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Economical Assess of Concentrated Solar Tower Power Plants in the Brazilian Scenario

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Abstract: Renewable energy integration has been used as one the most common alternatives for governments that chase a diverse energetic matrix and a sustainable expansion of economy. Developing countries with high values of Direct Normal Irradiation (DNI) such as Brazil tend to consider photovoltaic power plants as a valuable option, but the small capacity factor of these systems is often an obstacle. As the energy demand increases, this creates an opportunity for the integration of concentrated solar tower (CST) plants. In this context, an appropriate economical evaluation becomes urgent so to introduce and consolidate this technology into the Brazilian reality. This paper, whose goal is to assess the economical viability of the Solar Tower technology at the Regulated Contracting Environment (RCE), appraise a variety of financial indicators of a power plant simulated in Brazil. The conducted analysis can be an important tool for governments and agencies to make the CSP technology an attractive solution to investors. The results of this paper show that a reduction of 33% on the initial costs and 14% on the discount rate can reduce the Levelized Cost of Energy (LCOE) up to USD 0,027 per kWh.

Keywords: CSP; Economic Assessment; Net present value; Regulated Conctracting Environment; Renewable Energy

1. INTRODUCTION

As an emerging economy country, Brazil has registered an increase in energy demand. However, the dependence on hydro sources is still a barrier for both a consistent production capacity growth and a diversification of the energetic matrix. Based on the data released by the National Agency of Electrical Energy (Aneel) in 2018, roughly 60% of the energy produced in the country was generated by hydropower systems (HPS) ANEEL (2018). Nonetheless, Brazil has an appropriate climate for the integration of solar-based systems of generation, as a consequence of the high rates of Direct Normal Irradiation (DNI) in some regions of the country.

In this sense, a substantial expansion of Distributed Generation (DG) is observed as photovoltaic systems are becoming more popular and financially viable, specially since Normative Resolution 482 (REN 482/2012) was published by ANEEL, whose goal was to stimulate and also regulate the integration of mini and micro systems of DG ANEEL (2012). If, on the one hand, the integration of photovoltaic sources are positive, on the other the photovoltaic systems are limited by some factors that restrict their consolidation. Among these factors, the intermittence on generation and the costs associated with the storage systems (whose application is pointed out as the main solution for this issue), are the ones that stand out, as shown by Ju et al. (2017).

In this context, it is worth mentioning the possibility of bringing into the Brazilian matrix new solar-based sources, with the same advantages of the photovoltaic systems, such as the production of renewable energy with low emission of greenhouse gases, and without their disadvantages. Technologies such as the Concentrated Solar Power (CSP), specially the Solar Tower (STP) and the Parabolic-trough Collectors (PTC) power plants, have gained strength in the global scenario (Islam et al. (2018); Amadei et al. (2013); Shabbirr and Liang (2018)). Through the usage of molten salt as storage system, this technology allows the production of energy in a ceaseless manner, enhancing the capacity factor without impacting the final cost of the power plant, as shown by Ju et al. (2017) and Islam et al. (2018).

Although the literature is already indicating the viability of these projects in a variety of countries, both technically and economically, studies considering the Brazilian scenario are still embryonic, which delays, for example, the implementation of possible government incentives and regulatory benefits. Therefore, an appropriate economical assess plays a crucial role in determining the viability of a certain technology. When comes down to this kind of evaluation with CSP plants, the studies developed by Purohit and Purohit (2017); Abbas and Merzouk (2012) are good examples. By simulating power plants with typical technical data in several sites and by estimating the total cost associated with their implementations, it is possible to measure the Levelized Cost of Electricity (LCOE) associated to the CSP system and hence determine its viability.

However, it is also clear from the literature that most economic assessments are made by analyzing LCOE as the main and sometimes the only indicator capable of determining whether the technology is viable to be implemented or not. It is crucial to consider other financial indicators, such as the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Payback. Besides, it is worth performing the sensitivity analysis with the most important variables of the study, one of them being the energy purchase price. From this analysis it is possible to determine possible incentives to be created by the government.

Based on these facts, and also in the Brazilian potential for integrating solar-based sources, this work aims to evaluate, by using the previously mentioned indicators and analysis, the viability of building and integrating CSP plants into the national matrix. To do so, the technical characteristics of the Gemasolar project and its associated costs were used, and one site in Brazil with suitable climate conditions was chosen to execute the simulations. The technical characteristics and the associated costs were both extracted from the literature (De Oliveira et al. (2019); Starke et al. (2018); Turchi and Heath (2013)).

In the following sections, the technology overview of the solar tower project is presented. The methods applied for determining the energy production, for gathering the required data associated to the total cost of the CSP plant implementation and also for performing the economical assess are then described. In the sequence, the results are presented and analyzed. Finally, the conclusions are discussed and future measurements are proposed in other to make CSP economically viable.

2. TECHNOLOGY OVERVIEW

In regard to the topology considered, the CSP technology examined in this work is the Central Receiver System (CRS), also known as Solar Tower Power plant (STP), which shares the same working principle of the other topologies. The Gemasolar power plant was built following the CRS topology and uses the molten salt (60% KNO_3, 40% $NaNO_3$) as Heat Transfer Fluid (HTF), due to its capability of storing the thermal energy, allowing electricity generation in absence of solar radiation (Ju et al. (2017); Islam et al. (2018)). Figure 1 shows the full view of the Gemasolar power plant, located in the province of Seville, Spain.

Figure 1. Gemasolar power plant (Torresol (2018))

By means of the circulation of the HTF, it is possible to store the solar energy collected and concentrated by the reflectors. These are optical devices capable of reflecting the sunbeams to a desired focusing point, which in this case are the collecting tubes inside the central receiving tower. Throughout them flows the HTF. Once the appropriate operating temperature for each technology is reached ($300 - 1000^oC$), the HTF goes to a series of heat exchangers where the thermal energy is used to heat water and generate a super-heated steam. The steam feeds the turbine and then goes to the condensing unit where it returns to its liquid state, so that the water can be reused on the generation cycle. The turbine is coupled to a generator, which is responsible for generating electrical energy to be injected on the grid.

3. METHODOLOGY

The developed study was divided into 4 main stages, as shown in table 1.

To examine the technical viability of the CSP plant, simulations utilizing the System Advisor Model (SAM) software were made employing the Gemasolar project data available on the literature (Torresol (2018); Amadei et al. (2013)), as well as the weather data for one Brazilian city (Bom Jesus da Lapa). It is worth emphasizing that the data applied here have typical meteorological year (TMY) extension and were extracted from National Solar Radiation Database (NSRDB). Through the simulations, it was possible to obtain a variety of outcomes, including the total energy produced over the power plant's total lifetime of 30 years.

Validation of the plant's technical data and performance was made comparing the simulation results with other works (Amadei et al. (2013); De Oliveira et al. (2019)). Once the output data was endorsed, the next stage of the analysis consisted in the evaluation of the plant's economic

Table 1. Methodology

Stage	Activity	Objective
1	Simulation of a CSP plant with technical attributes similar to the GEMASOLAR project, considering the Brazilian scenario.	Acquisition and validation of energy generation data, comparing it to the results achieved results by Amadei et al. (2013).
2	Building the cash flow model, considering the associated costs and taxation of the power plant, as well as the gross revenue obtained by selling the energy on the Brazilian RCE.	Deterministic analysis of the cash flow model, utilizing well established indicators, to assess the feasibility of the STP plant under the Brazilian scenario.
3	sensitivity analysis of the proposed indicators, taking into account technical and economical parameters that may affect the economic viability.	Evaluating how the cash flow model and the economic indicators react to the variation of specific parameters.
4	Simulation and examination of the system's performance in a proposed optimistic scenario.	Establishing the potential benefits of investing in a STP plant under favorable economical conditions, contemplating the sensitivity of the model to the parameters of the previous stage.

viability, taking into consideration the Brazilian energy market scenario, and that the energy produced is traded on Regulated Contracting Environment. Table 2 presents the project's cash flow model, designed to measure all cash inflows and outflows through the plant's lifetime, considering that the sale of electricity generated by the plant occurs through contracts resulting from electricity auctions carried out by the Chamber of Electric Energy Commercialization.

Table 2. Cash flow model

Cash Flow Model	
(+)	*Gross Revenue*
(-)	*Gross Revenue taxes*
(=)	*Net Revenue*
(-)	*Operational expenses*
(=)	*Profit Before Income Tax (PBIT)*
(-)	*Income Taxes*
(=)	*Net profit (NP)*
(+)	*Return of Investment Capital*
(-)	*Investment*
(=)	*Free Cash Flow to Equity (FCFE)*

Having established the cash flow model in view of the previously mentioned scenarios, the deterministic economic analysis was carried out with the use of economic indicators such as the Net Present Value (NPV) and Levelized Cost of Energy (LCOE), presented in (1) and (2), respectivelly.

$$NPV = \sum_{j=1}^{n} \frac{C_j}{(1 + r_{disc})^j} \tag{1}$$

$$LCOE = \frac{I_0 + \sum_{j=1}^{n} \frac{A_j}{(1+r_{disc})^j}}{\sum_{j=1}^{n} \frac{E_j}{(1+r_{disc})^j}} \tag{2}$$

In (1), C_j is the net cash flow on the year j, and r_{disc} is the discount rate of the NPV. In (2), I_0 represents the initial investment, A_j is the annual cost on the year j, and E_j is the total energy generated by the system on the year j. Other indicators considered were the discounted payback and IRR.

After performing the deterministic analysis of the data collected via simulation, the next step consisted in the identification of the technical and economical parameters that impact the most on the presented indicators and, consequentially, on the STP plant feasibility on Brazilian territory. According to (1), the NPV of a project is susceptible to two parameters: net cash flow and discount rate. The former contains many variables, such as the gross revenue, taxes, installation costs and equipment depreciation. The discount rate is calculated by ANEEL using (3), where r_f is the rate of return on risk-free assets, β is the leveraged beta according to the Brazilian market, $r_m - r_f$ is the risk premium of the reference market, and r_b is the Brazilian risk premium (ANEEL (2014)).

$$r_{disc} = r_f + \beta.(r_m - r_f) + r_b \tag{3}$$

In this work, the investigated parameters were the discount rate, the unit cost of the plant's equipment and the energy purchase price under the Brazilian RCE. A sensitivity analysis was made, with the purpose of comparing the direct influence of these parameters and pointing which incentives might be effective to encourage investment in CSP plants. Finally, an optimistic analysis was proposed, observing the inflows and outflows of the cash flow model under more favorable conditions to investors, and how the economic indicators could suggest which variables must be focused in order to make solar thermal energy a appealing energy source in Brazil.

4. RESULTS

Table 3 presents the technical data used on the simulations conducted to validate the plant's model, and table 4 shows the technical and financial parameters adapted to the Brazilian base case, as well as the taxes applied to the gross revenue under the Presumed Profit taxation scheme.

The results for the economical assessment are presented in the following order: firstly, the result for the plant's model validation is displayed. Subsequently, it is shown the result of the base case simulated on Bom Jesus da Lapa, under the present conditions. Lastly, the results achieved by the sensitivity analysis and the simulation of an optimistic scenario are shown.

Table 3. Simulated plant's technical data

Category	Parameter	Value
Climate	Latitude [°]	37,42
	Longitude [°]	-5,9
	DNI [kWh/m^2]	2089
	Wind's average speed [m/s]	3,66
	Average ambient temperature [K]	291,45
Systems's Design	Operation point (DNI) [W/m^2]	880
	Design HTF inlet temperature [K]	565
	Design HTF outlet temperature [K]	290
	Solar Multiple	1,90
	Full load HTF operation hours	15
Heliostats	Number of Heliostats	2650
	Heliostat area [m^2]	120
	Mirror reflectance	0,96
Central Tower	Tower height [m]	140
	Receptor height [m]	14
	Receptor diameter [m]	8,5
	Receiver design thermal power [MW_t]	92
Power Cicle	Design turbine output [MW_e]	19,9
	Rated cycle conversion efficiency	0,375
	Boiler operating pressure [bar]	100

Table 4. Base case simulation inputs

Parameter	Value
Latitude [°]	-13,26
Longitude [°]	-43,41
DNI [kWh/m^2]	2099,1
Tower Height [m]	1126,47
Receptor Height [m]	9,81
Receptor Diameter [m]	8,20
Heliostat Number	28,79
Income Tax [%]	8
Gross Revenue Taxes [%]	3,65
Discount rate [%]	7,16
Energy purchase [USD/kWh]	0,18
Total equipment cost [USD]	179.850.000,00

4.1 Model validation

After acquiring the weather data and implementing it on the simulation software, the simulated system's performance was compared to results achieved by other works in different contexts. Table 5 shows the SAM simulation output and then compares to a similar power plant model simulated by Amadei et al. (2013) in the Chinese scenario. Comparing both cases, the error found is fairly low, which endorses the model proposed by this study. The small discrepancy might be explained by an incompatibility between the meteorological data used in each study, since any difference in the plant's technical attributes can impact on it's efficiency and energy generation.

Table 5. Model Validation

Data	Simulation	Amadei et al, 2013	Error (%)
Annual Generation (GWh)	85,49	87,62	-2,43
Efficiency (%)	14,14	13,67	+3,44

4.2 Results of the base case

The base case is the model's economic performance considering the present Brazilian scenario. Figure 2 presents the cash flow chart for the simulated CSP power plant. The initial investment was obtained considering the costs associated with HTF, tower, mirrors, turbines and other equipment, as well as the technical data provided by Torresol (2018). The installation costs, as shown, are considerably high, reaching about USD 200 million. The gross revenue in this simulation was composed by the sale of the energy generated by the simulated power plant, using the average purchase price of solar energy on the Brazilian power purchase agreement ANEEL (2019). At the end of the plant's lifetime, it is also included the plant's residual value, estimated as 12% of the initial investment according to Brazilian federal norms (RFB (2017)).

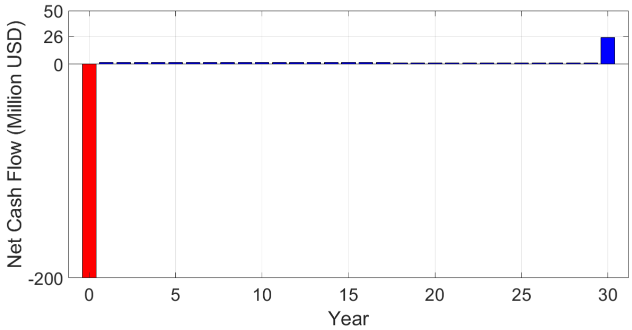

Figure 2. Cash flow of the solar thermal project.

Using (1), the simulation obtained a LCOE of USD 0,055 per kWh, and a NPV of -USD 178,5 million, considering a discount rate of 7.16% per year. The negative NPV indicates that the project is not economically viable, as the cash flows obtained through the plant's lifetime cannot compensate the high installation costs.

4.3 Sensitivity analysis

Figure 3 shows the sensitivity of the NPV to the variation of the discount rate. As expected from (1), it represents an hyperbolic function, in which the NPV increases with lower discount rates. Figure 3 also highlights the Net Present Value on Brazil's present scenario. It can be concluded from the curve that the NPV is not very affected by the discount rate, although lower rates can impact the economic viability under favorable circumstances.

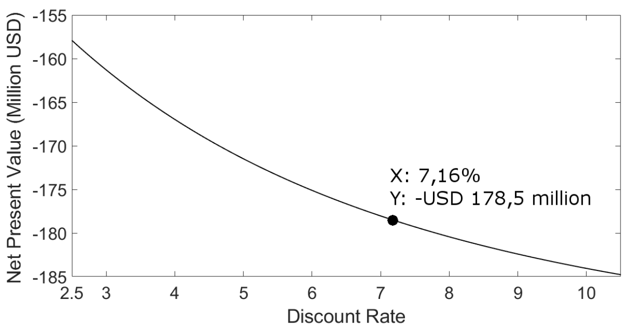

Figure 3. Variation of the NPV in function of r_{disc}

As it is shown in Figure 4, the relation between the NPV and the energy selling price is linear, as expected, and the former is heavily impacted by increase of the energy prices. The price variation starts with the base case scenario, represented in red on Figure 4, which takes into account the average purchase price of solar energy. It is important to emphasize that even an increase of 400% on the selling price is not enough to make the project economically viable, as the installation costs are still very high. The project would only become viable if the energy was to be sold with prices higher than USD 0,27 per kWh, an increase of 575% on the average auction price.

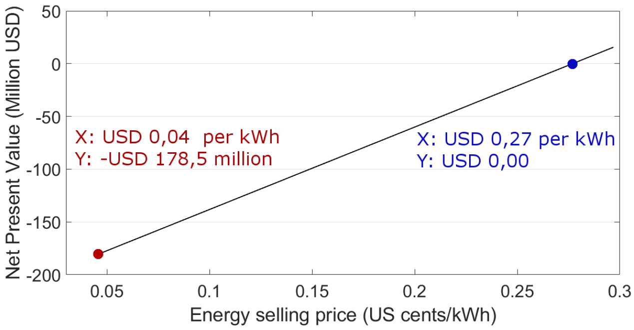

Figure 4. NPV sensitivity to energy selling prices variation.

Figures 5 and 6 show that the relation between the economic indicators and the the variation of the power plant's installation costs is also linear. A decrease of 60% on the unit costs is responsible for an increase of nearly 70% on the NPV, and a decrease of 55% on the LCOE, which is very promising. The reduction of energy generation costs is a global tendency, as observed by international reports (IRENA (2018)). In the Brazilian scenario, the falling costs can also be caused by government incentives, exchange rates and tax reductions.

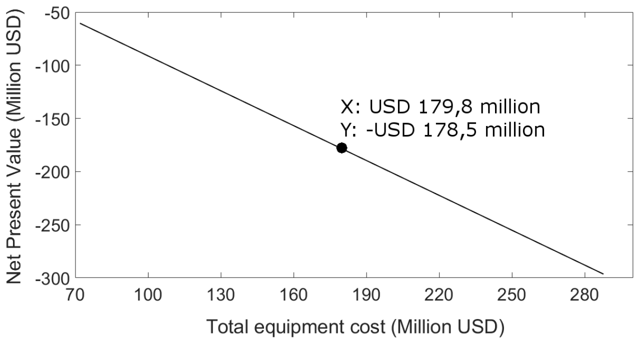

Figure 5. NPV as a function of the total equipment cost.

4.4 Optimistic Scenario

The optimistic analysis was made taking into consideration the system's response to the parameters that were investigated on the sensitivity analysis. The purchase price on the RCE was chosen from the American sales revenue prices of 2018 (EIA (2019)).

International reports (IRENA (2012)) estimate a decrease of nearly 40% on the overall CSP costs, in an aggressive scenario. The local manufacturing the CST equipment could decrease the costs even more.

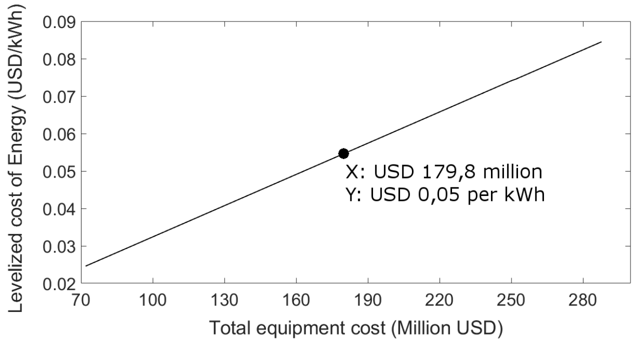

Figure 6. LCOE as a function of the total equipment cost.

The discount rate used on this analysis also reflect the decrease of Brazilian risk premium under an optimistic scenario. The study inspect the system's financial performance under the Central Bank's federal funds rate (BACEN (2019)).

Table 6 shows the result of the proposed study, comparing it to the outcome of the base case. The installation costs were reduced by 33%, and the discount rate was reduced by 42%. The LCOE obtained by the simulation was USD 0,027 per kWh. The high increase on the NPV shows that the investment can be very profitable with the proper incentives.

Table 6. Comparison between the base and optimistic scenarios

Parameter	Base case	Optimistic Case
Energy Price [USD/kWh]	0,04	0,17
Discount Rate [%]	7,16	4,25
Total installation cost [USD]	179.850.000,00	107.910.000,00
NPV [USD]	-178.457.814,65	50.697.453,02
TIR [%]	-4,77	7,52
LCOE [USD/kWh]	0,055	0,027

Figure 7 shows the Net Cash Flow for the power plant's optimistic scenario. This result is consistent with the research made by international organs on the matter of renewable energy (IRENA (2018)), and it signalizes a promising future for Solar Tower power plants and other CSP technologies, since there has been a global trend of energy cost reducing.

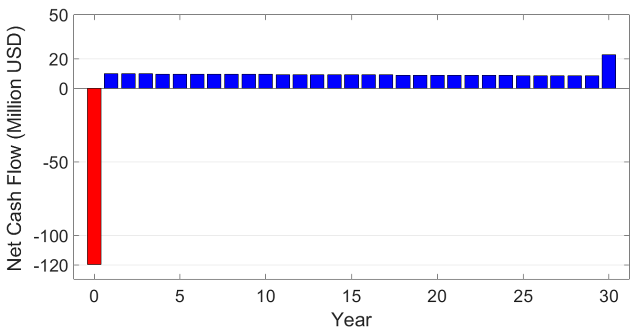

Figure 7. Net Cash Flow for the optimistic scenario

5. CONCLUSIONS

This study provides the input for the decision-making process regarding the implementation of the CST technology on Brazil, and the incentives needed in order to make it an attractive solution to investors on renewable energy.

The results shown in this paper confirm that while the Solar Tower technology isn't economically profitable on Brazilian territory at the present moment, the construction of a similar plant as the Gemasolar in Brazil can be viable with the proper incentives.

Simulations have outlined the variables that impact the most on the economic indicators considered. Reduction of the installation costs were appointed as having the biggest influence on the economical feasibility of the project. This is promising, since the general energy production costs have been declining through the years (IRENA (2018)).

There are no incentives from the brazilian government to the Solar Tower technology yet. The CST cost depends, to a certain degree, on price fluctuations of the underlying nonfuel commodity inputs. Some examples of commodities used for CST components are steel, concrete, sand, aluminium and plastic. The degree to which commodities can be supplied locally, as well as the CST technology prices, can have great impact on the installation costs of the power plant. Manufacturing mirrors, turbines and other components on local territory can lead to high price reduction, making the project economically feasible.

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