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Linear Fresnel reflector technology in Brazil: a techno-economic evaluation

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Abstract. This study aims to present the results of applying a computational tool developed to perform a technical-economic feasibility analysis of a large-scale Linear Fresnel Reflector (LFR) solar power plant. The viability analysis indicators were obtained considering that the electricity produced trades at the Regulated Contracting Environment of the Brazilian Electricity Market. The parametric structural optimization method is used to optimize the technical parameters of the plant. A case study was conducted to analyze the viability of Implementing a 100 MW LFR power plant in the five regions of Brazil. The results indicated that Northeastern is the best region to install this power plant. However, the project is not viable in all cities analyzed. A sensitivity analysis (SA) of some strategically selected variables was conducted to evaluate its impacts on the project's net present value of an optimized LFR plant located in the city with the best technical performance. Finally, an optimistic scenario was evaluated considering the net present value's response to the parameters investigated in the SA. For this scenario, the results indicated the project's economic viability.

Keywords. Economic Viability, Linear Fresnel Reflector, Regulated Contracting Environment, Univariate Sensitivity Analysis.

1. Introduction

Despite enjoying a great energy potential, with emphasis on renewable energy sources (hydraulic, wind, solar and biomass), Brazil has faced the challenge of diversifying its electrical matrix for some years. In this context, it should be noted that the Brazilian energy scenario has an electrical matrix of predominantly renewable origin, which corresponds to 84.8% of the domestic supply of electricity. Despite this high level, it is not consistent with a proportional division of the electricity matrix, as the water source accounts for 65.2% of the internal supply, according to the Energy Research Company (EPE) [1].

Aiming for the diversification and expansion of the Brazilian electrical system, some specialists have encouraged the use of dispatchable generation [1]. In this sense, it is important to highlight the possibility of using photovoltaic plants (PV) and Concentrated Solar Power (CSP). Photovoltaic systems, although they have notable advantages, are not usually used for large-scale production, due to the high costs to maintain constant production using electric batteries [2]. On the other hand, CSP systems, on the rise, allow the uninterrupted supply of energy with the use of thermal storage. Despite the high investment costs, the possibility of uninterrupted supply can make them more viable. It should be noted that, among the available CSP topologies, Linear Fresnel Reflector (LFR) have a low implementation cost due to their simple composition and the need for intense security measures [3].

In the literature, it is possible to find some studies involving CSP [4-6]. In [4], the authors inferred that in Latin America, especially in Brazil, there is still a lack of research on the heliothermic theme, which culminates in the nullity of CSP plants in commercial operation. In [5] is suggested based on the energy efficiencies, that for an LFR plant to be competitive, it must have a cost of up to 70% of the cost of the Parabolic Through Collectors (PTC), since it has fewer optical losses. In [6], a technical-economic analysis of several optimised LFR plants in different locations in Algeria was developed. In this study, the Levelized Cost of Energy (LCOE) was used, calculated through the Annual Energy Produced resulting from simulations in the System Advisor Model (SAM). However, it is worth noting that in this work, the authors did not include thermal storage, which would enhance their results, making them more viable.

Considering the aspects mentioned above, there is a lack of studies on the technical-economic viability of CSP plants in South America. It is worth mentioning that, regarding the LFR type, this limitation occurs worldwide. As a result, the idea of developing this study arose, whose general objective is the development of a tool for analyzing the technical and economic viability of LFR plants operating in the Regulated Contracting Environment (RCE) of the Brazilian energy market. The tool contemplates a technical-economic optimization that proposes to offer greater competitiveness to LFR technology when compared to standard conditions. It is also part of this study to carry out a SA in order to verify which economic parameters most impact the economic viability of the LFR plant. With this, it is possible to establish an optimistic economic scenario that validates the feasibility of investing in plants of this type in Brazil. The proposed tool in this work is characterized as a way to encourage the emergence and consolidation of the country in the construction of new sustainable energy solutions concerning heliothermal energy.

2. Methodology

For this paper, a software prototype was developed for the technical and economic simulation of a large-scale LFR power plant operating in ACR of the Brazilian Electric Energy Market. The proposed methodology adopted in this study comprises four major stages. The first stage consists of developing the physical modelling of the elements that make up the plant: the solar field, the receiver, the power cycle, and the thermal storage. Based on this modelling, it is possible to quantify the annual net electricity production of the plant.

The second stage aims to obtain the plant's cash flow throughout its useful life. This study employs Damodaran's basic structure of Discounted Cash Flow (DCF) [7]. It is important to emphasize that the DCF model was modified to consider the particularities of taxation in the Brazilian market. This study considered that all annual electricity produced is sold in the ACR at a fixed price (auction price). Therefore, the economic viability of the investment is based on the analysis of the following economic indicators: Net Present Value (NPV), Modified Internal Rate of Return (MIRR), Discounted Payback (DPP), and Levelized Cost of Energy (LCOE).

In the third stage, initially, a parametric structural optimization technique is applied, approaching the optical and financial aspects of the plant to obtain the best configuration of the plant. In this study, an objective function was defined that relates to the maximization of the plant's energy production and the minimization of investment costs. For the maximization of energy production, the plant's capacity factor (CF) parameter was chosen. This parameter addresses the relationship between the plant's energy production and its nominal production capacity. Therefore, maximizing its value results in producing greater amounts of energy efficiently, so that there is no underutilization of system capacity. For the minimization of the investment cost, the LCOE was adopted as a parameter. In a simplified way, it represents the cost of energy production, so that the lower its value, the more economical the system's energy production becomes.

Having defined the objective function to be maximized, the design variables of the LFR plant that directly impact the objective function are defined. For this study, the following were chosen: the opening area of the solar field, the number of hours of thermal storage, the nominal power of the plant, and the efficiency of the power cycle. Simulations result from the permutation of design variables, so the number of simulations results from multiplying the number of steps for each variable. For each possible combination, the simulation is performed and the result of the objective function is obtained. In the end, the combination of variables that obtains the highest result for the objective function is selected. With the results of the parametric optimization, the best configuration of the project is obtained, considering the limits of the proposed intervals. In view of the optimized project, a new analysis of the technical-economic viability of the plant is carried out.

In the fourth stage, a sensitivity analysis (SA) is carried out to determine how the economic parameters, energy sales price, installation cost, exchange rate and minimum attractive rate of return, affect the economic viability through the NPV indicator. It should be noted that the sensitivity analysis is carried out on the already optimized LFR plant, to expand the results to an optimistic scenario.

The power absorbed by the solar field reaching the receiver tube is given by Equation 1 [8].

$$Q_{abs.h}^{SF} = \alpha \cdot \tau \cdot \rho \cdot \gamma \cdot K(\Theta_h) \cdot A_a \cdot I_h \quad (1)$$

In (1), $Q_{abs.h}^{SF}$ is the power absorbed by the solar field (SF) reaching the receiver (W) in the hour h; α is the absorbance of the absorber tube (dimensionless); τ is the transmittance of the receiving glass envelope (dimensionless); ρ is the concentrator reflectance (dimensionless); γ is the collector interception factor (dimensionless); $K(\Theta_h)$ is the incidence angle modifier (dimensionless); Θ_h is the incidence angle in hour h (degrees); A_a is the total opening area of the primary collector array (m^2); and I is the Normal Direct Irradiance (DNI) (W/m^2).

The receiver is responsible for producing the power that will feed the power cycle. The useful power gained by the heat transfer fluid (HTF) can be obtained from the power balance of the solar receiver. Due to the difference in temperatures between the envelope and the ambient, two modes of heat transfer occur, i.e., radiation between the sky and the glass envelope and convection between the ambient air and the envelope. The modelling of the heat losses from the HTF to the ambient is reported in detail in reference [9]. Taking into consideration the solar power absorbed by the absorber tube and the thermal losses from the receiver, the useful power in the receiver in the hour h can be calculated by Equation 2.

$$Q_{U,h}^{Rec} = \left(Q_{abs,h}^{SF} - Q_{losses,h}\right) = \;_{th} \cdot Q_{abs,h}^{SF} \qquad (2)$$

In (2), $Q_{U,h}^{Rec}$ is the useful power in the receiver in hour h (W); Q_{losses} is the power that is lost in the receiver due to convective and radiative heat transfer in hour h (W); $_{th}$ is the thermal efficiency of the receiver (dimensionless).

Thermal storage capacity (Q_{TES}), given by Equation (3), is conventionally expressed in equivalent full-load hours of thermal energy storage (TES). The magnitude of this value indicates the number of hours that thermal storage can supply energy to operate the power cycle at its full design point output (Q_{nom}^{PC}). TES is based on a simple process; during a typical storage charge, the excess heat delivered by the solar field is sent to the TES circuit and heats up the HTF passing from the cold tank to the hot tank. During temporary weather transients (storage discharge), the opposite process takes place and thermal energy is transferred from TES fluid to HTF and typically delivered to the power block [10].

$$Q_{TES} = Q_{nom}^{PC} \cdot \Delta t_{load} \qquad (3)$$

In (3), Q_{TES} is the maximum power of thermal storage capacity (W); Q_{nom}^{PC} $is\ the$ nominal power of the power cycle (PC) (W); and Δt_{load} is equivalent full-load hours of TES (dimensionless).

Given the storage capacity, four strategic modes of operation for TES are defined. Such strategies consider three parameters: the useful power of the receiver; the nominal power of the power cycle and the maximum power of thermal storage capacity. This approach aims to satisfy the nominal power of the power cycle, using the available resources of the receiver and the TES system, in an order of priority [11]. The strategies are described as follows.

i) Strategy 1: Cases in which the total energy produced by the solar field is not enough to feed the power cycle and the TES does not have reserves to support production. In these cases, the storage will behave inertly, that is, it is not supplied and does not supply the power cycle. Such a strategy is the so-called standby mode.
ii) Strategy 2: Cases in which the solar field is fully focused but needs TES to supplement the power sent to the power cycle.
iii) Strategy 3: Cases in which the useful power of the receiver exceeds the energy that can be used in the power cycle or in the TES. The solar field must be partially blurred, rejecting the remaining energy that cannot be harnessed.
iv) Strategy 4: Cases in which the useful power of the receiver exceeds the demand of the power cycle, but all the excess of thermal energy can be diverted to the TES.

The useful power generated by the power cycle can be obtained by equation 4 [9].

$$Q_{U,h}^{PC} = \;_{PC} \cdot Q_{U,h}^{Rec} \qquad (4)$$

In (4), $Q_{U,h}^{PC}$ is the useful power generated by the power cycle in the hour h (W); and $_{PC}$ is the power cycle efficiency (dimensionless).
The total annual energy can be calculated according to equation 5.

$$E_U^{PC} = \sum_{h=1}^{8760} Q_{U,h}^{PC} \qquad (5)$$

In (5), E_U^{PC} is the annual electricity generated by the power cycle (MWh) for the first year of operation; 8760 is the number of hours in a year. The energy production is projected for the remaining years of the useful life, considering a straight-line depreciation.

For the LFR, the gross revenue in the year y is obtained using Equation 6.

$$GR_y = E_{U,y}^{PC} \cdot \$_{RCE} \qquad (6)$$

In (6), GR_y is the gross revenue in the year y ((BRL); $E_{U,y}^{PC}$ is the annual electricity generated by the power cycle (MWh) in the year y, and $\$_{RCE}$ is the energy price in the RCE environment (BRL/MWh).

For the optimization of the electric generation, it was applied the parametric structural optimization methodology. In this study, we use the Equation 7 as an objective function.

$$\uparrow F_{objective} = \frac{\uparrow\left(\frac{E_{U,y}^{PC}}{E_{nom}^{PC}}\right)}{\downarrow\left(\frac{I_0 + \sum_{y=1}^{T} \frac{C_y}{(1+MARR)^y}}{\sum_{y=1}^{T} \frac{E_{U,y}^{PC}}{(1+MARR)^y}}\right)} \qquad (7)$$

In (7), E_{nom}^{PC} is the rated annual energy (MWh); I_0 is the capital expenditure – CAPEX (BRL); C_y is the operation and maintenance expenditures (O&M) in the year y; $MARR$ is the minimum attractive rate of return (% p.a.); T is the total period (lifetime) (years).

The Python programming language was chosen for the modelling process of the different stages of the electric energy generation process, given the existence of the interface between Python and the SAM, called NREL-PySAM. Thereby, class diagrams were used to describe better how the relationships between objects are formed and how optimisation takes place at the computational level. Moreover, the plant is modelled by concepts of object-oriented programming, which resorts to classes, objects, methods, and attributes.

Noteworthy is that the model of the plant in question was built with the intention of having the liberty to control the simulation equations and variables, mainly concerning financial aspects. Thus, it is possible to contemplate the Brazilian market's characteristics properly.

3. Results

At first, this study approaches the results of the technical analysis of an LFR power plant applied in the five regions of Brazil: North (Manaus), Northeast (Recife and Bom Jesus da Lapa), West-Center (Brasília), Southeast (Rio de Janeiro) and South (Porto Alegre). Thereafter, the economic viability indicators are displayed for the city with the best technical performance. The model improved through parametric optimization is then exposed. The SA is performed considering some economic variables, and, finally, an optimistic scenario was analyzed, considering the system's response to the parameters investigated in the sensitivity analysis.

A. Technical Analysis

Meteorological information for each region is extracted from the NSRDB (National Solar Radiation Database). This database mainly collects hourly historical data on solar irradiance, wind speed and ambient temperature, as well as regional static properties such as latitude, longitude and time zone, requirements for simulating the created models. The data used in this study were acquired for the year 2020. From the meteorological data analysis, it is observed that the city of Bom Jesus da Lapa has the highest levels of solar irradiance, which characterizes this region as an excellent place to implant an heliothermal plant, regardless of the adopted topology. Table I summarizes the main parameters defined for the LFR plants simulation [12].

Table I. - Technical Parameters for the LFR plant simulation

Class	Parameters	Value
Solar Field	Solar multiple	2,3
	Average room temperature	42 °C
	Number of loops	150
	Opening area of a loop	7,524.8 m²
	Opening area	1,128,720 m²
	Total occupied area	180.59 ha
	Reflectivity of mirrors	0.935
	Degree of dirt on the mirrors	0.95
	General optical losses	0.732
	Optical efficiency	0.6118
Receiver	Receiver model	Evacuated Tube
	Receiver HTF type	Hitec solar salt
	Glass emissivity	0.861
	Glass transmittance	0.96
	Thermal efficiency	0.983
Power Cycle	Rated power	100 MW
	Efficiency	0.397
	Electric conversion factor	0.9
Thermal Storage	Model	Two tanks
	Storage HTF type	Hitec solar salt
	Number of hours of storage	4 h
	Storage volume	6,273.1 m^3
	Thermal storage capacity	1,119.5 MW_th
	Min. operating temperature	238 °C
	Max. operating temperature	593 °C

Table II exhibits the annual energy production, and the annual capacity factor obtained at each simulated location. Table II shows that from all cities analyzed, Bom Jesus da Lapa has the highest annual capacity for producing electricity and a higher annual capacity factor. This is due to the region's favourable climatic conditions.

Table II. - Annual energy production and the annual capacity factor of simulated cities

	Manaus	Recife	Brasilia	Rio de Janeiro	Porto Alegre	Bom Jesus da Lapa
Energy (GWh)	128.63	194.25	188.40	140,23	150.64	229.25
CF (%)	14.68	22.18	21.51	16.01	17.20	26.16

B. *Economic Analysis*

For the economic analysis of the LFR plant in Brazil, it was opted to adopt the results of the technical analysis carried out for the city of Bom Jesus da Lapa. For that, the generation data of the LFR power plant of this city feeds the cash flow model to obtain the financial indicators calculated in this study. All construction, operation, and maintenance costs of the plant are approached in this evaluation, in addition to the taxes and tax rates levied on the revenue collected from the sale of energy in the ACR of the Brazilian Electric Energy Market (MEEB). In this study, the developed analysis considered a capital structure without financing, i.e., totally with equity capital. Additionally, the sale price used for the analysis seeks to represent a proper scenario for installing energy sources with high production costs. Table III presents the used for the execution of the economic viability analysis.

Table IV presents the financial indicators results raised to the LFR power plant analysis in the city of Bom Jesus da Lapa. Adopted values for the insertion in the construction of the free cash flow to equity (FCFE) are based on the work of [12] and [13]. It must be emphasized that, for the selling price of energy, it was adopted the Reserve Energy Auction (LER in Portuguese) value happened in 2015. In this study, it was considered that energy production has an annual generation degradation of 0.5% per year [12].

The indicators NPV, MIRR and DPP show that the investment is financially impractical in the presented conditions. The LCOE is above the average value of 75 USD/MWh predicted by IRENA for the CSP plant, which indicates the unfeasibility of the project. However, given the high investment cost, in the order of billions, it can be considered that the LFR-type CSP technology is at least competitive, as its production was able to keep the LCOE close to the value predicted by IRENA for 2021 [14].

Table III. – Data used in the simulation [12,13]

Parameters	**Value**
Deployment Costs	BRL 1,458.00 Mi
Project useful life	30 years
Contract price (August 2015 – ANEEL)	BRL 305/MWh

MARR	Equal to the cost of equity
Investment rate	Equal to the cost of equity
Financing rate	Equal to the cost of third-party
ANEEL Inspection Fee	0.5% of gross revenue
Tariff for Use of the Transmission	BRL 1.5/kW.month
O&M - Fixed	BRL 70/kW/year
O&M - Variable	USD 3/MWh
Exchange Rate	BRL 5.40/USD
Linear Depreciation	30 years
Tax Regime	Presumed Profit
Cost of equity and third-party [13]	
Risk-free rate	4.59% p.a.
Market risk premium	5.79% p.a.
Unleveraged middle beta	0.44
Country risk premium	3.52% p.a.
US average inflation	2.47% p.a.
Cost of equity (nominal)	10.65% p.a.
Cost of equity (actual)	7.95% p.a.
Credit risk premium	2.93% p.a.
Cost of third-party Capital (nominal)	11.04% p.a.
Cost of third-party Capital (actual)	8.34% p.a.

Table IV. - Financial indicators results.

Indicator	Value
Net Present Value (NPV)	-860,536,428.93 BRL
Modified Internal Rate of Return (MIRR)	4.787% p.a.
Discounted Payback Period (DPP)	>30 years
Levelized Cost of Energy (LCOE)	100.94 USD/MWh

C. *Optimisation*

The LFR power plant optimization reinforces the possibility of changing the financially impractical scenario to a favourable one. The parametric optimization was applied to the original project, aiming at maximizing the capacity factor and minimizing the LCOE. Such optimization is a work of exploration of the space of possibilities for the interest variables according to an objective function. Therefore, an analysis of which variables have the greatest influence both on energy production and installation costs becomes necessary to determine the conduction of parametric optimization. Table V shows the interest variables with their respective intervals with initial and final values and the incremental step.

Table V. - Design variables for optimisation problem

Design Variable	Initial Value	Final Value	Step
Opening area of the SF (m²)	800,000	1,400,000	100,000
Hours of storage (h)	4	8	1
Rated power (MW)	75	125	10
Power cycle efficiency	0.36	0.46	0.02

The adopted values for the opening area of the solar field and the number of hours of storage is calculated in the paper of R.P. et al. [15]. The interval of the adopted values for the power cycle efficiency comes from Dunham [16]. For nominal power, we chose the interval between 75 MW and 125 MW, with an incremental step of 10 MW. This interval was chosen taking the nominal power value of 100 MW of the initially modelled project as the central value. The lower and upper limits were obtained by varying up and down by 25%.

Table VI presents the best result of the design variables with the application of the proposed parametric optimization. With the data from the parametric optimization process, a technical and economic analysis of the project viability can be executed.

Table VI. - Best result obtained with the application of the parametric optimization method

Design Variable	Best Result
Opening area of the solar field (m²)	1,100,000.00
Number of hours of storage(h)	7
Rated Power (MW)	75
Power cycle efficiency	0.46
Capacity factor (%)	39.71 %
LCOE (USD/MWh)	82.00
$f_{objective}$	0.484

Table VII. - Changed data for the project due to optimisation.

Parameters	Values	
	Not optimized	Optimized
Solar multiple	2.3	3.49
Rated power (MW)	100 MW	75 MW
Opening area of the solar field	1,128,720 m²	1,100,000 m²
Number of hours of storage	4 h	7 h
Storage volume	6,273.10 m³	8,120.85 m³
Thermal storage capacity	1,119.50 MWh	1,268.11 MWh
Power cycle efficiency	0.397	0.46
Deployment costs	BRL 1,458.00 Mi	BRL 1,347.83 Mi
Results		
NPV (BRL)	-860,536,428.93	-681,390,911.83
MIRR (% p.a.)	4.787	5.445
DPP (years)	Exceeds the useful life (>30)	Exceeds the useful life (>30)
LCOE (USD/MWh)	100.94	82,00

Table VII summarizes the technical and economic data that have changed due to the result of the parametric optimization.

The condition in which there is a nominal power of 75 MW with a solar field opening area of 1,100,000 m² and a power cycle efficiency of 0.46 results in a solar multiple of 3.49. Worth noting that 7 hours of thermal storage with 75 MW of nominal power results in a storage volume of 8,120.85 m³ and a thermal capacity of 1,268.11 MWh. All these modifications to the components reduce the investment cost to 1,347.83 million BRL.

Because of the optimization results, it was found that, despite the decrease in the nominal power of the plant, there is an increase in the annual energy production of 13.79%, which demonstrates the productive capacity of the plant when looking for its optimum point of operation. Furthermore, the NPV increased by 20.82%, the MIRR increased by 13.75 pp and the LCOE decreased by 18.76%. These results derive from the increase in energy production with the decrease in investment cost. Due to these results, the parametric structural optimization made the investment technically and financially more attractive. The notable improvements in results between the non-optimised design and the optimized design were not enough to make it viable in the Brazilian territory.

Additionally, it should be noted that the value of the LCOE was even closer to the value of 75 USD/MWh predicted by IRENA for 2021 [14] indicating that technically it is a competitive project, which would be able to be viable in a more profitable economic scenarios. However, the sale price of energy and the exchange rate applied to the investment cost are determining factors in setting up the FCFE, which end up making this type of investment unfeasible in Brazil.

D. *Univariate Sensibility Analysis*

Faced with scenarios of the financial unfeasibility of the LFR power plant in Brazilian territory, it is necessary to evaluate which variables have the greatest impact on the indicators used, and what could be done to make the investment viable. In this sense, it is proposed to carry out a SA for the NPV indicator, whose result can be considered sufficient to determine the technical-economic viability of an investment.

This analysis was carried out considering only the optimized plant located in Bom Jesus da Lapa. It approached four parameters: the sale price of electricity in the ACR (BRL/MWh), the plant installation cost (R$), the exchange rate (R$/USD) and the MARR (% p.a.).

The energy sale price, which is defined in bidding in the auction modality, is the main economic parameter that defines the income of power plants. For this purpose, a range from 70 USD/MWh to 375 USD/MWh was considered [9]. The exchange rate is equal to R$ 5.40/USD (2021 average quotation). From this sensibility analysis, it is possible to verify that: i) the NPV grows as the selling price increases, and ii) the optimised LFR power plant reaches economic viability for electricity sales prices above R$ 650/MWh.

The installation cost is inversely proportional to the financial indicators used in this study. The variation range used was from 40% to 160% of the installation cost of the optimized plant [10]. The SA shows a decreasing behaviour of the NPV due to the increase in the installation cost. It is also possible to conclude that the installation cost must be below R$ 600 million to be economically viable. For the real installation to reach this level, it would be necessary to reduce its cost by around 40%.

The exchange rate SA considered a range of values from R$ 1.00/USD to R$ 6.00/USD. These values were taken from the work of [10]. It should be noted that according to TH Institute of Applied Economic Research Ipea -, the exchange rate in Brazil from 1997 to 2021 varied between R$ 1.08/USD and R$ 5.40/USD [12]. It is possible to notice that there is a significant dependence of the NPV on the import costs imposed by the exchange rate. From R$ 2.5/USD, the plant begins to show economic unfeasibility.

The MARR used in the scenarios evaluated in this study was equal to the WACC defined by ANEEL [13]. However, for the SA, values for the MARR varying according to the SELIC rate of recent years are considered. The SA shows that the NPV has exponentially decreasing behaviour in relation to MARR. From this analysis, it appears that a lower MARR rate provides a greater financial return. Furthermore, it is noted that no SELIC rate throughout Brazilian history would be, by itself, capable of establishing the economic viability of the undertaking in question.

In view of the results of the SA, it is concluded that the parameter with the greatest impact on the economic viability of the optimized LFR power plant installed in Bom Jesus da Lapa was the energy sales price, followed by the exchange rate and the direct cost of equipment.

E. *Optimistic scenario.*

Based on the obtained results via SA, a simulation considering an optimistic scenario for the installed optimized LFR power plant in Bom Jesus da Lapa was performed. Table VIII displays the applied data in the optimistic scenario simulation.

Table VIII. - Changed data for the project due to optimisation.

Parameters	**Not optimized**	**optimistic**	**Difference**
Sale price (BRL/MWh)	305	488	+60%
CAPEX (Mi BRL)	1,347.83	673.92	-50%
Exchange rate (BRL/USD)	5.4	3.65	-32.41%
MARR (% p.a)	7.95 % p.a.	6.4 % p.a.	-19.5 pp

With regard to the installation cost, the historic percentual reduction of the unit cost of heliothermal generation between 2010 and 2020 [10] was used. The sale price was estimated considering the degree of variation in the sale prices of the results of generations auctions publicly displayed by ANEEL as done in [9]. The exchange rate adopted was the average value of 2020. The MARR corresponds to the SELIC rate of the same year. The results found in the optimistic scenario, as well as those referring to the standard scenario, are shown in Table X.

Table X. - Comparison of results between non-optimistic and optimistic scenarios for LFR installation

Scenario	**NPV (BRL)**	**MIRR (% p.a.)**	**PBD (years)**	**LCOE (USD/MWh)**
Standard	-681,390,911.83	5.445	>30	82.00
Optimistic	511,704,847.08	9.455	11.33	52.99
Difference	+175.10 %	+7.365 pp	-	-35.38 %

Through the data, it is noted that all financial indicators showed significant improvement. The NPV became positive, generating profit for shareholders, an increase of 175.10% in relation to the non-optimistic scenario (standard). The MIRR increased to 9.455%, above the MARR, defined as 6.4% p.a., which means that the project is attractive to investors. The DPP, in turn, was reduced to 11.33 years. This means that in the twelfth year, investors start to make a profit from the venture. It should also be mentioned that the LCOE was reduced to 52.99 USD/MWh, making the plant even more competitive.

4. Conclusion

This paper showed a new methodology for the deterministic analysis of the technical-economic viability of investments in an LFR solar power plant in Brazil. With that, the solar field, the receiver, the power cycle and the thermal storage were modelled. To achieve accurate results, the financial indicators used contemplate the legislative and tax particularities of the Brazilian electricity market.

To validate the methodology, technical analyzes of a 100 MW LFR solar power plant were carried out in five regions of Brazil. The economic analysis was carried out in the city of Bom Jesus da Lapa, a place that exhibited the best energy production indices, among those evaluated. In this place, there is an energy production of more than 229 GWh and a capacity factor of 26.16%. Through the electric energy produced and considering its commercialization in the ACR, the cash flow model was built to extract the financial data and raise the hypothesis of project viability. As a result, the indicators pointed to the economic unfeasibility of the modelled plant.

Using the optimized design, a new technical-economic feasibility analysis was carried out. The changes resulted in an increase of 13.79% in the annual electricity produced and an increase of 51.80% in its capacity factor. For the economic analysis, the optimized design achieved an increase in NPV and MIRR of 20.82% and 13.75%, respectively, and a reduction in LCOE of more than 18%. Despite the improvement in technical and economic results, the LFR plant for the city of Bom Jesus da Lapa remained economically unviable according to the NPV, MIRR and Discounted Payback indicators. On the other hand, it was found that the LCOE was reduced to a value that made the project more competitive, however, still financially unfeasible. With this, a sensitivity analysis of the NPV was carried out in relation to variations in economic parameters: energy sales price in the ACR; installation cost; exchange rate; and the minimum attractive rate of return. The results showed that the energy sales price, the installation cost and the exchange rate have a greater impact on economic viability.

Based on the results of the sensitivity analysis, an optimistic scenario was established for the city of Bom Jesus da Lapa regarding the optimized plant. The results pointed to the viability of the investment with a positive NPV, MIRR above the MARR value, Discounted Payback below the useful life duration and LCOE below the forecast by IRENA. From the analyzes carried out in this study, it can be concluded that the evaluated technology has a high potential to develop in the coming years in Brazil.

To improve the economic viability of LFR plants it is recommended: i) Reduction of taxes on the import of the main components to reduce the total investment cost, the creation of subsidies, exemptions, and/or the offer of credit at reduced rates through the competent institutions; ii) Strategies that help the investors, such as income tax exemption. Furthermore, it is suggested the creation of new public policies to attract researchers and enthusiasts in the development of heliothermic generation; iii) Incentive to national industry to create the components of the heliothermic plants, aiming at reducing the total cost of the investment; iv) Evaluate the environmental gains from using clean technology and all positive externalities resulting from implementing heliothermic energy in the many spheres of society. The insertion of the revenue from carbon credits could significantly contribute to the economic feasibility of these types of enterprises.

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