Techno-economic analysis of a solar tower CSP Plant with thermal energy storage in southern Honduras

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Abstract. For many years, solar thermal energy has been relegated to second place to photovoltaic solar energy in terms of electricity generation. At the end of the 1980s, an alternative to solar photovoltaic plants emerged, Concentrated Solar Power (CSP) technology. This type of technology presents a commercial option for grid-connected solar plants for the utility market due to its high performance and efficiency in energy conversion, as well as its clean generation of electricity without greenhouse gas emissions. Currently, in Honduras the use of solar thermal energy is reduced to heating processes and product sanitation in the industrial sector, wasting the country's great solar thermal potential. This document focuses on the evaluation of a Solar Tower CSP plant with 10 hours thermal storage in the southern area of Honduras, analyzing the departments of Valle and Choluteca. The methodology used for this research is a quantitative approach based on collecting meteorological data of the solar resource in the area and costs associated with the plant, this to test a hypothesis. This evaluation was carried out from a technical, economic and environmental point of view. The research managed to determine values of Levelized Cost of Electricity (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR) and project recovery period for the different scenarios presented in the two departments analyzed. Putting all the results together, it was found that the department of Valle has the lowest LCOE compared to the department of Choluteca. Likewise, the values of NPV, IRR and recovery period determine that the project is more profitable in the department of Valle.

1. Introduction
The growing world energy demand and the desire to decarbonize electricity production due to the enormous dependence of countries on fossil fuels represent a current problem. This has led society to seek sustainable development based on the use of clean and renewable energy. According to the Global Status Report, the world's electrical matrix has 27.3% participation by renewable energy [1]. In comparison with developing countries that have many natural resources, this participation increases. In Honduras, the participation of renewable energies in the electrical matrix in 2018 reached 67% according to the General Energy Balance of the respective year [2].

Over the years, conventional renewable conversion technologies, such as solar or wind, have become more efficient. Also, new technologies have appeared in development that promise to lessen the fluctuations and limitations that conventional technologies present when depending entirely on the energy resource. Among these technologies is concentrated solar power.
Concentrating Solar Power (CSP) consists of capturing direct normal solar irradiation and concentrating solar heat from it at one point by means of different reflective technologies. The heat produced is transferred to a working fluid that is responsible for heating water and thus generating steam to drive a steam turbine. This type of working fluid can be used together with energy storage systems in tanks at high temperatures and thus allow the plants to operate constantly, since part of the heat is stored. This allows steam production to be monitored and power to be supplied in the absence of solar radiation, adding more hours of plant availability and stable power generation regardless of fluctuations caused by the primary energy resource.

Several articles and studies evaluate the feasibility and current status of this type of technology around the world. Muñoz, Rodríguez, and Abanadés evaluated the DESERTEC mega-project, a German proposal to secure energy resources for the main areas of the Middle East in Europe and North Africa (MENA) [3]. Romero, Buck, and Pacheco presented an analysis of the technology situation evaluating projects such as Solar Tres and PS10, as well as hybrid plants SOLGAS, SOLGATE and CONSOLAR [4]. Ahmed, Bernardos, Fernandez, Solvang, and Branth analyzed the profitability of a CSP plant using parabolic cylinders and central receiver in Tanzania using System Advisor Model [5]. Xiaoru, Xinhai, Wenrui, and Wenfu, conducted an LCOE analysis of a Solar Tower CSP plant with different types of molten salts in China [6]. Musi, Grange, Sigouridis, Guedez, Amstrong, Slocum, and Calvet, made a techno-economic LCOE analysis of CSP plants analysing all 74 CSP plants worldwide [7].

Like the previously mentioned articles, this research focuses on a techno-economic study of the implementation of a CSP plant, specifically a Solar Tower with an installed capacity of 50 MW and thermal storage of 10 hours, with the novelty of being the first CSP project in Central America and the second in Latin America, after the Cerro Dominador Project in the Atacama Desert, Chile. Due to the location of the country in terms of solar radiation, the southern area of Honduras is analyzed considering the departments of Valle and Choluteca as the ones with the most direct normal irradiation. A comparison will be made between the values of LCOE, NPV, IRR and recovery period presented in both departments.

Through this research, it is sought to encourage the implementation of this type of solar thermal power plants in the country as an alternative for a stable renewable generation without fluctuations due to the primary energy resource as it is the case of solar or wind energy. In this way, it will be possible to diversify the country's energy matrix with new renewable technologies and leaving aside the dependence on fossil fuels and thermoelectric plants when looking for a firm power.

The rest of the document is structured as follows. The “Methodology” section presents the methodology and input parameters used for the research. “Results and Analysis” section presents the output parameters and the discussion of the results. The last section “Conclusions” presents the final thoughts based on the results and analysis that was made.

2. Methodology
In this research a Solar Tower CSP Plant has been modelled in two locations in southern Honduras, specifically the departments of Valle and Choluteca, using the System Advisor Model (SAM) provided by the U.S National Renewable Energy Laboratory (NREL). The technical and environmental analysis were made in SAM, while the economic analysis was made using Microsoft Excel.

2.1. Modelling and Optimization
The modelling and optimization of the Solar Tower CSP plant was performed on SAM software version 2020.2.29. SAM calculated the power generation of the plant over the 30-year project lifetime. For the plant model in this research was used SAM CSP Power Tower Molten Salt performance. The optimization option generates the heliostat field array by placing each heliostat in an optimal position to decrease losses from shadowing or shielding. The heliostat field layout is made based on the geometry of the central tower and the receiver. The fluid used in this research is molten salt composed of 60% NaNO₃ and 40% KNO₃. Molten salt is the most used fluid in the industry today due to its low cost and high calorific value among other advantages. For the piping system, it was selected AISI316 stainless steel recommended by SAM for its high performance when interacting with molten salts, thus
meeting the needs of the working fluid. For the power block a Rankine cycle was chosen, consisting of two heat exchangers where the thermal energy is transferred from the working fluid to the water, a pre-heater, an evaporator and an over-heater. SAM presents design parameters for the Rankine cycle based on the 50MW installed. A storage with two tanks was chosen, the first for the storage of the hot molten salt and the second for the cold storage.

2.2. Financial parameters
With the values obtained in the SAM simulations, a techno-economic analysis was developed. The economic analysis was done based on two financing scenarios for the initial investment: With financing and without financing. In both scenarios two considerations were taken for the initial investment: considering the land cost or not considering the land cost. The O&M costs are the same for both situations. In the scenario with financing a 70% debt is projected by means of a loan and 30% of the investment is run by the shareholders. Meanwhile, in the case without financing the total investment comes from the shareholders. The LCOE is calculated as the main output parameter in this research. The LCOE is the division of all the costs, such as initial investment, O&M costs, etc., presented in the project during its lifetime by the energy generated in those years. Other output values as NPV, IRR, payback period and cash flow during the life of the project are also calculated. For the initial investment, SAM provides cost of the plant components and O&M costs. Land cost and Cost per building and environmental permit are specifically for projects build in Honduras. Table 1 presents all the costs associated to a Solar Tower CSP Plant.

| Item                        | Value                  |
|-----------------------------|------------------------|
| Heliostat field             | 140 $·m⁻²              |
| Land cost                   | Based on the department|
| Cost of the tower           | Based on its dimensions|
| Cost of the receiver        | Based on its dimensions|
| Thermal energy storage      | 22 $·kWh⁻¹             |
| Power cycle                 | 1,040 $·kWₑ⁻¹          |
| Contingency                 | 5%                     |
| Insurance                   | 0.7%                   |
| Fixed O&M cost              | 65 $·kW⁻¹              |
| Cost per Environmental Permit| 0.10%                 |
| Cost per Building Permit    | 1%                     |

Depending on the scenario studied, without or with financing, certain specifications and input parameters to be taken are presented. For the electric power rate, the corresponding sale value for solar energy in Honduras was used in both scenarios. Table 2 presents the financial input parameters taken for this research.

| Parameter                  | Without financing | With financing  |
|----------------------------|-------------------|-----------------|
| Electric power rate        | 0.141 $·kWh⁻¹     | 0.141 $·kWh⁻¹   |
| Inflation rate (annual)    | 1.5%              | 1.5%            |
| Loan interest rate         | -                 | 8.5%            |
| Loan term                | -                 | 10 years        |
| Financing (Loan-Investor)  | 0%-100%           | 70%-30%         |
| Discount rate             | 10%               | -               |
| Weighted average cost of capital | -              | 8.95%          |
3. Results and analysis

3.1. Annual electricity generation

The simulations in SAM determine the annual electricity generation in the two departments based on the dimensions and parameters defined for both scenarios. An annual degradation factor of 0.2% caused by the degradation of the reflective capacity of the heliostats was applied to the system. Figure 1 shows the annual electricity generation in both departments.

![Figure 1. Annual electricity generation in Valle and Choluteca during the project’s lifetime.](image)

The generation of electric energy in the department of Valle in the first year of operation is 216.90 GWh while in Choluteca there is a generation of electric energy in the first year of operation of 197.37 GWh. The total energy generated for the project during its lifetime in both departments is 6,321.85 GWh in Valle and 5,752.77 GWh in Choluteca. This represents that Valle has 9.89% more power generation than Choluteca, due to the meteorological conditions of the department.

3.2. Initial investment, operation and maintenance costs

The specific capital cost of a central tower CSP plant with storage over 8 hours is between 4,077 - 5,874 $/kWh\(^1\). These values vary depending on the type of CSP technology used and whether the plant has thermal storage. A thermal storage system increases the specific capital cost, but this is offset by an increase in the plant’s plant factor due to the hours of operation it provides [8]. The Specific Capital Cost for each department considering and without considering the land cost are shown in Figure 2.
It is noted that the inclusion of the land cost represents an increase in the specific cost of capital, with the total cost of the land being $5,600,000 in Valle and $6,700,000 in Choluteca. In the department of Valle, without considering the price of land, the value of the specific capital cost is $4,837.74 per kW. When considering the land, the value increased to $4,937.74 per kW. In the department of Choluteca, the same behaviour was observed as the inclusion of the land. Without considering the value of the land the specific cost of capital has a value of $4,800.67 per kW. The cost of the land in Choluteca is lower in comparison to the values found in the Department of Valle so the specific cost of capital taking into consideration the value of the land presents a lower increase in this department with $4,934.68 per kW. The operation and maintenance costs of the project in both departments have the same value of $3,250,000 annually taking into consideration the cost values presented by NREL (National Renewable Energy Laboratory).

3.3. Ground coverage and land cost
The cost of the land varies according to the municipality, location and conditions. For all these variations an average of the values found was made based on quotations made in the area. For the department of Valle, it was estimated that the land cost was $12,600 per block and for Choluteca the value amounted to $12,800 per block.

The project floor coverage in both departments depends on the dimensions of the heliostat field, the central tower, the thermal storage and the power block. Because of different values in the heliostat field, the ground coverage varies in both departments. In Valle the total area of the project is 440 blocks of land while in Choluteca it is considered a total area of 520 blocks, this is since the number of heliostats is higher in this department.

3.4. LCOE
For the calculation of LCOE, two project financing scenarios are considered: With financing and without financing. Within these two scenarios, two considerations are taken into account. In the first one, the land cost is not included in the initial investment, while in the second consideration it is.

The global weighted average of the CSP LCOE in 2019 was $0.182 per kWh considering the four technologies. The LCOE value may vary due to the implementation of thermal storage. In 2018 there were projects in China that presented LCOE values of $0.10 per kWh. IRENA projects for 2021 an LCOE value between $0.075-0.094 per kWh [8].

3.4.1. LCOE without financing. In this scenario it is considered that the total value of the project will be financed only by the investors. Two considerations were taken: without considering the land cost and considering it. Figure 3 and 4 show the LCOE of both departments without financing and considering or not the inclusion of the land cost.
Figure 3. LCOE, without financing and without considering the land cost in both departments

Figure 4. LCOE, without financing and considering the land cost in both departments

The LCOE values of both departments are presented, taking into account the corresponding scenarios and considerations. Without considering the land cost, for the department of Valle a LCOE of 0.0675 $\cdot$ kWh$^{-1}$ is presented. The department of Choluteca presents a higher LCOE with a value of 0.737 $\cdot$ kWh$^{-1}$. Considering the land cost, the LCOE value increases in both departments but the same behavior is observed. Valle presents a lower LCOE with 0.0684 $\cdot$ kWh$^{-1}$ than Choluteca with 0.744 $\cdot$ kWh$^{-1}$. Table 3 shows the financial output parameters without financing for the two considerations presented.

|                           | Without considering the land cost | Considering the land cost |
|---------------------------|----------------------------------|---------------------------|
|                           | Valle                            | Choluteca                 |
|                           | Valle                            | Choluteca                 |
| NPV ($)                   | 11,475,587                       | -5,700,488                |
| IIR (%)                   | 10.6%                            | 9.2%                      |
| Recovery period (years)   | 8.01                             | 8.08                      |
| ROI (%)                   | 5%                               | -2%                       |
| LCOE ($\cdot$ kWh$^{-1}$) | 0.0675                           | 0.0737                    |

Table 3. Financial output parameters and without financing

Taking into consideration the input parameters and the corresponding scenario, the output values were determined. Without considering the land cost, the NPV of the project in the department of Valle is greater than zero so it can be said that the project is profitable. The opposite is true for the department of Choluteca, where the NPV is negative and the project is not profitable. The Internal Rate of Return (IRR) in the department of Valle (10.6%) is 15.2% higher than in the department of Choluteca (9.2%). However, the recovery period is similar for both departments. When considering the land cost, the IRR of 10.3% is presented in Valle and 9.01% in the department of Choluteca. The recovery periods for the departments of Valle and Choluteca are projected to be less than 10 years. The NPV presented in the department of Valle presents a value greater than zero so it can also be considered profitable. Choluteca presents a negative value in the NPV, which means that the project in these conditions is not profitable.

3.4.2. LCOE with financing. In this scenario, it is considered that the total value of the project will be financed 70% by a financial entity and the remaining 30% by the investors. Two considerations were taken: without considering the land cost and considering it. Figure 5 and 6 show the LCOE value of the project in each department with financing and considering or not the inclusion of the land cost.
The LCOE values for the departments are presented taking into account the specified considerations. It is shown that with financing, the LCOE increases in both departments. Without considering the land cost, Valle shows a LCOE of $0.1083\,\text{kWh}^{-1}$ and the department of Choluteca presents a higher value with $0.1183\,\text{kWh}^{-1}$. Considering the land cost, the department of Valle presents a LCOE of $0.1101\,\text{kWh}^{-1}$, as in the other scenarios studied, it presents a lower LCOE value than Choluteca with $0.1207\,\text{kWh}^{-1}$.

The output values corresponding to the scenario studied in this section are presented in Table 4. Without the land cost, it is observed that the NPV values for both departments are less than 0 so the project is not profitable. The recovery period of the project is between 15 and a little more than 18 years. The IRR in both departments is less than 6.0% so the interest to be received for the project investment will be low.

Considering the land cost, the economic output parameters are not promising. Observing the NPV values for both departments, it is concluded that the project is not profitable since both values are lower than 0. The IRR in both departments presents values lower than 6% so the interest received from the project will be low.

### 3.5. Environmental analysis
The CSP power generation plant in its operation stage does not generate greenhouse gas emissions. With its implementation, approximately 293,000 tons of CO$_2$ emissions would be avoided. If Honduras were part of an emissions market, the project could sell its emissions to thermoelectric generation plants at $30$ per ton of CO$_2$ (price in the European market). This sale of emissions would represent an annual income of $8,790,000.

Another factor to consider is the water consumption of the project due to the cleaning of the heliostats. A weekly cleaning is planned for the optimal operation of the heliostats in both departments. Due to the number of heliostats that the project has, the water consumption in the department of Valle, 42,335 m$^3$ of water per year, is higher than the consumption in Choluteca with 41,570 m$^3$ of water per year.
4. Conclusions
The research presented has managed to evaluate in a technical, economic and environmental way the implementation of a CSP central receiver plant with thermal storage in the South of Honduras that has an installed capacity of 50 MW and thermal storage of 10 hours. The research revealed the following results:

- The techno-economic analysis shows that the best location for the CSP plant is the department of Valle, since it has a higher direct normal irradiation. Valle has a solar resource of 6.33 kWh·m⁻² per day, while Choluteca has a direct normal irradiation of 5.97 kWh·m⁻² per day. Valle has more promising financial output values than Choluteca.
- It is shown that the Department with the highest electricity generation is Valle with a total generation of 6,321.84 GWh during the 30 years that the project will be in operation. The Department of Choluteca has an estimated generation of 5,752.76 GWh over the life of the project. This represents a difference of approximately 570 GWh between both departments.
- The initial investment values vary in both departments due to the size of the field and the cost of the land. The department of Choluteca presents lower investment costs in both scenarios presented in the investigation, without considering the land with a total investment capital of $240,033,823.10 and considering the value of the land with $246,733,823.08. Valley on the other hand presents an initial investment without considering the land of $241,887,025.09 and considering the value of the land of $247,487,025.09.
- The financial analysis presents values of LCOE, NPV, IRR, recovery period and ROI for the project in both departments. Taking into account LCOE values, it is concluded that Valle presents lower values than Choluteca in all the analyzed scenarios. It is shown that the project presents positive NPV values for Valle not considering and considering the value of the land in a scenario without financing. When analyzing the financed scenario, negative NPV values are shown for this department. On the other hand, the department of Choluteca presents negative NPV values in both non-financed and financed scenarios.
- The CSP technology of central receiver allows the generation of electric energy producing zero emissions of greenhouse gases. The environmental analysis presented that the implementation of this type of technology would allow to stop emitting approximately 293,000 tons of CO₂ emissions.

The main limitation for the research was the lack of updated information from the Solar Tower CSP technology specifically, because the reports presented information on the CSP projects in general, including the four technologies. Some of these technologies are still not well developed so they present high investment costs and LCOE that significantly affect the weighted average of these values in the general reports of the CSP technology.

Despite this limitation, it is expected that this work will serve as a basis for decision makers or companies interested in implementing new technologies in Honduras or in other countries where no such project has been executed.

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