

Feasibility Study for the Construction of a Thermodynamic Solar Power Plant in Togo

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Abstract The potential of concentrated solar power plants technology (CSP) in Togo is evaluated through the simulation of a plant prototype with a capacity of 50 MW in the climate of Dapaong (Togo). The simulated prototype is the Andasol 1 plant in operation in Aldeire Granada (Spain). Such an installation which produces a net electrical energy of 139 348 MWhel at the output of the system in Spain can produce a net electrical energy of 107 525 MWhel in Togo. For this purpose, three types of technologies most used by stakeholders of the domain, namely: Solar tower, Fresnel mirror and Parabolic trough sensors are presented and an analysis of their economic feasibility has been carried out. On the basis of the analyzed solar irradiation data, the solar tower power plant can produce a net electrical energy of 113 915 MWhel, a power plant using Fresnel mirrors can produce a net energy of 121 054 MWhel against 107 525 MWhel for the parabolic trough technology and this for the same solar field surfaces. A techno-economic analysis places the solar power plant based on FRESNEL mirror ahead of other technologies. The technologies used are equipped with storage allowing production even at night when there is no sun. It was therefore found that Togo has an average potential for the production of electricity from the CSPs, especially in the northern region of the country.

Keywords: renewable energies, solar energy, thermodynamic solar energy, storage, simulation

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1. Introduction

Access to electricity is fundamental to the development of any country. In West Africa, access to electricity average is 52%, with power cut-offs up to 80 hours per month [1]. The price per kilowatt-hour remains relatively high, which is delaying development in some regions. For many years, Togo has been depending on Nigeria, Ghana and other countries in the sub-region for electricity [2]. It can be expected that these countries will reduce their exports while domestic demand will increase in Togo. Indeed, Ghana's Volta Region Authority (VRA) and the Compagnie Ivoirienne d'Electricité (CIE) had reduced their deliveries from 140 MW to 80 MW per day; an energy crisis that had seriously affected the lives of businesses and the general population [2]. It is therefore necessary to look for ways to produce its own electricity in a sustainable way. The development and use of renewable energies, particularly solar energy, has grown rapidly in recent years, and many countries have found it to be an efficient and sustainable way to produce their own energy [3,4]. Due to the relatively large amount of solar energy available throughout the country, solar power

plants are an opportunity to increase access to electricity and reduce the cost of fossil fuels. It is in this context that several solar projects and programs have been initiated and developed, such as the sizing and management of photovoltaic equipment. Thus, in its permanent search for a solution, the country aims to equip each of the five economic regions with a solar power plant, in accordance with the national electrification strategy, which aims to provide all Togolese with access to energy by 2030, compared to the current rate of nearly 60%. Accordingly, the Blitta solar photovoltaic plant was launched in February 2020 [5]. It should be noted that electricity can be produced by solar power plants in two ways: photovoltaic solar power, which is the direct conversion of solar radiation into electricity, and thermodynamic solar power, which produces electricity through thermodynamic cycles. The efficiencies of the photovoltaic modules often used for solar photovoltaic power plants varies between 9 and 20%. However, by concentrating the sun's heat in concentrated solar power plants, efficiencies can reach 30% [6]. Concentrating solar power plants (CSP) are therefore a new solution for increasing access to electricity in a sustainable way. In addition, CSP allows for easier smoothing of production due to cheaper thermal storage than battery systems [6].

In this paper we propose to study the feasibility and operation of a solar thermodynamic power plant in Togo. We also aim to simulate the different types of technologies in this field and to highlight the most cost-effective one.

2. Materials and Methodology

It is difficult to build prototype power plants to make accurate measurements for better prediction of potential CSP projects. In such a situation, the use of simulation tools to predict the annual performance of a plant is imperative. Several simulation tools are available on the market. Among them, one can mention for example the System Advisor Model (SAM) and GREENIUS which are powerful tools that can be downloaded free of charge. For the simulation and modelling investigation we have done in our study, we used GREENIUS v4.5.0 to assess the performance of the CSP plant.

2.1. Presentation of GREENIUS Software

The Greenius simulation software was developed by the Solar Research Institute of the German Aerospace Center (DLR). This center was founded in 2011 and conducts research in the field of renewable energy based on concentrated solar thermal energy. DLR is the largest German research institution in this field and plays a leading role in Europe and worldwide in the development and qualification of related technologies [7].

The Greenius simulation software is designed to facilitate fast and simple performance calculations of concentrated solar power (CSP) and other renewable energy systems based on simulations of hourly plant performance for a typical year. It allows quick and easy

predictions of electrical performance and is particularly useful in the early stages of projects and for feasibility studies. The software focuses mainly on solar thermal plants. It offers the possibility to use different technologies and to dimension them.

In addition to the technical simulation of power plants, an economic section is also included in the software. Typical key figures such as capital value or depreciation time are part of each project simulation. Some studies have already used GREENIUS to simulate and predict the power output of a CSP plant [4,8].

2.2. Meteorological Data

In addition to the input parameters defining the technology, a weather data file must be loaded for the specific site. These data are not implemented in Greenius but third-party data formats can be imported: for example, TMY2, TMY3, METEONORM or S@tel-Light formats. Once all input parameters have been adapted, the simulation can start.

In our work, we used the meteorological data of the METEONORM 7.3 software, which is a world-wide meteorological database [9]. This software contains several cities and gives us the possibility to create our site or city that does not exist and then to interpolate the data from some of the surrounding cities. This way, we can get the data for our site.

2.3. Description of the Study Site

Dapaong, capital of the Savanes region, is located 650 km north of Lomé and 35km from the border between Togo and Burkina Faso in the extreme north of the country as shown on Figure 1 which is an over view of the North region of Togo.

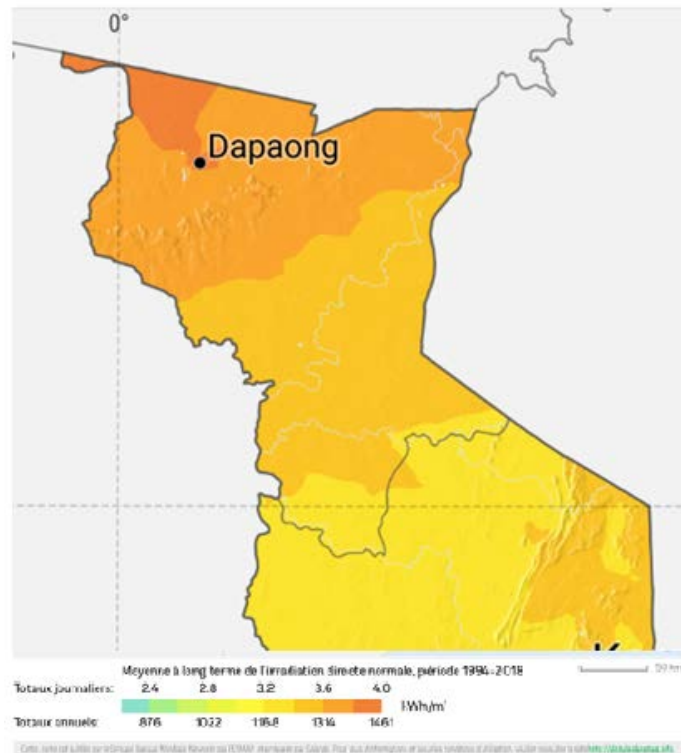


Figure 1. Focus on the Savanes region of Togo [10]

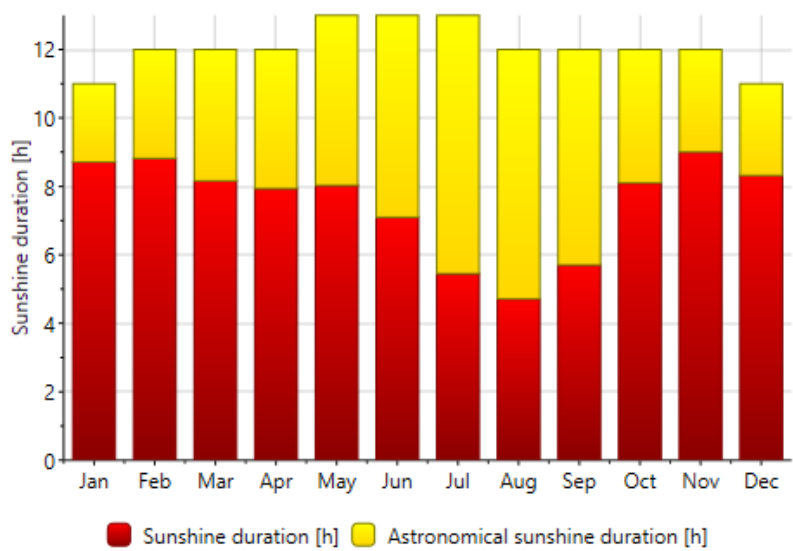


Figure 2. Monthly sunshine duration [11]

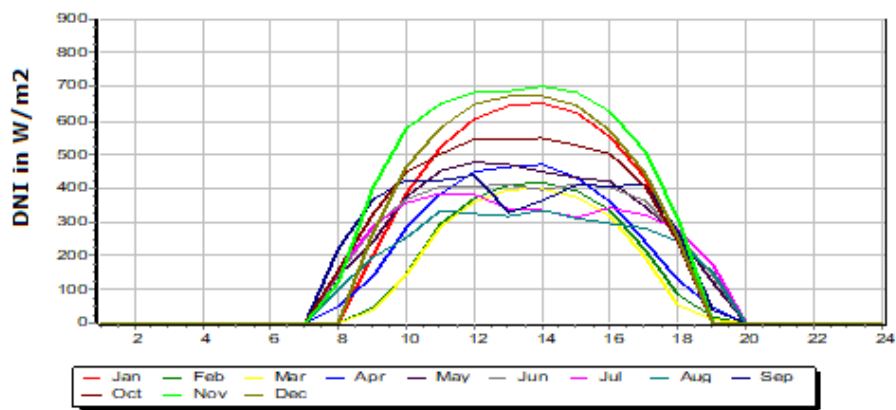


Figure 3. Monthly comparative values of DNI in W/m^2

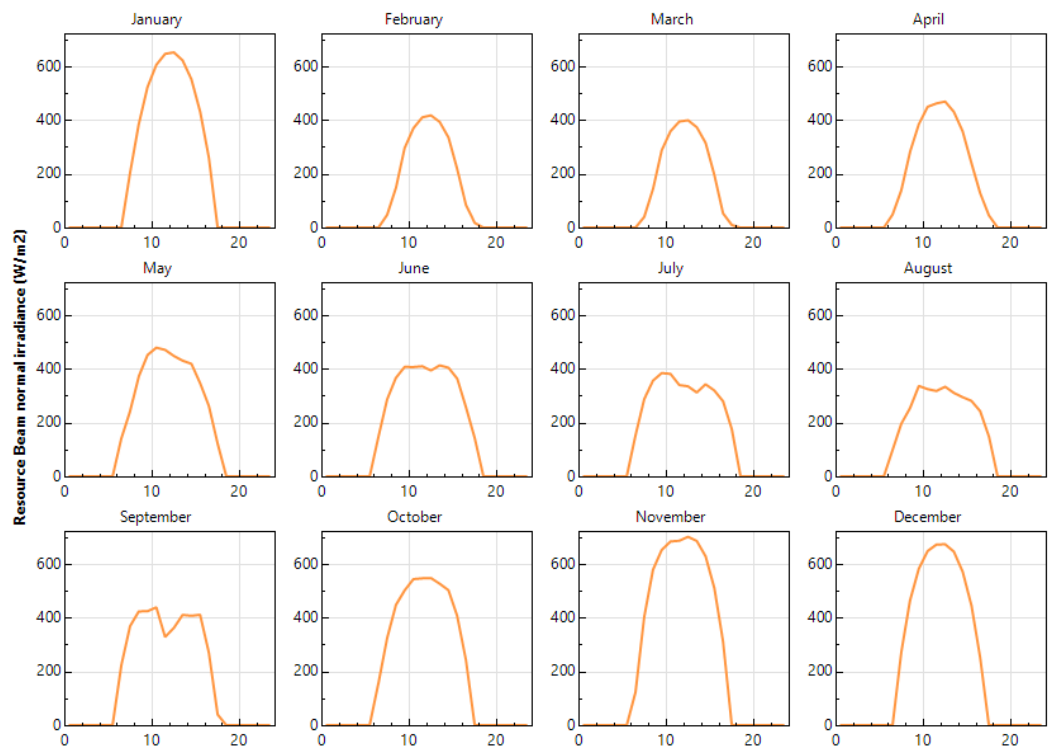


Figure 4. DNI profile per month in W/m^2

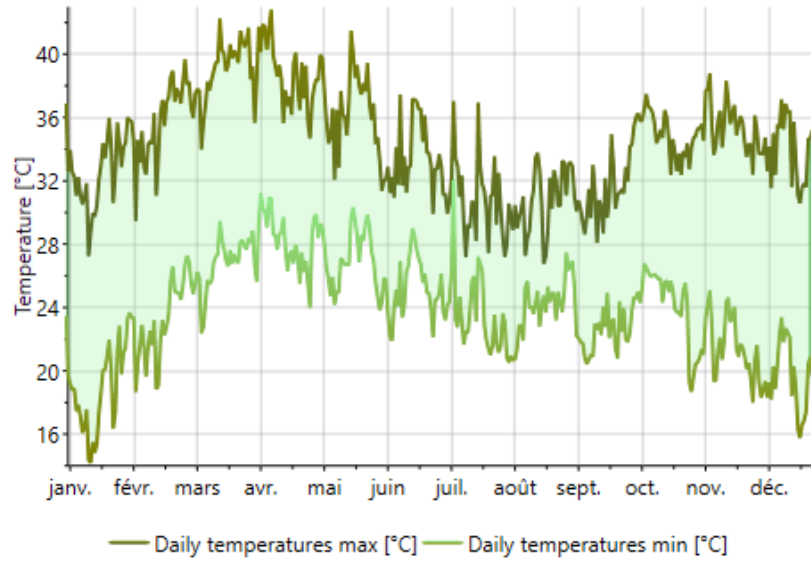


Figure 5. Ambient temperature variation

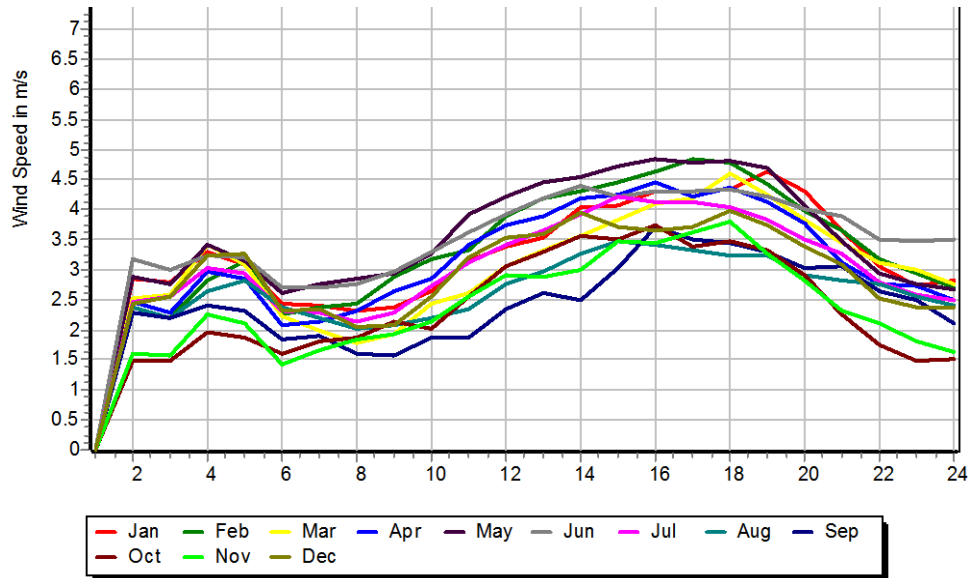


Figure 6. Wind speed variation

Its population is about 60,000. The geographical coordinates of the chosen site are 10.88° Latitude North and 0.17° Longitude East for an altitude of 305 m above sea level. The region is characterized by a high sunshine rate with an average of 8 hours of real daily insolation. In Figure 2, we have a graph of the sunshine duration of each month for one year.

The annual sum of Global Horizontal Irradiance (GHI) is about 2081 kWh/m² with a maximum of 1129 W/m² in March. In contrast, the annual sum of Direct Normal Irradiance (DNI) is 1482 kWh/m² with a maximum power of 918 W/m² obtained in September. But globally the period corresponding to a maximum of direct sunshine is the month of November as can be seen in Figure 3 and Figure 4. We can clearly see that the DNI value (the most important component for a CSP) received by Dapaong is average. Generally, during the operating hours of the power plant between 10:00 and 17:00, the DNI values vary between 400 and 700 (W/m²) for almost every month.

From the same data, we have the variation of the ambient temperature in Figure 5 which ranges from 14.2°C in January to 42.8°C in April.

The evolution of wind speed is one of the factors that influence electricity production [12,13]. It can be seen in Figure 6 that the speed profile is almost the same throughout the year.

2.4. System Modelling and Simulated Configuration

The model chosen for the simulation is the same as that of the Andasol-1 site (in Spain). The Andasol-1 CSP plant has been operational since 2008 [14].

It is presented in Figure 7 and the characteristic values are presented in Table 1. This same model will be used for the simulation at our study site Dapaong and its meteorological data.

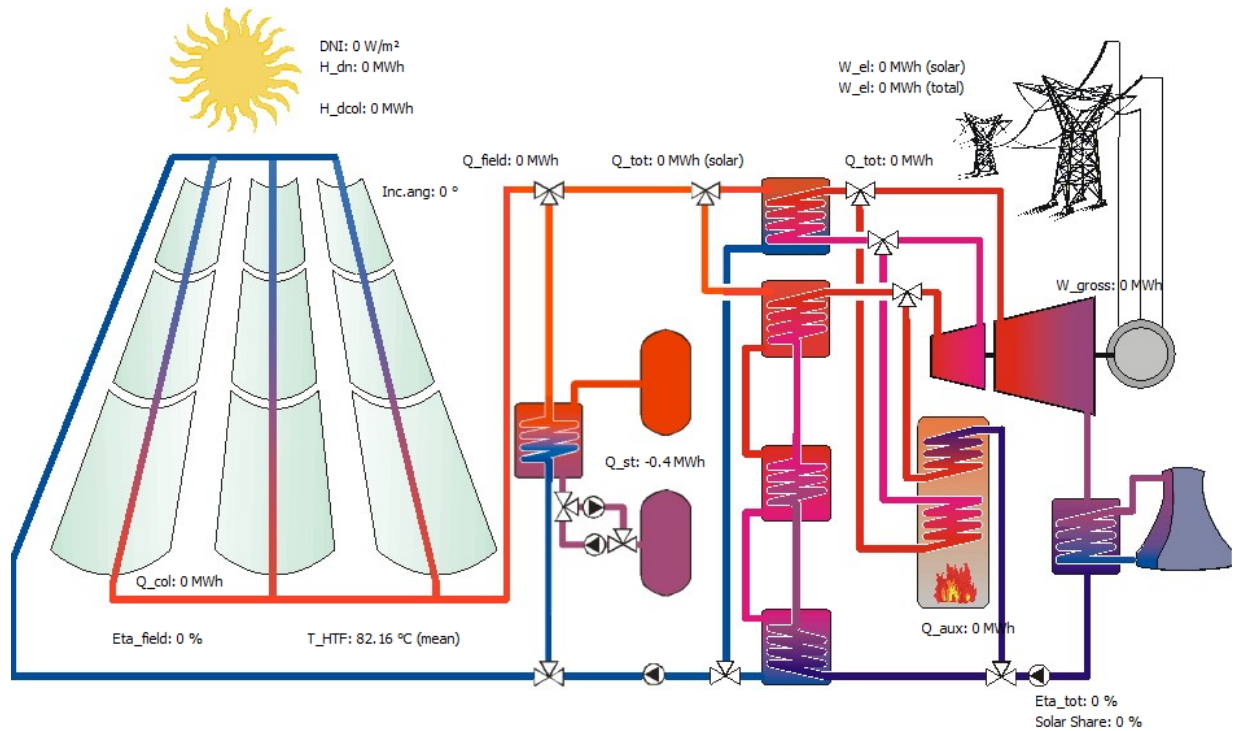


Figure 7. Diagram of the model (Greenius) [11]

Table 1. Configuration of the simulated model

Technology	Parabolic trough sensors
Location	Dapaong (TOGO)
Lat./Long of the site	10.88°N; 0.17°E
Area of the site	200 hectares
Solar resources	1482 kWh/m ² /yr
Solar field area	510 120 m ²
Total number of sensors	624 (156 loops of 4 collectors)
Turbine power	50MW

3. Results and Discussion

3.1. Validation of the Results with the Andasol-1 Model

The Andasol-1 solar power plant is Europe's first commercial parabolic trough power plant (50 megawatts), located near Guadix in the province of Granada, Spain. The Andasol-1 plant was commissioned in November 2008 [14] and has a thermal storage system that absorbs

part of the heat produced in the solar field during the day. In order to better appreciate the electricity production in Dapaong, we will use the Andasol-1 plant to simulate and compare their production.

The configuration of the Andasol-1 site is summarized in Table 2 below.

The curve of the evolution of the direct radiation power at the Andasol-1 site in Spain in Figure 8 shows that the maximum solar radiation is obtained in June. There is a sharp drop in radiation from June to December.

Table 2. Presentation of the site Andasol-1

Technology	Parabolic trough sensors
Status	Operational
Location	Aldeire Granada (Spain)
Lat/Long of site	37°13'50.83" N ; -3° 4' 14.08"E
Site area	200 hectares
Solar resource	2 136 kWh/m ² /yr
Expected electricity generation	158 000 MWh/yr
beginning of construction	03 July 2006
beginning of production	26 November 2008
Solar field area	510 120 m ²
Total number of collectors	624 (156 loops of 4 collectors)
Turbine power	50MW
Storage	Storage Capacity (7,5h- 1010 MWh)

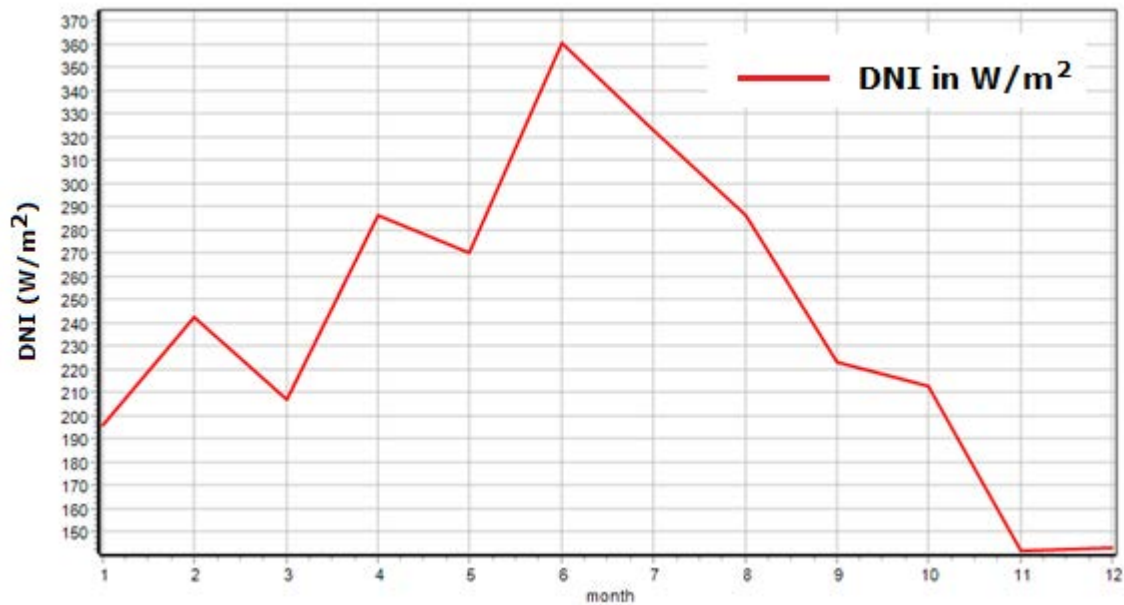


Figure 8. Evolution of the DNI of Andasol-1

The results of the Andasol-1 simulation are summarized in Table 3 below.

The graph of daily electricity production at the Andasol site shows that this production is not stable from day to day, but varies from one day to another, and the

maximum production is obtained in June, as predicted by the curve of direct normal radiation (DNI) received. Figure 9 and Figure 10 show us respectively the daily and monthly evolution of this production on the Andasol site.

Table 3. Simulation result of Andasol-1

Direct normal irradiance (DNI)	2110.7 kWh/(m ² ·yr)
Average annual ambient temperature	17.35 °C
Thermal energy at the field outlet	439 761 MWh _{th}
Net electrical energy at system output	139 348 MWh _{el}
Gross electrical energy at system output	156 736 MWh _{el}
Average field efficiency	40.84%
Average system efficiency	12.94%

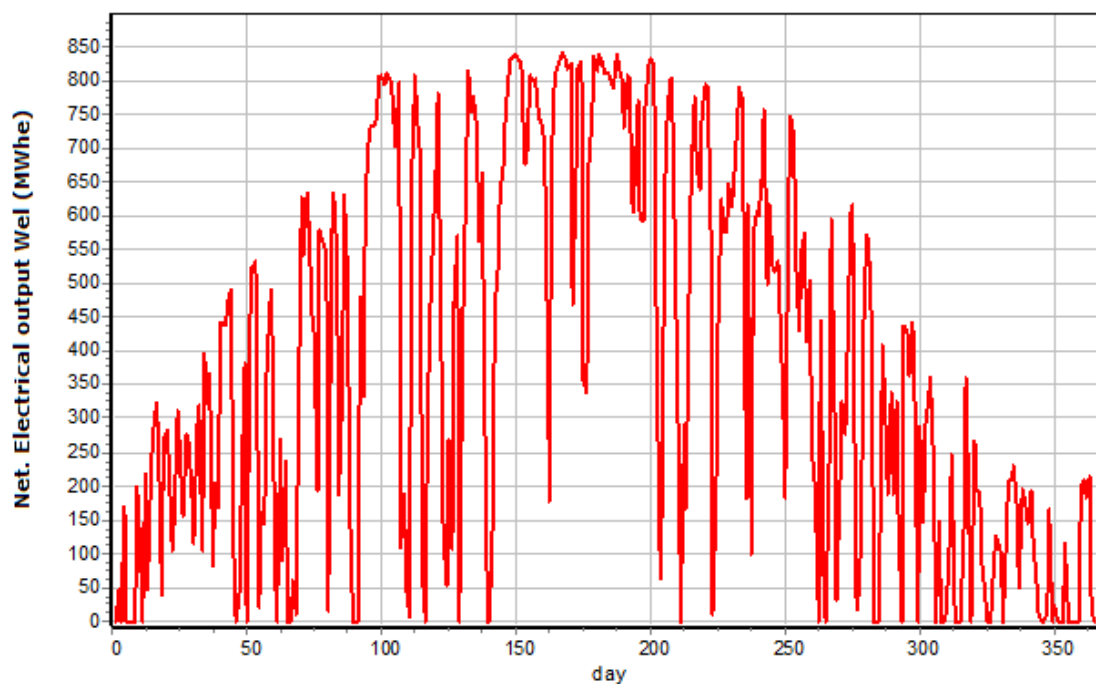


Figure 9. Evolution of the daily electricity production of Andasol-1

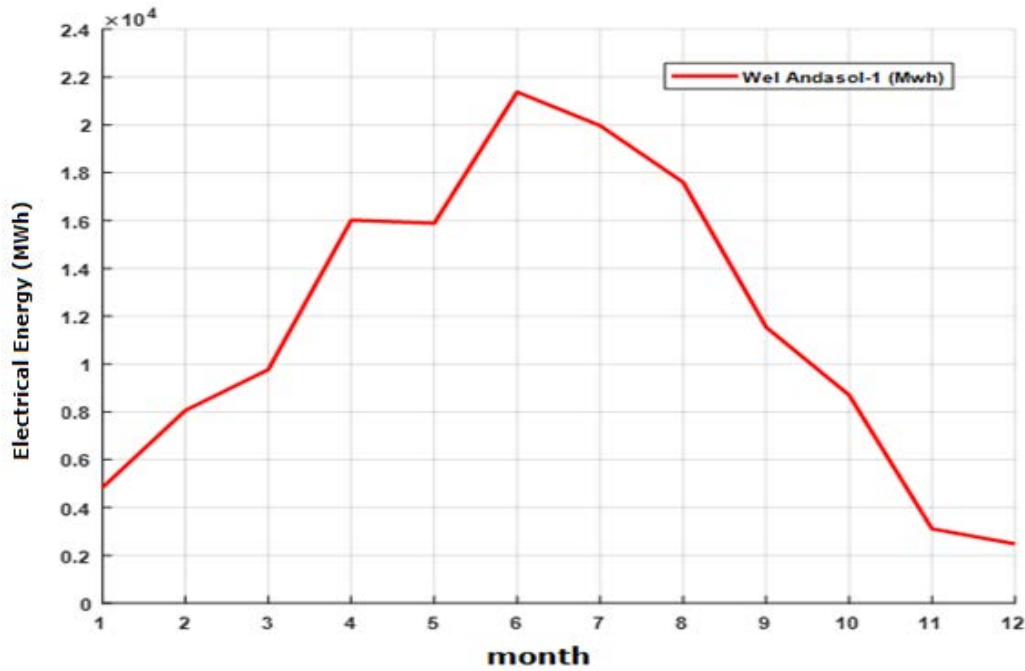


Figure 10. Evolution of the monthly electricity production of Andasol-1

In our further work, these daily and monthly productions will be taken as reference values in order to better appreciate the production of such a power plant in Togo, more precisely on the Dapaong site.

3.2. Results of the Simulation of the Same Configuration in Dapaong

In this section, we will present the results of the simulation under the Dapaong radiation. The simulation of a parabolic trough solar power plant with a capacity of 50 MWh can provide an average of 107 525 MWh_{el} of net electrical energy for one year of operation.

The results of the simulation are summarized in Table 4. The daily production varies according to the profile of the daily DNI obtained and passes through a maximum of 729 MWh on day 256 of the year as shown in Figure 11.

The maximum electricity production is obtained in the month of November with 13,570 MWh_{el} as can be seen in Figure 12 while the minimum production is obtained in the month of March with 4,181 MWh_{el}; this is explained by the DNI values.

The monthly production for the year is summarized in Table 5.

Table 4. Results of the simulation in Dapaong

Direct normal irradiance (DNI)	1482 kWh/(m ² ·yr)
Average annual ambient temperature	28.83 °C
Thermal energy at the field outlet	326 398 MWh _{th}
Net electrical energy at system output	107 525 MWh _{el}
Gross electrical energy at system output	119 846 MWh _{el}
Average field efficiency	43.17 %
Average system efficiency	14.22 %

Table 5. Monthly values of the simulation

	DNI (W/m ²)	T _{amb} (°C)	W _{el} (MWh _e)
January	203	25	10471
February	114	29	4181
March	107	32	4949
April	143	33	7920
May	174	32	9804
June	167	29	8969
Juilly	153	28	8326
August	131	27	7401
September	171	27	9594
October	198	30	11261
November	248	28	13570
December	218	27	11078
Mean	169	29	8 960
Annual sum	1 481 999		107 525

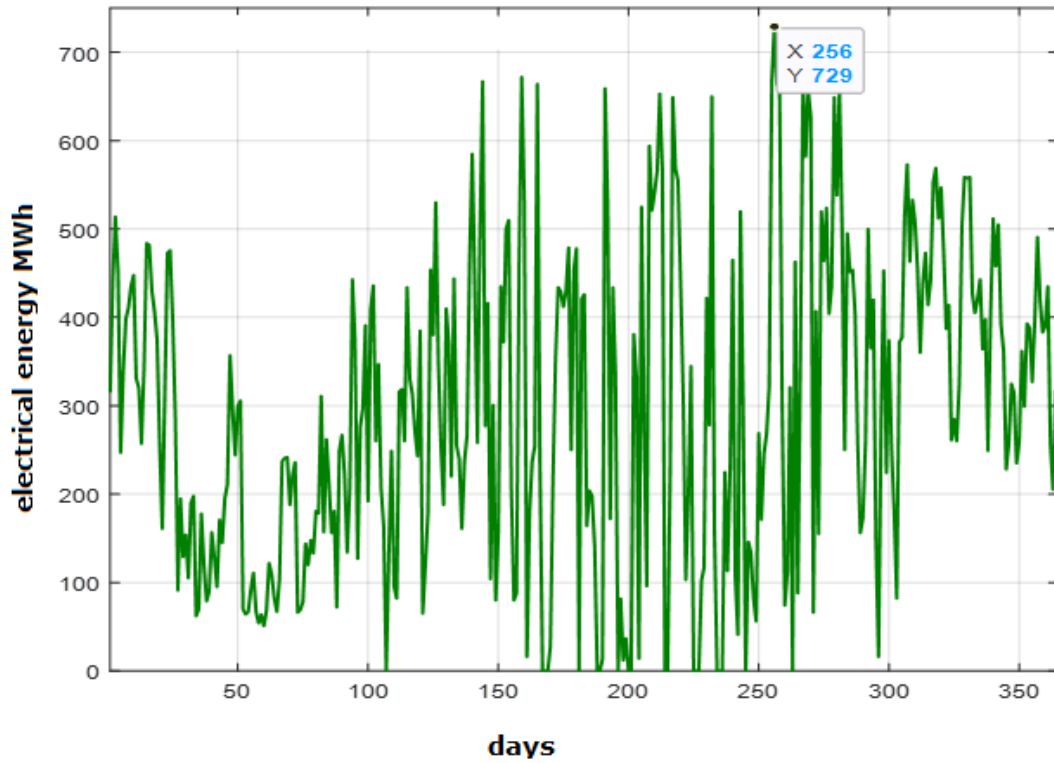


Figure 11. Evolution of daily electricity production in Dapaong

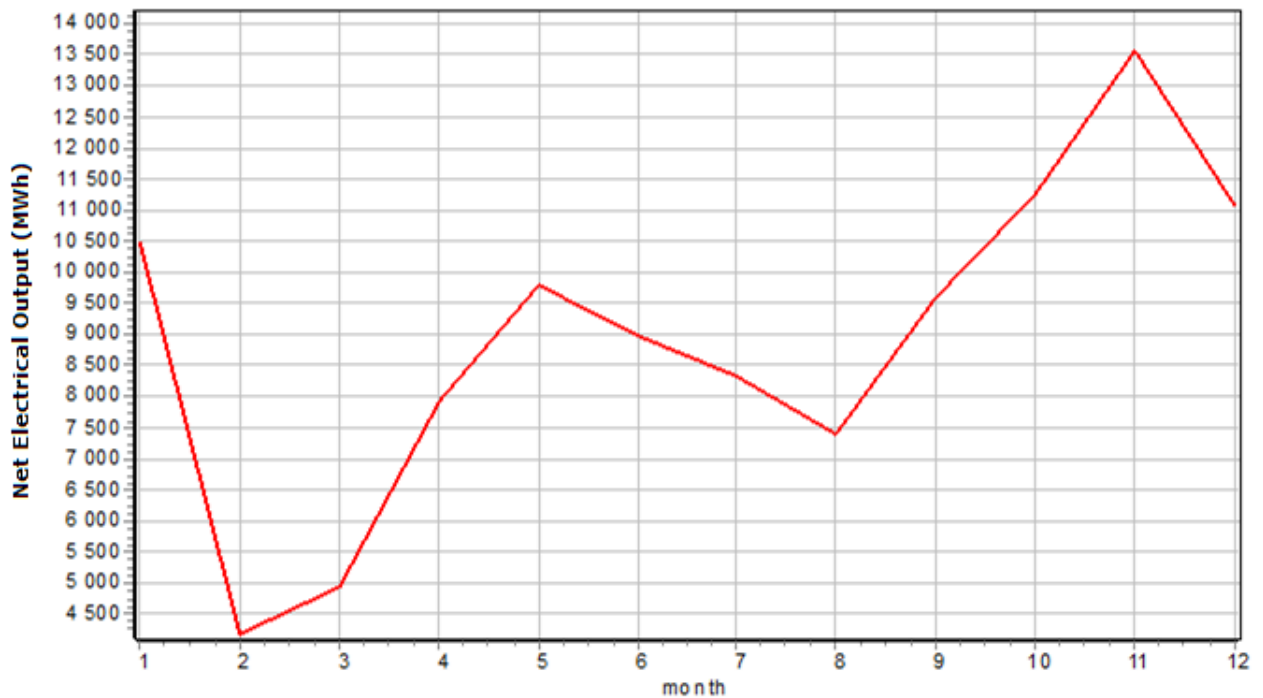


Figure 12. Evolution of monthly electricity production in Dapaong

3.3. Comparison of Dapaong's Electricity Production with Andasol's Result

In order to better appreciate the electricity production of the Andasol installation on Dapaong, we make a comparison with the results of Andasol. As shown in Figure 13, the results clearly show that the installation is more productive in Andasol than in Dapaong due to the difference in DNI (direct normal radiation). It should be noted, however, that the total production for the year

at Dapaong represents 77% of the production at Andasol.

The electricity production at the reference site (Andasol-1 in Spain) is sufficient to cover the electricity needs of 200,000 people [14]. Therefore, the electricity production of such a facility at the Dapaong site is more than sufficient to cover the needs of the population of Dapaong, which is only 60,000 people. This installation can therefore be connected to the grid to solve the load shedding problems of the surrounding towns.

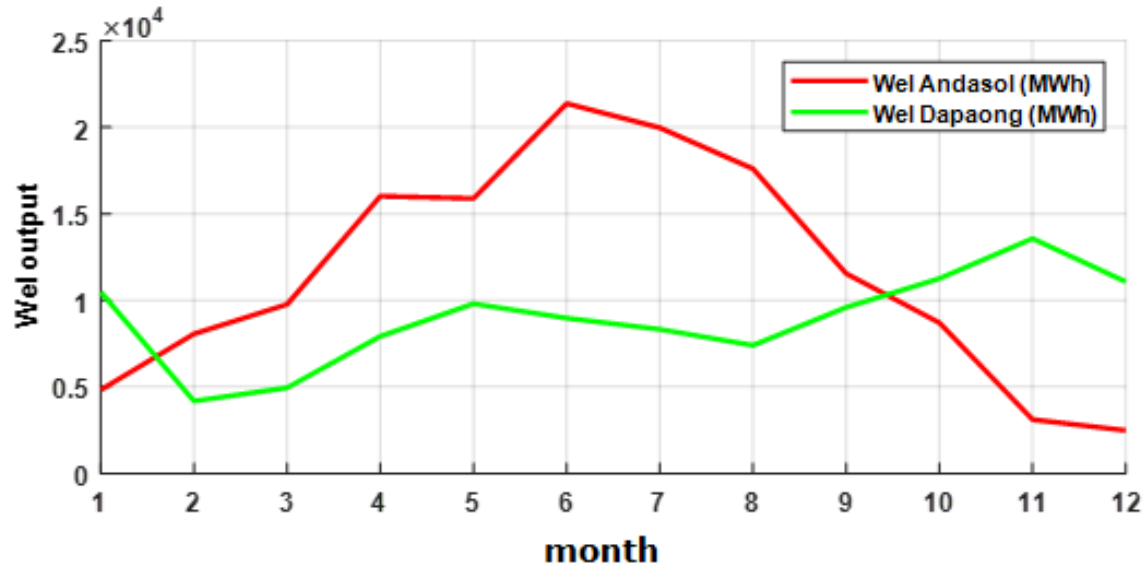


Figure 13. Comparison of electricity production between Andasol and Dapaong

However, compared to the NOOR I thermal power plant in Morocco, which has been operational since 2016 and produces 160 MW of electricity on a 480-hectare facility [15], a thermal power plant of the same technology in Dapaong is relatively less profitable. It is also interesting to note that a comparative study of the same configuration of Andasol has been carried out in South Africa for an installed capacity of 50 MW [16]. This study showed the advantages of storage in such a facility.

3.4. Comparison of Power Generation with other Technologies

It is also possible to use a solar power plant with Fresnel mirrors in the solar array instead of parabolic trough mirrors. This is a less common technology but also less expensive to manufacture, which would reduce the cost of building the plant.

In addition to Fresnel mirror solar power plants, the next most common technology after parabolic troughs is the solar tower.

In this section we simulated the electricity production for both technologies for equal solar field areas and compared it to the Andasol installation but still under the Dapaong climate.

The results of the simulation are summarized in the Table 6 below.

The simulation results show that the electrical energy production is 113 915 MWh_{el} per year for the solar tower technology with an efficiency of 16.18% for the system while a Fresnel mirror solar array for the same area would produce an annual electrical energy of 121 054 MWh_{el} with an overall efficiency of 16.01%. Table 7 and Figure 14 show us the comparison of the electrical energy production of a solar tower plant, a Fresnel mirror plant and a parabolic trough plant.

We can see that the Fresnel mirror technology produces the best electrical energy of the three technologies, accounting for 87% of the total electrical energy produced by the Andasol installation, and therefore this technology seems to be the most appropriate for the Dapaong site.

Table 6. Comparison of the results of the three plants

Technology	Solar tower	Fresnel mirror	Parabolic trough sensors
Location	Dapaong (TOGO)	Dapaong (TOGO)	Dapaong (TOGO)
Solar resource	1 482 kWh/m ² /yr	1 482 kWh/m ² /yr	1 482 kWh/m ² /yr
Solar field area	510 120 m ²	510 120 m ²	510 120 m ²
Total number of sensors	624 (156 loops de 4 collectors)	624 (156 loops de 4 collectors)	624 (156 loops de 4 collectors)
Turbine power	50MW	50MW	50MW
Direct normal irradiance (DNI)	1482 kWh/(m ² ·yr)	1482 kWh/(m ² ·yr)	1482 kWh/(m ² ·yr)
Average annual ambient temperature	28.83°C	28.83°C	28.83°C
Thermal energy at field output	323 986 MWh _{th}	369 540 MWh _{th}	326 398 MWh _{th}
Net electrical energy at system output	113 915 MWh _{el}	121 054 MWh _{el}	107 525 MWh _{el}
Gross electrical energy at system output	129 075 MWh _{el}	135 438 MWh _{el}	119 846 MWh _{el}
Average field efficiency	51.21%	48.88%	43.17 %
Average system efficiency	16.18%	16.01%	14.22 %

Table 7. Monthly electricity production of the 3 technologies

Value	W_{el} Parabolic trough (MWhe)	W_{el} Solar tower (MWhe)	W_{el} Fresnel mirror (MWhe)
January	10471	12636	11729
February	4181	5156	5077
March	4949	5337	5914
April	7920	7446	8847
May	9804	9419	10942
June	8969	8678	10005
Jully	8326	8052	9479
August	7401	7063	8443
September	9594	9278	10662
October	11261	11799	12481
November	13570	15394	15047
December	11078	13657	12429
Mean	8960	9493	10088
Annual sum	107 525	113 915	121 054

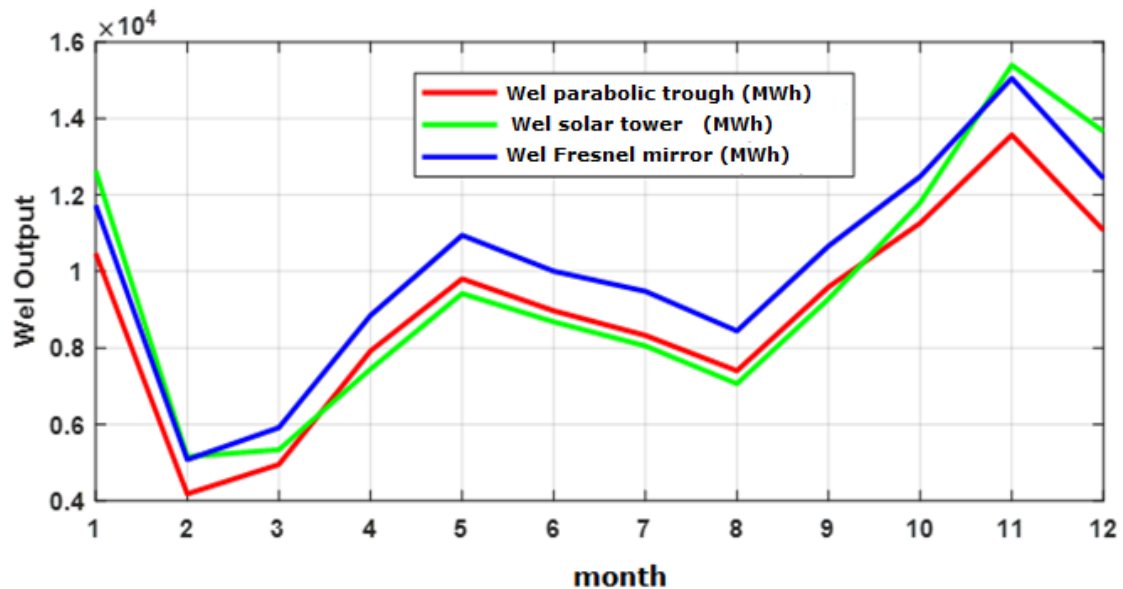


Figure 14. Comparison of the power generation of the three technologies

3.5. Assessment of Investment Costs

From the above results, it is clear that among the three simulated technologies, we will choose a solar power plant with a Fresnel mirror solar array. But a technical analysis alone is not enough to choose the right technology. A financial analysis of the total cost of the installation should also be carried out. This analysis allows to forecast the levelized electricity cost (LEC) per kWh.

The GREENIUS software also gives an idea of the LEC of the installation.

In this section we will therefore present the economics of plant construction for the three technologies simulated in this paper.

According to a market study, Fresnel mirrors cost almost three times less than parabolic trough collectors [17], which offers a major advantage for the use of this type of plant, especially as it has a better technical

performance than that using parabolic trough collectors. The investment costs and kWh prices for each type of plant are summarized in Table 8 below. This comparison proves that the Dapaong site can accommodate a Fresnel mirror plant for better efficiency and financial profitability.

3.6. Environmental Impacts

One of the advantages of renewable energy is that it is clean energy. They greatly reduce the emission of greenhouse gases. The results of the simulation give the CO₂ reduction values summarized in Table 9. This is therefore proof that renewable energies contribute to the protection of the environment. This plant would contribute to the development of the region as it will be self-sufficient in electricity with less risk to the population of Dapaong of developing diseases related to the increase of CO₂ in the atmosphere.

Table 8. Comparison of capital cost and LEC

		DAPAONG			
	ANDASOL	PARABOLIC TROUGH	SOLAR TOWER	FRESNEL	
Total Investment Costs (IC)	174	171	173	117	Mrd CFA
Levelized Electricity Costs (LEC)	124	158	158	101	CFA/kWhe

Table 9. CO₂ reduction values

	Parabolic trough	Solar Tower		Fresnel mirror
Annual CO ₂ reduction (t CO ₂)	64 515.49	68 349		72 634

4. Conclusion

The objective of this work was to study the possible implementation of a solar thermodynamic power plant in Togo in order to solve the problems of access to electricity, since renewable energy sources are proving to be the alternative to the energy problem in Africa. The simulations we carried out on solar thermodynamic power plants under the climate of Dapaong allowed us to realize that solar thermodynamic power plants can really help Togo in the quest for solutions to solve the energy problem and at the same time decrease its energy dependence on neighboring countries. A simulation of a prototype parabolic trough power plant with a capacity of 50MW reveals a possible production of 107 525 MWhel of net electrical energy with an average efficiency of 14.22%. In Africa, many countries such as Morocco, South Africa and Algeria have already proven that thermodynamic solar power is possible with functioning installations.

In this study, the comparison of the electrical energy production of three types of solar thermodynamic power plants allows us to make a choice on the type of solar thermodynamic power plant adapted to our meteorological data.

The results of the simulations clearly show that a Fresnel mirror solar power plant could produce up to 121.054 MWhel of net electrical energy and can offer Togo a possibility of electricity production since it has the lowest investment cost and therefore the lowest cost per kWh.

In addition, a hybrid photovoltaic/concentrated solar power (PV-CSP) system is being considered as one of the current research directions in the field of solar energy, due to its various advantages over stand-alone PV and CSP technologies. Compared to stand-alone PV systems, hybrid PV-CSP can produce higher quality electricity [18], so a study in this perspective would be a major asset for energy independence and for increasing the production of electrical energy.

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