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Technical-economic feasibility analysis of a large-scale parabolic trough collectors solar power plant in Brazil

M. E. Lopes[1], G.F. Azevedo[1], B.A. Menezes[1], O.H.F. Rabelo[1], L.B. Brito[1], A.B. Dias[1], A. L. F. Filho[1] and E. G. Domingues[2]

[1] Department of Electrical Engineering - University of Brasília
Darcy Ribeiro University Campus – Gleba A, Avenida L3 Norte, 70.910-900, Brasília-DF (Brazil)
Phone/Fax number: +55(61) 984350000, e-mail: **leles@ene.unb.br**

[2] Electrical Engineering/Control and Automation Engineering Program - Federal Institute of Goiás - Câmpus Goiânia
Rua 75, nº46 - Centro, Goiânia - GO, 74055-110 (Brazil)
Phone: +0055 62 3227-2769, e-mail: **elder.domingues@ifg.edu.br**

Abstract. This study aims to present the results of the application of a computational tool developed to perform a technical-economic feasibility analysis of large-scale Parabolic Trough Collectors (PTC) solar power plants in Brazil. The gross revenue from cash flow is obtained through an energy trading model for the Regulated Contracting Environment of the Brazilian Electricity Market. The economic viability analysis uses the Net Present Value, Modified Internal Rate of Return, Discounted Payback, and Levelized Cost of Energy indicators. The parametric structural optimization method is used to optimize the technical parameters of the plant. A case study was conducted to analyse the feasibility of implementing a 100 MW PTC in the five regions of Brazil. The results indicated that the best region in Brazil to receive this technology is the northeastern region. However, the project is economically unfeasible in all cities analysed. Therefore, a sensitivity analysis of the main parameters that affect the project's net present value is carried out to evaluate the impact of the economic parameters on the economic viability of an optimized PTC plant located in the city with the best technical performance. An optimistic scenario was evaluated considering the system's response to the parameters investigated in the sensitivity analysis. For this scenario, the results pointed to the project's economic viability.

Keywords. Parabolic Through Collectors, Technical-economic Feasibility, Regulated Contracting Environment. Sensitivity Analysis.

1. Introduction

In Brazil, it is possible to observe that, at the same time that energy has its clean and sustainable production, it has an unfavourable framework for emergency cases or perennial situations. To increase the reliability of the electrical matrix, it is necessary to introduce alternative energy sources to ensure the electrical system's stability. From the available renewable solutions, nowadays, photovoltaic plants used in conjunction with storage systems are not financially viable for scale production due to the high costs of keeping constant production using electric batteries [1]. In contrast, heliothermic systems (Concentrated Solar Power - CSP) allow an uninterrupted energy supply using thermal storage. Although CSP systems depend on solar radiation for energy generation, they can reach high capacity factor values by using molten salt as a heat transfer route and storage fluid.

In the literature, it is possible to find studies that approach the applicability and efficiency of the CSP [2-7]. From these works can be observed that, in South America, despite its significant potential, the first solar thermal plant in Latin America was put into operation in 2021. Most of the authors of these studies employ the LCOE as the sole economic viability indicator. It is important to employ other economic viability indicators jointly with LCOE, such as the Net Present Value (NPV), Modified Internal Rate of Return (MIRR), and discounted payback (DPB) in the analysis of such kinds of projects. It is still possible to find in the literature studies that address the uncertainty of some magnitudes when evaluating the economic viability of some renewable sources [8-9]. In these two studies, the stochastic approach is used in conjunction with the Monte Carlo Method, aiming to characterise the risks of the Brazilian market.

This paper aims to present a computational tool to analyse the technical and economic viability of Parabolic Trough Collectors (PTC) heliothermic plants, considering that the electricity produced can be traded in the Regulated Contracting Environment (ACR) of the Brazilian Electric Energy Market (MEEB). Firstly, the PTC plant is modelled and then the parametric structural optimization method is used to optimize its technical parameters. For that, the parametric structural optimization method is used. A sensitivity analysis of the key parameters that affect the project's NPV is performed to evaluate the impact of the economic parameters on the optimized PTC plant's financial viability. From the results of this analysis, an optimistic scenario is defined. This scenario allows us to show that the project could be viable in Brazil. This paper still has the purpose of encouraging immersion and consolidation of the country to adopt new energy solutions from sustainable sources - concerning heliothermic energy. The developed computational tool can be used to assist in the decision-making of the investment viability of PTC plants in ACR, to perform the parametric structural optimisation applied to the PTC topology, and in the study of the impact of the most relevant economic variables on economic viability.

2. Methodology

The applied methodology in this study consists of four main stages. The first stage executes the mathematical and computational modelling of the solar field, the receptors, the power cycle, and the thermal storage, aiming at obtaining the annual produced electric energy throughout the lifetime of the plant.

In the second stage, the annual generated electric energy calculation result is used for the construction of the free cash flow to equity (FCFE) of the enterprise analysed. Based on FCFE, it is possible to extract the investment economic viability indicators. The economic viability analysis is obtained through the financial indicators which use the FCFE instalments as input, the minimum attractive rate of return (MARR), and the investment and financing rates. The cash flow model used in this study follows the basic structure defined by Damodaran [10]. However, such a model was modified to consider the particularities of the taxation of the Brazilian market. In the third stage, the plant was revisited to analyse the optimization possibility of the electric generation results.

Hence, in the third stage, we define the optimization elements (objective function, design variables, and constraints) and apply the so-called parametric structural optimization methodology [11] to maximize the objective function. The objective function was designed to maximize the capacity factor and minimize the LCOE of the plant. In this study, the opening area, the collectors' reflectance, and the number of hours of thermal storage were chosen as the design variables that directly impact the objective function. The simulation intervals were established for each design variable with appropriate incremental steps. In this study, discrete values were adopted. The number of simulations results from the permutation of design variables so that the number of simulations results from multiplying the number of steps for each variable. The simulation is performed for each possible combination, and the objective function's result is obtained. The optimized design of the PTC solar power plant corresponds to the combination of variables that results in the highest value of the objective function.

In the fourth stage, we conduct the univariate sensitivity analysis (SA). In this category of SA, the impacts on the indicator are measured through the variation of each of the parameters separately. In this work, for the SA, the NPV was taken as a financial indicator, whose evaluation takes place against the variation of the following economic parameters: energy price in the RCE, plant installation cost, exchange rate, and the minimum rate of attractiveness. It should be noted that the sensitivity analysis is carried out on the already optimized PTC 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 [12].

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

In (1), $Q^{SF}_{abs.h}$ 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 [13]. 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.

$$Q^{Rec}_{U,h} = \left(Q^{SF}_{abs,h} - Q_{losses,h}\right) = {}_{th} \bullet Q^{SF}_{abs,h} \quad (2)$$

In (2), $Q^{Rec}_{U,h}$ 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^{PC}_{nom}). 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 [14].

$$Q_{TES} = Q^{PC}_{nom} \bullet \Delta t_{load} \tag{3}$$

In (3), Q_{TES} is the maximum power of thermal storage capacity (W); Q^{PC}_{nom} $is\ the$ 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 [15]. 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 thermal energy can be diverted to the TES.

The useful power generated by the power cycle can be obtained by equation 4 [13].

$$Q^{PC}_{U,h} = {}_{PC} \bullet Q^{Rec}_{U,h} \tag{4}$$

In (4), $Q^{PC}_{U,h}$ 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.

$$E^{PC}_{U} = \sum_{h=1}^{8760} Q^{PC}_{U,h} \tag{5}$$

In (5), E^{PC}_{U} 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.

Finally, the project cash flow and the following economic viability indicators are obtained: Net Present Value (NPV), Modified Internal Rate of Return (MIRR), discounted payback (DPP), and the levelized cost of electricity (LCOE). In the present-day Brazilian electricity market, electric power can be traded through two distinct contractual environments: the Regulated Contracting Environment (RCE) and the Free Contracting Environment (FCE). In the RCE, trade is conducted through auctions where the amount of energy and sale prices are established. The proposed methodology is specific to the RCE, where gross revenue is composed of the sale of energy generated for the power plant at an established price. For the PTC, the gross revenue in the year y is obtained using Equation 6.

$$GR_{y} = E^{PC}_{U,y} \bullet \$_{RCE} \tag{6}$$

In (6), GR_{y} is the gross revenue in the year y ((BRL); $E^{PC}_{U,y}$ 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 Equation 7 as an objective function. The idea is to maximize the capacity factor (the numerator of the equation) and minimize the LCOE of the plant (the denominator of the equation). In this study, the opening area, the collectors' reflectance, and the equivalent full-load hours of thermal energy were chosen as the project variables of the CSP system that directly impact the objective function.

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

In (7), E^{PC}_{nom} 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 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 better describe how the relationships between objects are formed and how optimization 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 a PTC plant applied in the five regions of Brazil: North (Manaus), Northeast (Recife and Bom Jesus da Lapa), West-Centre (Brasilia), 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 sensitivity analysis is performed in the optimized plant considering some economic variables. And finally, an optimistic scenario is analysed, 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 and ambient temperature, as well as regional static properties such as latitude, longitude and time zone. They are 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 characterises this region as an excellent place to implant a heliothermic plant, regardless of the adopted topology. Table I summarizes the main parameters defined for the PTC plants simulation. Table II exhibits the annual energy production, and the annual capacity factor (CF) obtained at each simulated location.

From Table II, it is possible to observe that Manaus does not have a good capacity to produce electric energy via solar source, due mainly to the association of the low DNI in the region and the climatological conditions. Different from Manaus, the cities of Recife and Brasilia possess a high capacity for producing electric energy via solar sources. In the case of Brasilia, this is due to the high incidence of DNI together with the dry climate and few clouds of the Cerrado. The cities of Rio de Janeiro and Porto Alegre, on the other hand, have a low capacity for producing electricity via solar sources due to the low incidence of DNI. Added to this reason is the humid climate of the coastal city (Rio de Janeiro) and the cold weather of the Brazilian pampa (Porto Alegre). Electricity production and CF in the Bom Jesus da Lapa region are greater than in the other locations covered in this study. This is due to the region's favourable climatic conditions.

Table I. - Technical parameters for the PTC plant simulation

Class	Parameters	Value
Solar Field	Solar multiple	2
	Number of loops	181
	Opening area of a loop	5,248 m²
	Opening area	949,888 m²
	Total occupied area	332.65 ha
	Reflectivity of mirrors	0.93
	Degree of dirt on the mirrors	0.97
	General optical losses	0.851
	Optical efficiency	0.848
Receiver	Receiver model	Schott PTR80
	Receiver HTF type	Therminal VP-1
	Envelope emissivity	0.86
	Envelope transmittance	0.964
	Thermal loss	190 W/m
Power Cycle	Rated power	100 MW
	Power cycle efficiency	0.356
	Electric conversion factor	0.9
Thermal Storage	Model	Two tanks
	Storage HTF type	Hitec solar salt
	Number of hours of storage	6 h
	Storage volume	26,688.93 m^3
	Thermal storage capacity	1870.79 MW_th
	Min. operating temperature	238 Celsius
	Max. operating temperature	593 Celsius

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)	173.4 1	227.66	300.59	229.10	249.58	362.23
CF (%)	19.82	26.01	34.35	26.18	28.52	41.39

B. *Economic Analysis*

For the economic analysis of the PTC plant in Brazil, we 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 PTC plant of this city feed the cash flow model aiming to obtain the financial indicators calculated in this study. All the construction, operation and maintenance costs of the plants are approached in this evaluation, in addition to taxes and tax rates levied on the revenue collected from the sale of energy in the ACR of the MEEB. In this study, it was considered that the undertaking is carried out with equity capital, therefore, without resorting to financing. Incrementally, the sale price taken for the analysis seeks to represent a proper scenario for the installation of energy sources of production with high costs.

Table III presents the data used for the execution of the economic viability analysis.

Table IV presents the financial indicators result raised to the PTC plant analysis in the city of Bom Jesus da Lapa. 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 assumed an annual generation loss of 1% in the year.

The economic viability indicators show that the investment is financially impractical in the presented conditions. A negative NPV represents a loss to investors. The MIRR, which measures the investment attractiveness, is below the adopted value for the MARR, therefore denoting its unfeasibility. As the Discounted Payback Period exceeds the lifespan of the plant, one more indicator proves the impracticability of the investment, as well as the LCOE. Worth noting that even not counting on the financial viability in Brazil, the project is competitive.

Table III. - Data used in the simulation.

Parameters	Value
Deployment Costs	BRL 2.622 Bi
Project useful life	30 years
Contract price (August 2015 - ANEEL)	BRL 305/MWh
Minimum Attractive Rate of Return	Equal to the cost of equity
Investment Rate	Equal to the cost of equity
Financing Rated	Equal to the cost of third-party capital
ANEEL Inspection Fee (TFSEE)	0.5% of gross revenue
Tariff for Use of the Transmission System (TUST)	BRL 1.5/kW.month
O&M - Fixed	BRL 70/kW/year
O&M - Variable	USD 3/MWh
Exchange Rate (Average Quotation of 2021)	BRL 5.40/USD
Linear Depreciation	30 years
Tax Regime	Presumed Profit

Costs of equity and third-party [12]	
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)	- BRL 1.690 Bi
Modified Internal Rate of Return (MIRR)	4.38% p.a
Discounted Payback Period (DPP)	>30 years
Levelized Cost of Energy (LCOE)	52.28 USD/MWh

C. *Optimisation*

The heliothermic plant of the PTC type optimisation reinforces the possibility of changing the financially impracticable scenario to a favourable one. This study opted for parametric optimisation aimed at the maximization of the capacity factor and the minimization of the LCOE. Such optimisation is a work of exploration of the space of possibilities for the interest variables according to an objective function. Noteworthy that by altering the implementation costs due to the alteration of the project variables, the proportionality of each equipment cost must be obeyed, i.e., in case the plant scale is altered in a considered way, it is important to review the economic expenses. As in this study a constant rated power was adopted, the costs can be assumed as constant as well. Table V shows the interest variables with their respective intervals with initial and final values and the incremental step. Reflectance is characterised as a very important parameter for optical efficiency.

Table V – Design variables for optimisation problem

Decision Variable	Initial Value	Final Value	Step
Opening area of the SF (m^2)	800,000	1,400,000	100,000
Hours of storage (h)	4	8	1
collector reflectance	0.9	0.98	0.02

Based on the encountered values for the capacity factor and the LCOE in the executed simulations, the combination of the optimised parameters whose products result in the biggest value for the objective function is acquired. Table VI has the worst and the best combinations of the parameters for the objective function. In possession of the data from the parametric optimisation process, a technical and economic analysis of the project viability can be executed. The technical and economic updated data with the optimisation are shown in Table VII.

Table VI - A summary result of the simulations.

Decision Variable	Results	
	Worst Result	Best Result
Opening area of the solar field (m^2)	800,000	1,000,000
Number of hours of storage (h)	4	6
Reflectance of the collectors	0.9	0.9
Capacity factor (%)	39.97	41.80
LCOE (USD/MWh)	54.11	51.74
$f_{objective}$	0.738	0.808

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

Solar multiple		2.0074	
Opening area of the solar field		1,000,000 m²	
Number of hours of storage		6h	
Storage volume		29,688.93 m³	
Thermal storage capacity		1870.79 MWh	
Deployment costs		BRL 2.662 Bi	
Results			
Parameters	**Not optimised**	**Optimised**	**Difference**
Annual Energy (MWh)	362,233.8	366,000	1.03
CF (%)	41.3923	41.8	0.98
NPV (BRL)	- 1.690 Bi	- 1.682 Bi	0.5
MIRR (% p.a.)	4.38	4.4	0.45 pp.
DPP (years)	> 30	> 30	-
LCOE (USD/MWh)	52.28	51.74	1.03 %

The condition where the nominal power is 100 MW with the solar field opening area of 1,000,000 m² and the power cycle efficiency of 0.356 results in a solar multiple of 2.0074. It must be noted that the optimisation process did not aim at identifying the ideal nominal power. With that, given that the capacity of the plant production is not altered, it is not found to decrease or increase the enterprise cost even with a slightly bigger area. With plant optimization it is observed an increase in the annual production of energy, however, this increase is low. This fact proves that the choice of the initial parameters was right because even after the optimisation process, there are no verified big alterations of the indicators in the analysis. Searching for an optimal point of operation assists in increasing the productive capacity of the plant. Thus, it can be affirmed that, even with little impact, the parametric optimisation process made the investment more technically and economically attractive. Worth noting that the reflectivity suffered a reduction, i.e., the optimisation found a point where there is more energy generation with less performative mirrors.

Finally, note that the subtle improvements arising from the optimisation project were not enough to configure the economic viability of this type of investment in the Brazilian territory. Despite that, based on LCOE, it is possible to observe a competitive value in comparison with the value of 75 USD/MWh predicted in IRENA (2021). In other words, the project has an energy price very competitive and, in certain conditions, it would be feasible.

D. *Univariate Sensibility Analysis*

Considering that the investigated scenarios proved to be economically impracticable, it was decided to carry out a univariate sensitivity analysis of some parameters that impact the calculated indicators. Hence, actions that can become the investments feasible can be identified. From the cash flow analysis, it is possible to identify that the economic factors are big hindrances to the heliothermic topologies implementation, more specifically, the installation cost and the annual recipe. For that reason, in this study, the direct cost of installation, the sale price in the ACR, the exchange rate and the MARR will be applied as sensitivity variables. Noteworthy is that the direct cost of installation contemplates the contributions of many elements (solar field, storage systems, fluid of heat transfer, among others). The NPV will be the variable in evaluation. Next, the results obtained with the analysis of each of the cited variables will be exposed.

The recipe of plants like the one in question is the function of the produced electricity and the sale price in the ACR. In this case, the sale price of the energy is characterised as the main economic factor which defines the gross income of such plants. It was considered a range of variation from 70 USD/MWh to 375 USD/MWh for the selling price in the ACR. From the sensitivity analysis, it is verified that the optimized PTC plant is economically feasible for sale prices above R$ 875,29/MWh.

The financial indicators, as well as the cash flow, are directly affected by the installation cost. Such cost is inversely proportional to the cash flow since increasing the installation cost impacts it negatively. In this study, a rate of variation from 40% to 160% of the installation cost of the optimised plant was established. From the sensitivity analysis, it can observe i) the descending behaviour of the NPV based on the increase in the installation cost; and ii) for the economic viability of the project, the installation cost should be less than RS 850 Mi.. For the real installation to reach this level, it would be necessary to reduce its cost by an order of 70%.

The exchange rate is another parameter that affects the NVP indicator. It was adopted in this study a range of exchange rate values from R$ 1.00/USD to R$ 6.00/USD. Such values are valid for the Brazilian reality since the exchange rate varied between R$ 1.08/USD and R$ 5.40/USD between 1997 and 2021. From sensibility analysis, it can be observed that the NPV depends significantly on the import costs imposed by the exchange rate. The economic viability is present from the use of an exchange rate of R$ 1.79/USD. Given that the exchange rate has been above R$ 5.00/USD in the last few years, technological development policies focused on the national production of CSP plants are necessary, as well as tax exemptions for imports to facilitate the implementation of such ventures on Brazilian soil.

The MARR used in the evaluated scenarios in this study was equal to the WACC defined by ANEEL. Nonetheless, for the sensitivity analysis, the values for the MARR varying according to the basic interest rate of the Brazilian economy (SELIC Rate) of the last few years are considered. From the sensitivity analysis, it is possible to notice that the NPV has a descending behaviour with the increase of the MARR.

From the sensitivity analysis presented in this paper, it is possible to conclude that, among the parameters of the sensitivity analysis about the NPV, the energy sale price is what most impacts the economic viability of the PTC plant of Bom Jesus da Lapa. Subsequently, there is the exchange rate and the installation cost.

E. *Optimistic scenario*

Based on the obtained results via sensitivity analysis, a simulation considering an optimistic scenario for the installed PTC 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 optimised	Optimistic	Difference
Sale price (BRL/MWh)	305	488	46.15%
CAPEX ((Mi BRL)	2662	1400	62.13%
Exchange rate (BRL/USD)	5.4	4.6	16%
MARR (% p.a.)	7.95%	2.2% p.a.	113.3 pp

With regard to the installation cost (CAPEX), the historic percentual reduction of the unit cost of heliothermic generation between 2010 and 2020 was used. The energy sale price was estimated considering the degree of variation in the sale prices of the results of generations auctions publicly displayed by ANEEL. The exchange rate adopted was that 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 IX.

Table IX. - Comparison of results between the non-optimized design and the optimized design PTC plant.

Scenario	NPV (BRL)	MIRR (% p.a.)	Payback (years)	LCOE (USD/MWh)
Optimistic	1.256 Bi	8.02	27.52	27.21
Standard	- 1.682 Bi	4.4	>30	51.74

From Table IX, it is possible to observe that there is economic viability for the PTC plant optimised according to the aforementioned conditions. It should be noted that there was a generalised improvement in the financial indicators. For the first time, it is observed that the NPV is not negative, i.e., there is an indication of profit for the investors. The MIRR increased by 8.02%, staying above the MARR value (defined as 2.2% p.a). This means that for the requested rate, the development is attractive. The LCOE suffered a large decrease reaching the level of 27.21 USD/MWh, culminating in a significant increase in the plant's competitiveness. The DPP was reduced for 27 and a half years.

4. Conclusion

In this paper, it was developed a computational tool in Python for a technical-economic feasibility analysis of a PTC plant in Brazil. With that, the solar field, the receiver, the power cycle and the thermal storage were modelled. The tax regime of the Brazilian electricity market was adopted for the calculation of cash flow and economic viability indicators.

For the validation of the technical results found via the developed tool, an energetic production analysis of a 100 MW PTC solar power plant was carried out in five different Brazilian regions. Regarding the economic question, analyses were generated contemplating the city of Bom Jesus da Lapa (BA, Brazil) due to the excellent levels of solar irradiance in this location. Despite attesting to reasonable energy production rates for this city and a good capacity factor, the economic unfeasibility for this type of enterprise was verified when considering the following financial indicators: NPV, MIRR, DPP, and LCOE. The installation cost parameter was priced in foreign currency because the equipment is mostly imported.

To make the plant viable, parametric optimisation of the variables opening area of the solar field, number of hours of thermal storage and reflectance of collectors was carried out in order to identify an optimal point for an objective function. For this purpose, 175 simulations were performed, which indicated an improvement in energy production of only 1%, which means the choice of the plant had already been adequate. Regarding the economic aspects, after the optimisation, the indicators showed improvements in the same order of magnitude, however, the project continued to be economically unfeasible.
Next, a sensitivity analysis of the NPV was performed, taking the energy sale price in the ACR, the installation cost, the exchange rate and the MARR as variables. Thus, an optimistic scenario was created considering the results of the sensitivity analysis, which proved to be economically viable. Even though the optimistic scenario had shown to be economically viable, it must be noted that it takes 28 years for profits to be obtained. From the performed analyses in this study, it can be concluded that the evaluated technology has a high potential to be developed in the coming years in Brazil.

To improve the economic viability of PTC 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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