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Numerical simulation of Linear Fresnel solar power plants performance under Moroccan climate

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Abstract

This paper presents a numerical simulation for a 10MWe concentrating solar power (CSP) plant based on Linear Fresnel Reflector (LFR).For this study, GREENIUS software was used to predict the thermal and the electrical performances of the 10MWe systems under the climate of Oujda, Eastern Morocco. The simulation input data were measured using a High Precision Meteorological station (MHP) installed at the University of Oujda. The results of this study are very encouraging; with a DNI value of 2098kWh/m²/year the system was able to produce a total annual net electricity of 20621MWh$_{el,}$ with a field thermal efficiency of 29%.

Acronyms

CSP: Concentrating Solar Power
LFR: Linear Fresnel Reflectors
MHP: Meteorological High Precision Station
DNI: Direct Normal Irradiation (W/m^2)
GHI: Global Horizontal Irradiation (W/m^2)
IAM: Incidence Angle Modifier (deg°)
HTF: Heat Transfer Fluid
$\theta_{||}$: longitudinal angle (deg°)
$\theta_{\perp}$: transversal angle (deg°)

1. Introduction

Currently, the greenhouse gases and the global warming become a serious issue for our planet and for the existence of the human kind.To fight against such a problem, the shift to a renewable energy societyis an urgent need.Knowing the fact that the sun is the largest energy source available on our planet,solar energy can play a fundamental role -in the near future- to replace fossil fuels and reduce energy dependence of many countries. For instance, during the period 1999-2008, Moroccan energy dependence exceeded 96% [1-3], and yet the country has a huge solar potential (over 3000 hours of sunshine per year [4]). Thus, the country launched the Moroccan Solar Plan aiming the production of 2000 MW of electricity from solar energy by 2020.
Among the different thermodynamic solar concentrator technologies, the linear Fresnel technology is experiencing a growing interest due to its attractive combination of performance and ease of implementation[5]. In fact, this technology has many advantages, such as, the lower cost of the mirrors,in comparison to the parabolic troughs.The first prototype has been built in Marseille, France in 1964. However, the real development of this technology starts in 2008.The leaders in the high-temperature LFR development nowadays are Areva and the German company Novatec Solar. The most relevant projects with linear Fresnel reflector systems are summarized in Table 1.

Table1: The linear Fresnel reflector systems projects in different countries.

Project name	Country	Start year	Turbine Net capacity (MW)	Statutes	Solar field area(m²)
Augustin Fresnel1	France	2012	0.25	Operational	400
Alba Nova1	France	2015	12.0	Under construction	140 000
Kimberlina	Unites States	2008	5.0	Operational	25 988
Kogan Creek	Australia	2015	44.0	Under cons	
Liddell Power station	Australia	2012	9.0	Operational	18 490
Dhursar	India	2014	125.0	operational	----
Llo	France	2015	9.0	Under contract	120 000
Puerto Errado 1	Spain	2009	1.4	operational	21 571
Puerto Errado 2	Spain	2012	30.0	operational	302 000

Regarding research, several experimental and numerical studies have been conducted to prove the effectiveness of these plants. Sultana et al.[6]described the thermal performance of a new low-cost solar thermal micro concentrating collector which Linear Fresnel Reflectors, this system was designed to work with temperatures up to 220°C. Karouaet al.[7] studied the effect of different design parameters on the thermal performance of a Fresnel system theoretically and experimentally. In the same direction, Yu Qiu et al. [8] developed a 3D optical model to simulate the radiation transmission in the system with Monte Carlo Ray Tracing Method. They also studied the performance of linear Fresnel solar reflector using molten salt as heat transfer fluid.
Similarly, Pino et al. [9] simulated the performance of a solar Fresnel collector system using optical and thermal modeling approaches.The model results were compared with real values measured ata solar power plant in operation.Another interesting research was conducted by Flores Larsen et al. [10]. They used EnergyPlus software to predict the performance of LF plants,more precisely, they examined the heat loss of a linear absorber with trapezoidal cavity and an assembly of pipes used for linear Fresnel reflecting solar concentrator. Also, several studies have been made in order to compare the Linear Fresnel Reflector with the parabolic troughs[11-13].
In this paper we present the simulation results of a 10MWe CSP plant based on Fresnel collectors under the climate of Oujda, Eastern Morocco. This region demonstrated that it has a great potential to host large scale solar plants and to produce electricity with high efficiency from the sun[14-18].

2. The field of study

Our field of study is located on the north east of Morocco. This region has a surface area of 82800Km^2,which represent almost 12% of the country's area. The daily average global horizontal irradiation(GHI) and direct normal irradiation (DNI) are of 221 and 240 W/m^2 respectively. As for the temperature, the yearly average of 17°C. With these conditions, our field or study can be considered as very favorable to host CSP power plants[19].

3. Working principle

Similarly,to parabolic trough technology, linear Fresnel systems are composed of many row segments of flat or nearly flat mirrors. The solar radiation is reflected by a series of mirrors on a fixed receiver tube, where the heat transfer fluid (HTF) contained in this receiver heats up to 450°C, and evaporate the water to produce steam. The steam passes through a turbine and produce the electricity through a generator.
Finally, the vapor at low-pressure turbine outlet goes to the condenser to be liquefied before being pumped again in the solar fields.

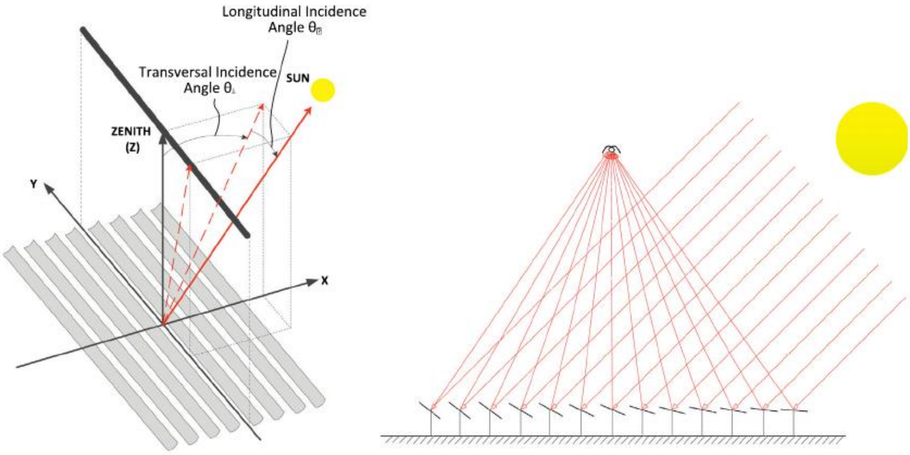

Figure 1: Schematic view of the incidence angles [20].

The main difference between the Fresnel and the parabolic collectors is in the Incidence Angle Modifier (IAM). This parameter is the responsible to convert the Direct Normal Irradiation (DNI) to the useful DNI to be converted to heat, thus, to electricity. The IAM depends on two incidence angles: the longitudinal angle $\theta_{||}$ and the transversal angle $\theta_{\perp}$, Figure 1.

4. Simulation inputs

In this part we will discuss the used software, the 10MWe plant's technical data, the meteorological data and their accuracy.Greenius is a software developed by the German Aerospace Center (DLR) and it's the one used in this study. This software is one of the most robust simulation tools for renewable energy systems simulations, and more precisely for CSP.

Figure 2: High precision meteorological station installed at the University of Oujda.

To run a simulation, Greenius requires a file of one year of meteorological data with one-hour steps (8760 hours in total). This file must include in addition to the classical meteorological parameters (humidity, ambient temperature, pressure, wind speed) the measurements of the three components of solar irradiation (Global, Direct and diffuse). The meteorological file used in this study was created based on the measurements from a high meteorological station (MHP) installed at the roof top of the University of Oujda (Figure 2) for one year.

This station measures the three components of the solar irradiation at the same time and with high precision. Indeed, the global horizontal irradiation (GHI) and the diffuse horizontal irradiation (DHI) are measured using a secondary standard Kipp&Zonen CMP21 pyranometer with an error of 1%. While, the direct normal irradiation was measured through a first class Kipp&Zonen CHP1 pyrheliometer. This device measures the DNI with a precision of ±1W/m^2.
For the period of one year, the one-minute data measured by the MHP stationwere averaged to get hourly data, and a meteo-file was created and uploaded to Greenius library to run the simulation. After that, the next step in the simulation was the design and the optimization of the solar field. In our study, a power plant with Fresnel reflectors and a nominal capacity of 10MWe was created. This plant is composed by 90 rows (loops), each one contains 6 collectors, i.e. 540 collectors in the overall. The collector's technical inputs are assembled in Table 2.

Table 2: Collector data using in this simulation.

parameter	value	unit
Collectors length	64.96	m
Aperture width	7.5	m
Effective mirror area	351	m²
Optical efficiency	64	%
Focal length	4	m
HCE diameter	6.55	cm

The Heat Transfer Fluid (HTF) used is a synthetic oil with a specific HCE mass of 3.78Kg/m² and a heat capacity of 0.136 Wh/Kg.K. The optical efficiency of the collector is 64%. We need to mention that in arid regions like Eastern Morocco the mirror's cleanliness is highly affected by soiling [21-23], which can cause a drop on the optical performances. In this study, we selected the flat cleanliness value of 97% as considered by default in the software.The power block used in this study is designed to run under a thermal output of 25.6MW, an ambient temperature of 30°C and a wet cooling system. Under the nominal conditions the turbine produces an electrical output of 10MWe.

5. Results and discussions

In order to evaluate the performance of the 10MWe Fresnel system under the climate of Eastern Morocco, the simulation results will be presented on three different time resolutions: Hourly, Daily and Monthly. The daily plot of the electricity production is presented on Figure 3. As it can be seen, the plant electrical production is a function of the DNI. The highest electrical values were measured during the days with the high amount of solar irradiation.Indeed, the electrical output is high during summer where the 10MWe Fresnel plant produces,in average, a daily electricityamount of 100MWe.

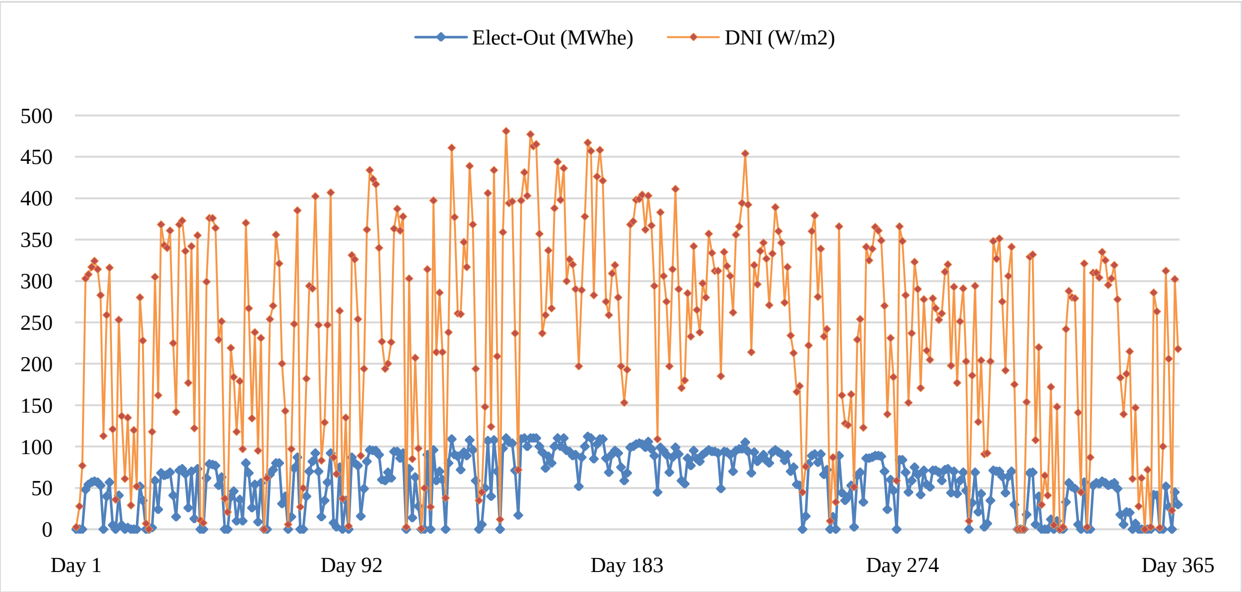

Figure 3: The daily electrical output and the DNI measurements.

During the winter and the autumn, the electrical production is very instable (due to the low DNI values), but, the daily production is around 50MWe which can still be considered as good.
The previous results can be confirmed by the daily thermal efficiency averages charted in Figure 4. Actually, the highest values were measured during spring and summer, where the thermal efficiency of the pilot reaches 43%. However, the lowest thermal efficiencies were measured during the autumn and winter, and the values are between 10 and 15%. Again, this is in accordance with the DNI values measured at the same time.

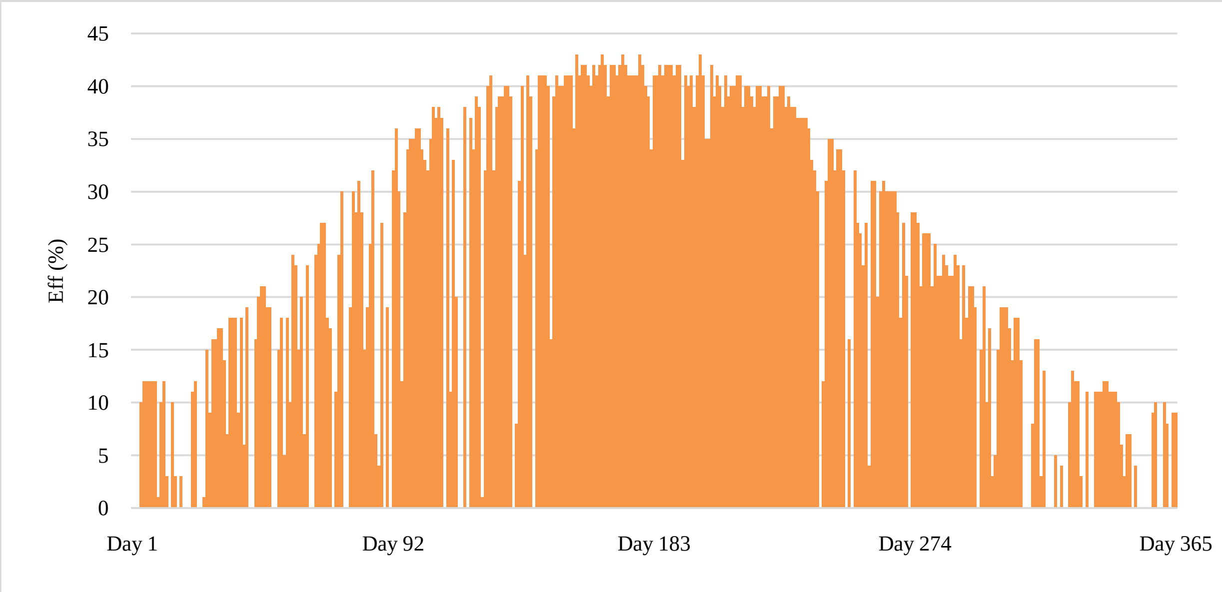

Figure 4: The daily thermal efficiencies of the 10MWe pilot.

In order to have a clear idea about the hourly performance of the simulated system, the hourly electrical productions were plotted together with the corresponding DNI values for the equinoxes. For the winter equinox, the DNI values were very low, and the electricity production was null during that day. Therefore, the results were presented only for the three remaining equinoxes (Figure 5):

- The 21th of Marsh.
- The 21thof June.
- The 21thof September.

From Figure 5, we can say that our system is considered as performant. In fact, the plant starts producing the electricity around 9:00AM, or in other words, with DNI values around 800W/m^2.The plant keeps producing electricity for at least 9hours. The production is always around 10MWe each hour and the highest production was observed during Marsh (~10.1MWe), while, in September the production was around 9.88MWe. This can be explained by the difference on the DNI values between Marsh and September.
Again, and for sake of precision, the hourly thermal efficiency and the thermal output of the simulated system were plotted on Figure 6.Relatedly, to the electrical production, the thermal output of the field can be considered as high, and it's around 78MW$_{th}$for all the equinoxes.
Concerning the thermal efficiency, the results were reversed, i.e. the lowest thermal efficiency values are measured during Marsh, whereas, the highest ones were measured during September. This is completely reasonable, because the turbine can't run above a threshold thermal input even though the DNI is high. Thus, in order to not damage the power block, the power plants operators should rather dump a part of the produced heat, or defocus a part of the solar field. This fact is translated by an efficiency drop.
Finally, Figure 7 represents the monthly values of the electrical output, the thermal efficiency and the total efficiency of our simulated system. In accordance with the previous results, the highest values were measured during June and July where the system produces respectively, 2.82 and 2.7GWhe of electricity, with 41% of thermal efficiency and an overall system efficiency of 6%. However, December is the month with the lowest electrical production with 800MWhe.

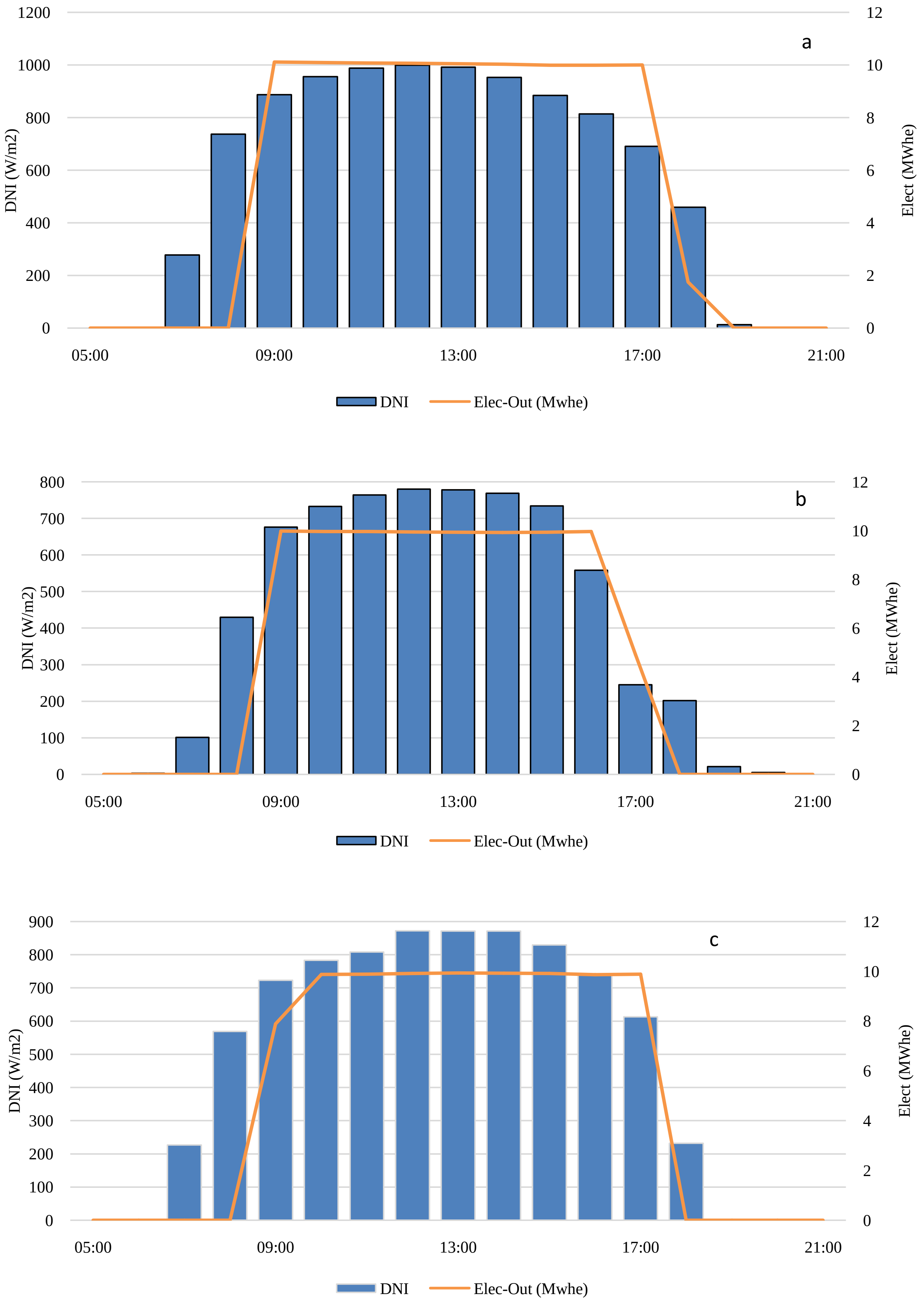

Figure 5: The hourly DNI and electrical output during the equinoxes. (a) The 21th of Marsh.(b) The 21th of June. (c) The 21th of September.

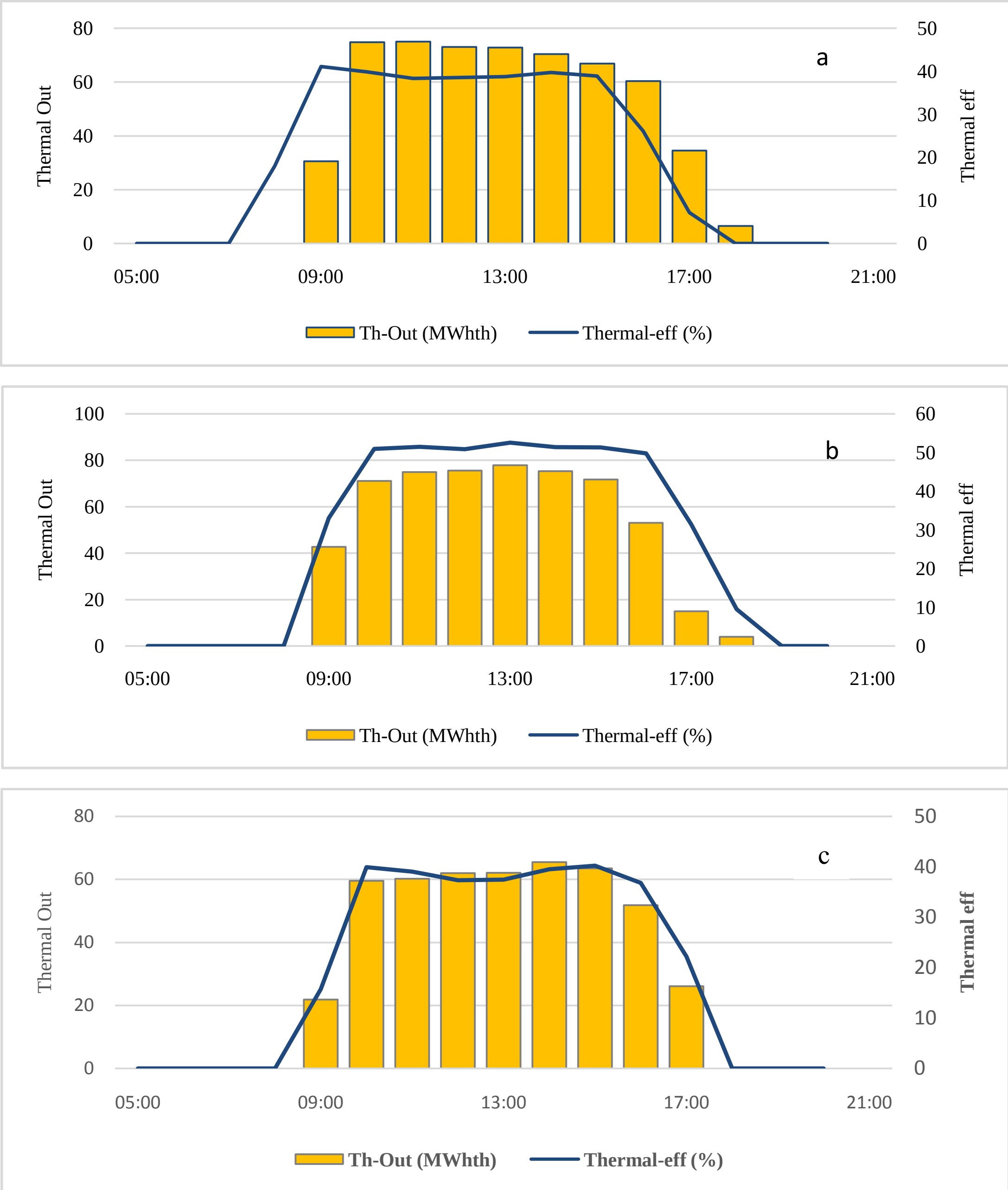

Figure 6: The hourly thermal output and thermal efficiency of the 10MW plant during the equinoxes. (a) The 21th of Marsh.(b) The 21th of June. (c) The 21th of September.

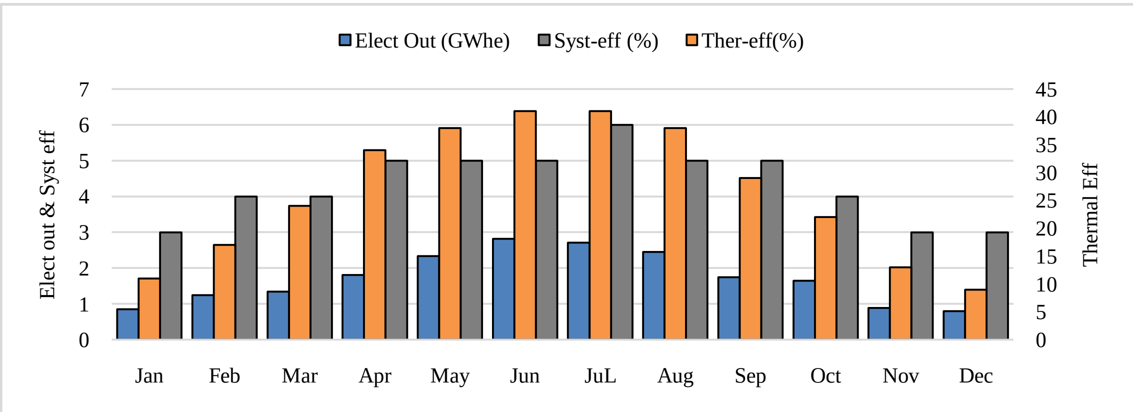

Figure 7: Monthly values of the system's total efficiency, electrical production and thermal efficiency.

Conclusions

This main purpose of the current study is to highlight the performance of linear concentrating solar systems in the eastern region of Morocco.For this purpose, a 10MWe Linear Fresnel Reflector (LFR) power plant was simulated under the climate of Oujda city.The main results of this study are summarized below:

- The daily electrical production of the 10MWe Fresnel system is around 100MWe in summer and it's around 50MWe during the winter and the autumn.
- Generally, with good DNI values the simulated system can produce the electricity continuously for 9 hours, with the nominal capacity(10MWhe).
- The monthly simulations show that the highest electricity production was recorded during June and July with an amount around2.8GWhe and a thermal efficiency of 41%.

These results are very satisfactory and may implicitly encourage the Moroccan government to exploit these natural resources for electricity production of solar origin, which will lead to a sustainable development of the region and the creation of new jobs.

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