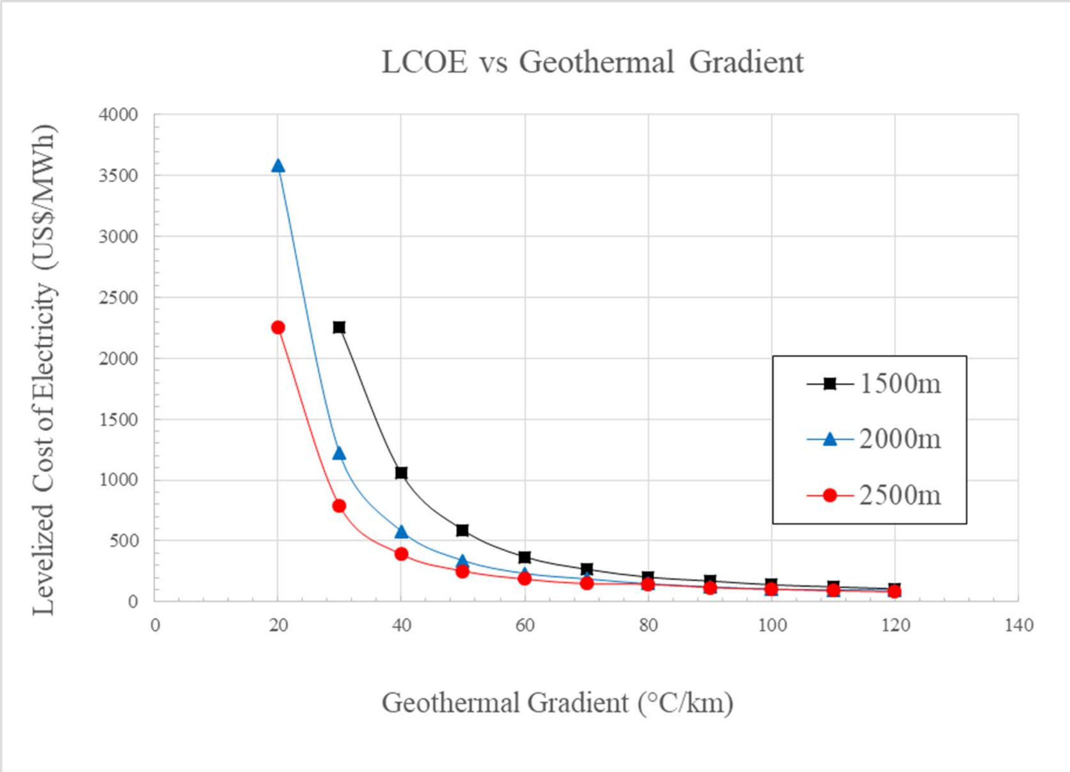

FIGURE 3. LCOE variation according to the geothermal gradient.

It is important to clarify the definition of the criterion 60 °C/km. Figure 4 Table 7 show that for every depth simulated, geothermal gradients greater than 60 °C/km provide LCOE lower than the sources that are currently operating in Brazil. Therefore, this “breaking point” highlights an opportunity to start an exploratory campaign to find geothermal resources.

TABLE 7. Results for GETEM simulations using the software default settings.

	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	-

The LCOE between geothermal energy and other energy sources was then compared using these data (Figure 4).

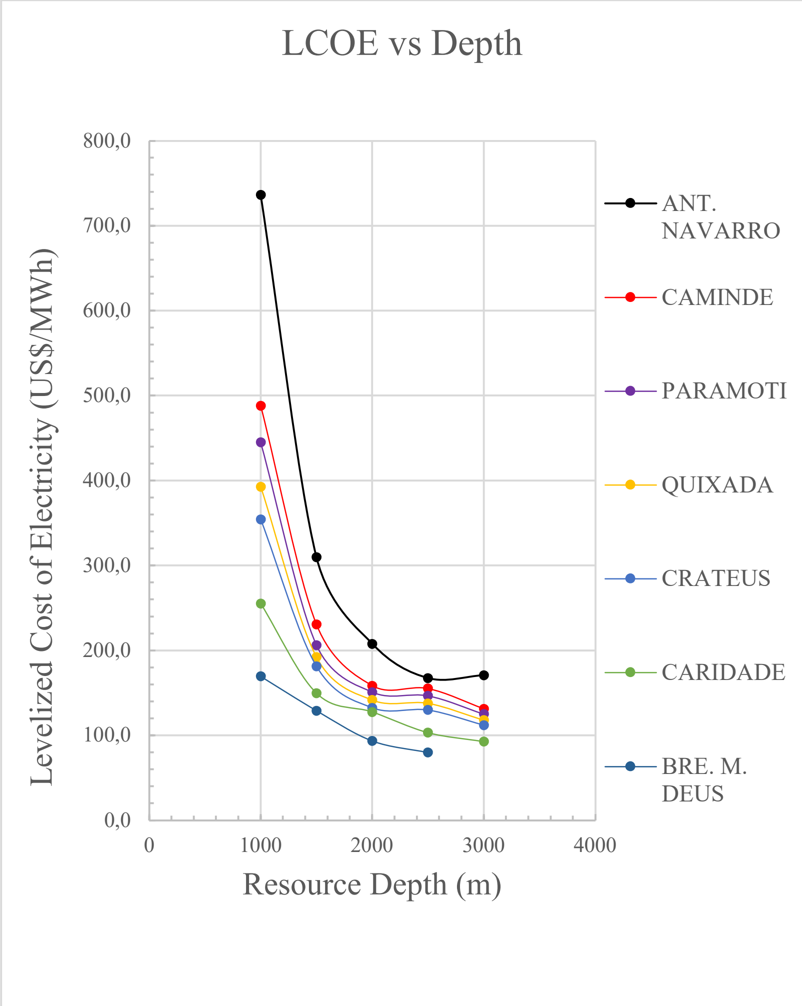

FIGURE 4. LCOE variation for different sites.

Data on levelized costs for different sources allow comparison of the economic viability of this energy source. However, the levelized cost of energy should not be the only criterion because it does not encompass all the benefits and costs of the use of each technology (Dutra & Tolmasquim, 2002). Table 8 shows a qualitative analysis of different renewable energy methods and their main characteristics that can be used to support a more strategic analysis if the Government and R&D issues are regarded as indicated by Xavier et al. (2022).

In Europe, geothermal energy can be cost-competitive and may win the renewable cost challenge. However, further research is required to reduce the investment risks (Clauser & Ewert, 2018). Geothermal systems can be a source of baseload energy production because they are not weather dependent and can be a renewable option for developing baseload capacity in energy production in countries, such as Turkey (Melikoglu, 2017).

TABLE 8. Qualitative comparison between renewable energy sources (Long, 2009).

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

GETEM has presented a more detailed description of costs (Figure 5).

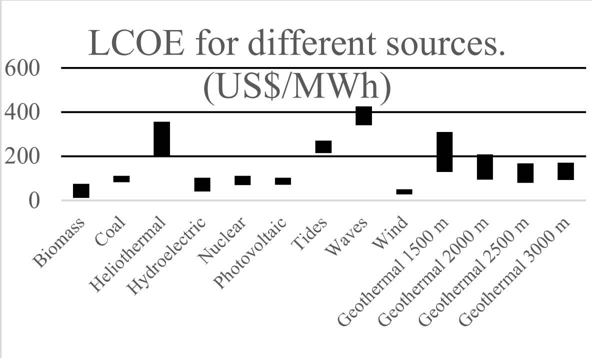

FIGURE 5. LCOE for different energy sources.

For EGS, well field capital and exploratory costs are nearly one-third of all costs impacting the LCOE. These data are critical because according to the Brazilian National Petroleum Agency, data on the overall production for every oil and gas well onshore in the Northeast Region can be obtained. There are approximately 3800 wells that did not produce either oil or gas from a total of approximately 10500 wells (ANP, 2018). There are extensive opportunities for exchange between the oil and gas industry and an eventual geothermal energy power plant using EGS technology, which relies heavily on well construction costs and technology.

Geothermal energy can be used to smooth the substantial change in services and rig demand caused by the volatility of oil prices. The maintenance of jobs in the region, especially in places that are highly dependent on the oil and gas industries, should also be considered by policymakers. Some regions in Brazil have the potential use of technologies needed to develop EGS in parallel with other O&G, such as shale gas, especially in the Sergipe–Alagoas basin (Péres et al., 2016) (Figure 6).

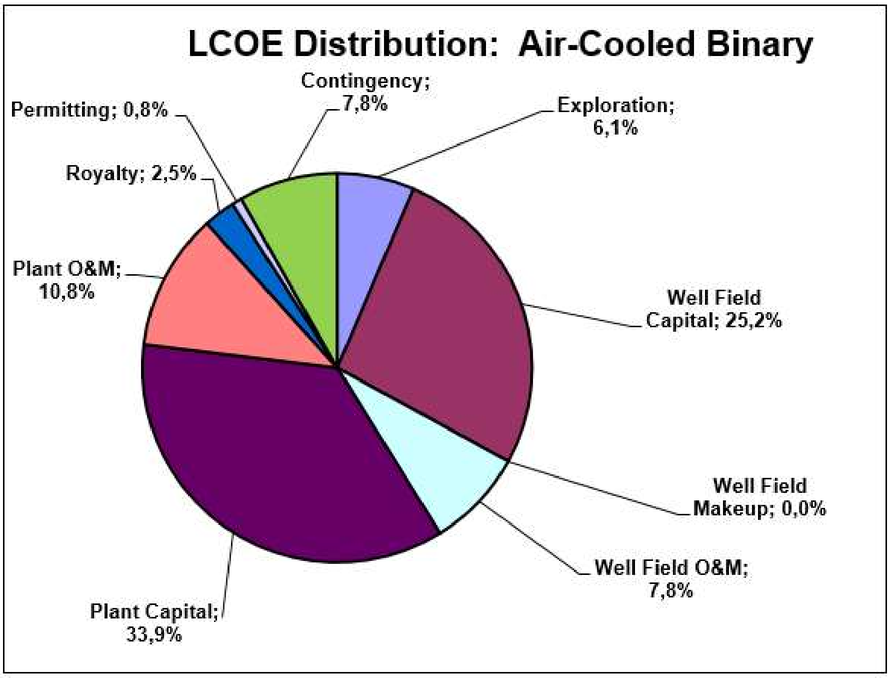

FIGURE 6. LCOE composition on GETEM: 1500 m scenario.

The installed capacity of the NEB electricity generation should also be considered (Table 9). The installed capacity has 31% reliance on thermal sources, with this number increasing to 79% in the state of Paraíba and to greater than 50% in the states of Ceará, Pernambuco, and Maranhão (Hanbury & Vasquez, 2018). Given that thermal energy generally consumes a substantial amount of freshwater to generate energy, geothermal energy can be considered suitable for regions with water-supply issues, as noted by Chandrasekharam et al. (2018).

In the context of freshwater production through desalination, traditional thermal energy is economically attractive. However, geothermal energy has a level of emissions that is three orders of magnitude lower than that of coal (Hanbury & Vasquez, 2018). The emissions for geothermal energy and EGS are generally lower than the emissions from fossil fuel energy sources (Table 10).

The high values for emissions for geothermal energy (Bayer et al., 2013) originated from the specifics of different technologies, with higher values associated with noncondensable gas in flash power plants. Closed cycles such as EGS tend to have zero emissions associated with the geofluid in the operational phase. Most of the CO2 emissions from EGS are derived from the consumption of diesel in construction and operations (Tomasini-Montenegro et al., 2017).

TABLE 9. Installed capacity of electricity generation (GW). Source: (Hanbury & Vasquez (2018).

	Total	Hydro	Thermal	Wind	Solar	Nuclear
Nordeste	32505	11568	10089	10157	691	0
Maranhão	3388	662	2505	221	0	0
Piauí	1834	119	68	1408	240	0
Ceará	3715	1	1934	1775	5	0
Rio Grande do Norte	4161	0*	511	3533	117	0
Paraíba	775	5	613	157	0*	0
Pernambuco	3500	764	1964	762	10	0
Alagoas	4044	3725	319	0*	0*	0
Sergipe	1707	1581	91	35	0*	0
Bahia	9381	4711	2085	2267	319	0

*negligible values

TABLE 10. Emissions for different energy sources.
Source: Tomasini-Montenegro et al. (2017).

Source	Emissions (kgC/MWh)
	122 (4-740)
	1100 (190-1300)
	847(520-1160)
	50 (15-800)
	500 (250-1234)
	31(0-410)
	20 (4-100)
	7,55-57,5

FUTURE PERSPECTIVE AND CHALLENGES

The prospects for the use of EGS for water desalination in the Northeast of Brazil are attractive because in addition to it being a clean and available renewable energy source that is relatively easy to use through the reuse of abandoned oil wells, it enables a low-carbon transition policy.

The challenges in the use of geothermal energy in northeastern Brazil with a view to the desalination of water refer to the development of national technology for the use of EGS, as well as the qualification of personnel to operate and scale the systems. Another challenge is the establishment of a public policy that is effective in providing drinking water for the northeastern population. This should be linked to these resources in the form of credits and counterparts for the development and operation of these systems.

CONCLUSIONS

In the form of EGS, geothermal energy can be a suitable option to address water scarcity in the northeast region in a sustainable and low-emission manner. The large number of oil and gas wells shows that there is an opportunity for further assessment of this potential solution, as demonstrated by this energy and economic feasibility study.

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