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Analysis of the operation of a Fresnel solar plant through experimental tests: Energy production and efficiency

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Abstract. There is currently a lack of information on the real performance of concentrating solar systems using Fresnel collectors. In order to promote the penetration of this technology in industrial facilities with thermal demand, numerous daily operational tests have been carried out in a 105.6 m^2 Fresnel solar plant in southwest Spain. An analysis has been conducted covering all months of the year and including real direct radiation data. The tests were classified according to their characteristics, and the duration, available solar energy, energy production, and real efficiency were calculated. The best operating conditions were achieved in summer, with an average daily energy production of 174.3 kWh in July and 160 kWh in August. The maximum average efficiency value, however, was reached in May, at 24.4%. The use of actual data measured at the solar plant provided information on the behaviour of a Fresnel installation under real operating conditions.

Key words. Solar plant, linear Fresnel collector, performance analysis, energy production, efficiency.

1. Introduction

Currently, despite the great efforts focused on reducing global CO_2 emissions, fossil fuels continue to be the main source of energy worldwide. The industrial sector is not an exception to this reality. More specifically, in Spain, renewable energies accounted for only 11.84% of final energy consumption in the industry according to data from 2022. Moreover, only 0.14% of this value came from solar thermal energy [1]. Although these percentages have doubled since 2010, the penetration rate of renewable technologies in industrial thermal generation is still low.

Fresnel technology has some particularly favorable characteristics for its use in industrial process heat generation, especially in medium and low-temperature applications [2],[3]. However, there are still very few examples of currently operational solar plants using this type of technology [4]. In addition, there are also very few experimental analyses of Fresnel installations in real plants, and there are almost no specific studies focusing on their actual operation in practical applications covering at least a one-year period [5]. Some studies address the energy production, efficiency, or operating hours of Fresnel installations, although many of them are based on simulations and very few rely on experimental data from full-size real plants.

Rodríguez Rodrigo et al. compared Fresnel and parabolic trough technologies for process heat generation at different locations in Spain. They concluded that efficiency decreases as fluid temperature increases, and parabolic trough cost is higher than Fresnel, but both cases are lower than conventional fuels [6]. Fadhel et al. performed a numerical and experimental analysis of a small laboratory-scale Fresnel prototype used for phosphate drying in Tunisia. They analyzed the average monthly hours of operation and the monthly thermal energy production, among other parameters [7]. Sebastián et al. carried out a theoretical study that included the monthly average efficiency of a Fresnel solar plant with N-S and E-W orientations in Almería (Spain), concluding that a north-south orientation achieves slightly higher annual average efficiency values [8]. Memme and Fossa performed a Ray-tracing analysis and agreed that the north-south orientation causes the largest differences in efficiency between different months, decreasing when approaching the east-west orientation [9]. Famiglietti et al. simulated the behavior of a Fresnel plant in Madrid. The analyzed plant used air as heat transfer fluid and had a surface area of 633.6 m^2. They obtained the monthly values of operating hours and the average monthly energy production. [10]. Dellicompagni et al. calculated the thermal power and efficiency of a 172 m^2 solar plant in Argentina. They selected representative days for each of the 12 months of the year [11]. Finally, Bellos et al. simulated a 27 m^2 Fresnel solar plant in Athens (Greece) and obtained results such as the energy production per month [12].

The lack of real experience in the long-term operation of these facilities supports the relevance of this work, in which a real 105.6 m^2 Fresnel solar plant was analyzed through numerous operational tests over several years. The plant is located in Spain, it has a NW-SE orientation, and it is fully automated to register minute data of various variables, including direct radiation.

The main objectives of this work were the classification of the operating days of the solar plant according to working time and radiation, the selection of valid tests for further analysis, and the calculation of monthly average values of energy and efficiency, to improve the information available on the expected performance and production over the year of this type of installations.

The tests conducted were classified according to the results obtained. Different levels of solar irradiation were studied, and the plant operating time, energy production, and efficiency were evaluated for every month of the year. Long-term monitoring of the behavior of a Fresnel system by means of performance tests at different dates is particularly interesting for the analysis, development, and potential integration of Fresnel technology in existing industrial processes.

2. Materials and methods

This work analyzes the medium and long-term performance of a prototype concentrating solar plant using Fresnel collectors for the production of steam with an indirect system.

The plant is installed in an industry near Cáceres, in the southwest of Spain (latitude 39.646º N and longitude 6.386º W). It is composed of 4 commercial collectors with 10 rows of Fresnel mirrors and a total area of 105.6 m^2, as described by Miranda et al. [4]. Due to space limitations at the location of the plant, the orientation of the solar field is NW-SE, with an angle of -42.3º with respect to the south.

Fresnel mirrors concentrate solar radiation over an absorber tube through which the primary circuit heat transfer fluid (pressurized water) circulates. The fluid then flows through the tube bundle of the kettle reboiler heat exchanger. There, it transfers the energy captured in the solar field, providing the necessary conditions for the generation of steam in the secondary circuit.

Fig. 1. View of the solar plant.

The plant control system and data download process are fully automated through a platform that supports remote monitoring of the system operation and enables the modification of control parameters. The main variables are measured and monitored through numerous pressure, flow or temperature sensors and thermal energy meters, which provide minute data.

There is also a meteorological station installed next to the solar plant, which provides measurements of the main variables of interest. It measures direct normal radiation (DNI), global horizontal radiation (GHI), ambient temperature, wind speed, and precipitation.

Daily operational tests have been carried out over several months under variable meteorological conditions. At the beginning of each test, the system is activated when the global radiation (GHI) exceeds the minimum level set at 200 W/m^2 [4], which leads to the start-up of the primary circuit pump and the focusing of the Fresnel mirrors. The test ends when the global radiation decreases below the minimum level.

The data analyzed comprise the daily energy production of the solar plant, the operational time of the system, the global and direct radiation levels, and the average efficiency of the plant. In this first analysis, only the primary circuit output was studied, without considering the operation of the secondary circuit and the steam generation.

Data was collected for a total of 30 months from 4 different years, including 679 days and 540 operational tests. This will provide the opportunity to analyze the influence of the main variables, the energy production, or the efficiency of the system, as well as the most appropriate working strategies depending on the date and radiation levels. Information has also been collected on the plant's non-operational periods and the different types of operational errors detected during the analysis process.

The development of the daily tests involved the classification of the different data files generated with the measurements from the solar plant sensors, the radiation data from the weather station, and the analysis and processing of the information collected.

First of all, due to the large volume of data generated, different criteria were defined to classify the days analyzed. These criteria took into account both the radiation levels and the operating conditions of the solar plant. For this purpose, the following parameters were calculated for all days included in the analysis:

1) *Theoretical duration of days ($T_{theor\text{-}day}$).* Time between sunrise and sunset at the plant location, calculated theoretically using the solar equations.
2) *Time with global radiation above the minimum level of 200 W/m^2 ($T_{real\text{-}GHI}$).* Maximum possible duration of the test based on actual radiation data. The system only works when radiation exceeds this level.
3) *Ratio between time with radiation above 200 W/m^2 and theoretical duration of the day ($T_{real\text{-}GHI}/T_{theor\text{-}day}$).*
4) *Real plant operating time ($T_{real\text{-}test}$).* Time with the solar plant in operation and the mirrors positioned, according to the real operating data.

Based on these parameters, the different days were classified according to the following categories:

A. *Days not valid for the analysis.*

1) *Days with no data.*

2) *Days with the plant inactive.* According to Equation (1), days with real operating time ($T_{real\text{-}test}$) below 10 min are not valid.

$$T_{real\text{-}test} < 10 \text{ min} \quad (1)$$

3) *Days with operating errors.* Days with critical errors that put the system out of service, according to the information collected.

B. *Valid days.*

1) *Incomplete days.* Days without relevant errors, but with a test duration ($T_{real\text{-}test}$) shorter than the time with radiation ($T_{real\text{-}GHI}$), as shown in Equation (2).

$$(T_{real\text{-}GHI} - T_{real\text{-}test})/T_{real\text{-}GHI} > 0{,}3 \quad (2)$$

2) *Well-functioning days.* Days with correct operation.

The number of days included in each of the categories by month was calculated. Afterward, energy and efficiency values were obtained for each day analyzed.

A. *Daily energy production, E_{day} (kWh):* Measured by the energy meter installed in the primary circuit.

B. *Daily solar energy, E_{solar} (kWh):* Calculated with the actual direct radiation data (DNI) from the meteorological station and the reflecting surface ($S_{Fresnel}$), as shown in Equation (3).

$$E_{solar} = \Sigma_i \, DNI_i \cdot S_{Fresnel} \quad (3)$$

C. *Average daily efficiency, η_d:* It estimates the fraction of the radiation reaching the Fresnel mirrors that is captured by the primary circuit. It is calculated as the daily energy production (E_{day}) divided by the daily solar energy (E_{solar}), according to Equation (4),

$$\eta_d = E_{day}/E_{solar} \quad (4)$$

D. *Average theoretical optical efficiency, η_{opt}:* Estimated for each day of the year based on data provided by the manufacturer, as described by Miranda et al. [4] [13].

Finally, the monthly average values of the parameters and variables defined above were calculated in order to observe their evolution throughout the year. In all cases, the monthly average values were obtained considering two different criteria: taking all days classified as valid, and taking only well-functioning days.

Therefore, the monthly average values of the theoretical duration of days ($T_{theor\text{-}day}$), the time with GHI above the minimum level ($T_{real\text{-}GHI}$), the ratio between both parameters, the real plant operation time ($T_{real\text{-}test}$), the daily energy production (E_{day}), the daily solar energy (E_{solar}), the average daily efficiency (η_d) and the theoretical optical efficiency (η_{opt}) were calculated.

3. Results

A total of 679 daily files with minute data were collected via the control system of the solar plant, which monitors the main operating variables of the installation. These files, belonging to 30 months from the years 2020 to 2023, were classified and processed for further analysis. The data measured by the meteorological station was also used, and all available information was integrated into combined files for easier management.

It was found that the plant was out of operation for 139 days (days with the plant inactive), of which 75 days had a total solar energy of less than 200 kWh, and 20 of these days had less than 1 h with global radiation above the 200 W/m^2 level that activates the system. Therefore, part of the days when the plant did not work coincided with the days with the worst solar radiation conditions. Other days with the plant inactive corresponded to faults due to pressure drops in the primary circuit, mechanical errors in the primary pump, communication failures in the control system, etc. It was observed that this type of plant requires close monitoring and constant maintenance in order to ensure proper operation.

The data analyzed showed a total of 540 days with plant operation, of which 72 days had some kind of error once the test started (days with operating errors). These days on which errors were detected were not included in the subsequent analysis. The number of valid tests was therefore 468.

Valid tests were further divided into 350 days with correct operation (well-functioning days), in which the duration of the test coincides with the period of global radiation above 200 W/m^2, and 118 days with operation considered to be incomplete. In this case, incomplete days were mainly due to tests with short shutdowns due to the activation of some alarm signal or due to system maintenance needs. The classification of the days analyzed is summarized in Table I.

Table I. – Classification of days.

<table>
<tr><td colspan="4">Total days with data</td></tr>
<tr><td colspan="4">679</td></tr>
<tr><td>Days inact.</td><td colspan="3">Total days with plant operation</td></tr>
<tr><td rowspan="5">139</td><td colspan="3">540</td></tr>
<tr><td>Operat. errors</td><td colspan="2">Valid days</td></tr>
<tr><td rowspan="3">72</td><td colspan="2">468</td></tr>
<tr><td>Incomplete days</td><td>Well-funct. days</td></tr>
<tr><td>118</td><td>350</td></tr>
</table>

Once the days were classified and the different parameters defined for analysis were calculated, the average monthly values were obtained as described before. The monthly results are shown in the following figures and discussed below.

Fig. 2 shows the curves representing the monthly average values of the theoretical duration of days, the time with GHI above the minimum level, the ratio between both parameters, and the real plant operating time.

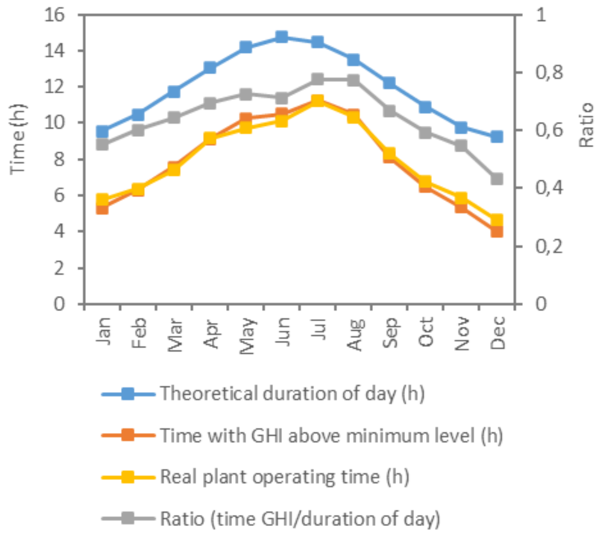

Fig. 2. Duration of tests and solar radiation.

The curve of theoretical duration of days ($T_{theor-day}$) has the expected behavior according to the movement of the sun throughout the year. Maximum values are reached in June (with an average duration of 14 h 45 min), as the summer solstice happens in this month, and minimum values occur in December (9 h 15 min), due to the winter solstice. This variable is not influenced by the meteorology of the site, as it is based solely on the theoretical calculation of sunrise and sunset. However, when dealing with the actual values of solar radiation and plant performance, the climatology of the location and the specific meteorology of the years under analysis play an important role.

This fact can be seen in the curve showing the average time that the global radiation exceeds the minimum value of 200 W/m^2 ($T_{real-GHI}$). This variable was calculated using information from all days with actual radiation data. Although the longest theoretical day duration occurs in June, the month with the longest time above the minimum GHI level was July, with 11 h 15 min. Both June and August had a value of about 10 h 30 min.

Concerning the representation of the ratio between both variables ($T_{real-GHI}/T_{theor-day}$), during July and August 77.5% of the average theoretical duration of days had a global radiation above the minimum level of 200 W/m^2. This implies that the solar plant could operate on average 77.5% of the hours of the day during those months. In June, however, this ratio dropped to 71%. According to the Atlas of Solar Radiation in Spain [14], in the province of Cáceres, where the plant is located, the month with the highest average solar irradiance is July, followed by June.

The observed differences can be attributed to the variability associated with the local climate. According to the mentioned Atlas of Solar Radiation in Spain, the standard deviation of direct radiation in Cáceres is 0.81 in June. This is the month with the highest standard deviation of the whole year. In contrast, July (0.36) and August (0.34), the main summer months in a Mediterranean climate, are more stable.

The value of the ratio oscillated between 43% and 77.5% over the year, with an annual average of 64%. In comparison, the study performed by Fadhel et al. in Tunisia showed percentages of operating hours between 50% and 90%, with an average annual value of 70% [7]. Considering the differences between the two locations and climates, as well as the minimum radiation level defined in the Spanish plant, the percentage of operating hours reached acceptable values in the current study.

Finally, the curve of real plant operation time ($T_{real-test}$) corresponding to the monthly average of the days classified as "Well-functioning" is shown. The days categorized as "Incomplete", despite being considered as "Valid" because they had no major errors, were left out of this analysis as their variable duration distorted the results. It can be seen that the actual hours of operation largely coincide with the hours with GHI above the minimum level. Therefore, this variable can be considered a good predictor of the expected duration of tests. The small differences between the two curves can be explained by the fact that the $T_{real-GHI}$ variable includes all days with available radiation data, while $T_{real-test}$ only includes the tests on days considered "Well-functioning".

Fig. 3 shows the monthly average values of energy production measured in the primary circuit of the plant during the execution of the tests, and the average daily solar energy for each month of the year, according to the data collected by the meteorological station.

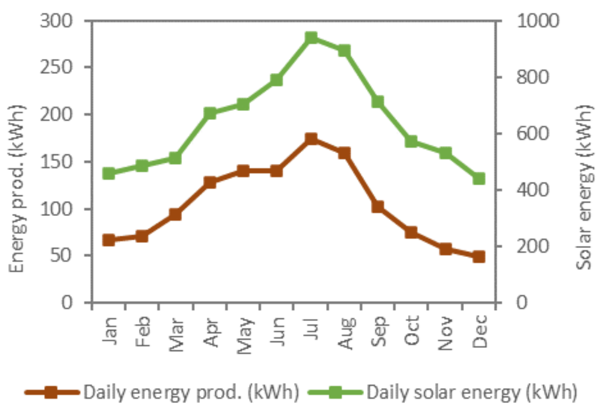

Fig. 3. Energy production and solar energy.

The average values of solar energy received each day by the total reflecting surface of the Fresnel collectors ranged from 938 kWh in July to 439.9 kWh in December. The months with the best data were those between April and September, and there were significant differences with respect to the most unfavorable months, corresponding to autumn and winter. These are real data provided by the meteorological station measurements throughout the period analyzed. Therefore, the irregularities between the different months are larger than those obtained from the average data of a typical year or from simulations, such as the one carried out by Bellos et al [12]. In addition, their analysis focused only on days considered favorable for solar production, so the results, especially in the winter months, were higher.

In terms of energy production per day, the best average values were achieved again in July and August, as shown in Fig. 3. According to the data recorded by the energy meter installed in the primary circuit of the Fresnel solar plant, the average values registered during those months were 174.3 kWh and 160 kWh respectively. During the most unfavorable months of the year, between October and March, the average daily energy production did not exceed 100 kWh, ranging from 48.9 kWh in December to 93.6 kWh in March. September and the months from April to June provided intermediate results, between 100 and 140 kWh. It was also observed that the energy production during spring was higher in relation to the available solar energy compared to the autumn months. Although the solar energy available in September was higher than the values for April and May, the energy production in September was actually lower than the two months mentioned above, being closer to the value for March. These issues are further discussed in the analysis of the efficiency of the solar installation.

Once the actual values of energy in the solar plant were obtained, they were compared with the results presented by other authors, taking into account the differences in the total mirror surface of the different Fresnel systems analyzed.

Both the simulations of Famiglietti et al. [10] and the results of Fadhel et al. [7] showed the maximum energy production in July, similarly to the present study. Meanwhile, Bellos et al. [12] obtained the highest energy value in June. In general, Fadhel et al. reported a higher production per m^2 than this work during all months, while the results of Famiglietti and Bellos showed greater differences between winter and summer months, with higher variations than the current study.

Finally, Fig. 4 shows the average monthly efficiency curves, including both the optical efficiency and the real efficiency of the plant. The optical efficiency was calculated using equations based on the incidence angle modifier (IAM) provided by the manufacturer and adapted to the specific characteristics of the Fresnel solar plant, as shown by Miranda et al [4]. The highest annual value is reached in June, at 33.4%, while the lowest value occurs in December, with a percentage of 14.7%.

The real efficiency of the system, on the other hand, was calculated as the ratio between the energy production measured at the plant and the solar energy available according to the radiation data. This variable reaches lower values because, besides representing the real performance of the installation, it includes parameters such as thermal losses that are not included in the theoretical optical efficiency of Fresnel collectors.

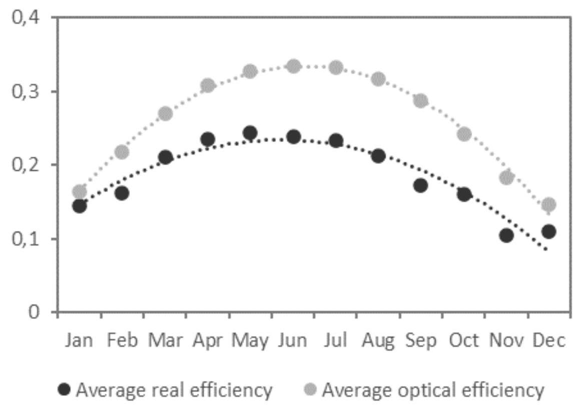

Fig. 4. Real and optical efficiency.

Unlike all the other variables analyzed so far, the maximum efficiency value of the plant was reached in May, with a percentage of 24.4%, followed by June with 23.8%. The lowest value was recorded in November, which reached an average efficiency of 10.4%, followed closely by December with 10.9%.

As already noticed during the analysis of energy production, there is a displacement of the efficiency curve, with the maximum values closer to the spring months. The decrease in efficiency is particularly noticeable in the months of September and November. In these specific cases, variations may be due to particular conditions of the tests included in the months affected, such as radiation levels or the duration of the tests. However, the displacement towards the spring months observed in the curve could be caused by other relevant factors. The orientation of the solar plant is NW-SE, with an angle of -42.3º with respect to the south. Sebastián et al [8] analyzed the monthly evolution of the plant efficiency for north-south and east-west orientations, with significant differences in winter and summer values. An east-west orientation provides a more constant efficiency throughout the year than a north-south orientation. Miranda et al [15] analyzed the influence of a NW-SE oblique orientation on the efficiency and energy production of the solar plant. For this purpose, a theoretical simulation model was applied, and a displacement in the daily curve was observed. It would be of great interest to expand this analysis using more real performance data. Regarding the efficiency values achieved, they were slightly higher than those described by Sebastián et al. [8], and lower than the results obtained by Dellicompagni et al. [11].

The use of real operating data from a Fresnel solar plant and radiation data from a solar station at the same location provides a new point of view, and makes it possible to observe the behaviour of this technology under the conditions of a real installation. In contrast, analyses derived from simulations make it more complicated to show the influence of meteorology, and the variability that exists in a real situation.

Although the number of days studied is high, it would be convenient to include new tests in the analysis. It would also be interesting to further analyze the influence of variations in radiation levels, as well as the reflectivity and soiling of the mirrors and thermal losses.

4. Conclusions

A large number of daily performance tests of a Fresnel solar power plant were classified and analyzed in this work. The use of experimental data from several years revealed the variability that exists under real working conditions, in contrast to the information provided by simulations and theoretical studies.

The parameters defined for the classification of the tests were useful for selecting the most appropriate days for the analysis. To calculate monthly average values, the best option was using only the days classified as "Well-functioning". Only half of the days with data could be used in the study.

The month with the highest duration of tests, available solar energy, and real energy production was July, although the month with the longest theoretical duration of days and the best optical efficiency was June. The plant operated 64% of the hours with solar radiation. The number of hours with radiation above the minimum level was a good reference to determine the expected duration of plant operation.

The months between April and September had the best values of solar energy received. Average daily energy production ranged from 48.9 kWh in December to 174.3 kWh in July. The system behaved better in spring than in autumn. The real efficiency reached the maximum value in May (24.4%) and the minimum in November (10.4%).

The results obtained are intended to contribute to the improvement of knowledge on this type of concentrating systems and to promote the substitution of fossil fuels for solar energy in thermal applications in industrial processes. Future work will extend the analysis with new tests, and will further evaluate the influence of meteorological variability, mirror soiling, or thermal losses.

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