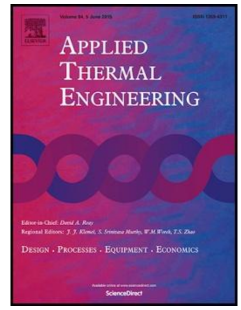

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Feasibility study of a wind-photovoltaic hybrid power generation system for a remote area in the extreme south of Algeria

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Highlights

- The feasibility of a hybrid renewable energy system for electricity generation in Timiaouine is evaluated.
- The software HOMER (Hybrid Optimization Model for Electric Renewable) is used.
- Full electricity demand for Timiaouine could be supplied by a hybrid energy system.
- The hybrid configuration consists of a wind system, a solar PV system and a backup diesel generator.

Abstract

The electricity supply for the large region of southern Algeria is generated by diesel power, which has an enormous technical and environmental impact. The alternative to this is to use renewable energy sources and to take advantage of the high potential of solar photovoltaic and wind energy. The average daily solar radiation in this region is equal to 7.82 kWh/m^2/day and the wind reaches a speed between 5 and 11 m/s. In this paper, we proceed to evaluate the technical and economic feasibility of using a hybrid generation system to satisfy the electricity demand for Timiaouine town, which is located in the extreme southwestern part of Algeria. Timiaouine, with more than 200 families, is not connected to the power grid. The feasibility of various configurations of renewable power generation was evaluated. The optimization results predict that 100% of the electricity demand could be supplied to the town by using a hybrid configuration composed of a wind energy system, a solar PV system and a diesel generator used as a backup system. The cost of electricity generation with this system was estimated at 0.176 US $/kWh. Carbon emissions to the atmosphere could approximately be reduced by 593.125 tons/year.

Keywords

- Wind energy
- Solar PV
- Hybrid energy system
- HOMER
- Timiaouine

Nomenclature

PV: photovoltaic

NPC: net present cost

COE: cost of energy

HOMER: Hybrid Optimization Model for Electric Renewable

1. Introduction

The remote rural area of Timiaouine, located in the province of Adrar in Algeria, benefits from an average wind speed of 5-9 m/s at 50 m elevation [1] and an average daily solar radiation of 7.82 kWh/m^2/day [2]. However, the lack of solar energy during the night and of wind energy for a few hours during the day makes hybrid configurations more attractive for electricity supplies, which rely on renewable energy sources. In the open literature, hybrid renewable electrical systems in off-grid applications have been reported as economically viable, especially in remote areas. The combined use of renewable energy sources, particularly wind and solar energy is becoming increasingly attractive and is being widely used as an alternative to fossil-fuel energy [3]. Within this perspective, the remote rural area of Timiaouine can readily be expected to have enough potential for generating its own electricity demand with a stand-alone hybrid renewable energy system and could also export the excess of electricity to nearby places. Timiaouine is the last village in southern Algeria, and is located on the border with Mali.

This study aims to explore how it would be possible economically to supply electricity to the town with the hybrid renewable energy system, since grid extension is either impractical or prohibitively expensive and the cost of fuel increases drastically with the remoteness of the location [3]. The software HOMER (Hybrid Optimization Model for Electric Renewable), developed by the National Renewable Energy Laboratory (NREL) in the United States, was used in this study to evaluate the feasibility of various hybrid systems, essentially due to the frequent increase in the price of fossil fuels in this region of the Sahara.

Recently, hybrid renewable energy systems combined with diesel generator have been used to deliver the power demand in various regions, especially remote areas [4-8]. However, increase in fuel prices, intensive maintenance and harmful carbon emissions have made them unsustainable and unattractive [9]. Some case studies were performed to define the utility of hybrid systems, such as that reported by Onar et al. [10], which studied the feasibility of using renewable energy sources to satisfy the electricity demand on the biggest island in Turkey. The feasibility of adding wind turbines to an existing diesel plant in a village in Saudi Arabia was also studied by Rehman et al. [11]. Another feasibility study was reported by Erdinc and Uzunoglu [12], where hybrid energy systems using hydrogen as an energy vector were evaluated for applications in Newfoundland, Canada. Hybrid stand-alone electricity generation systems are often considered more reliable and less costly than systems that rely on a single source of energy [13]. In various research papers [14-16], hybrid renewable electrical systems in off-grid applications were demonstrated to be economically viable, especially in remote locations. As the advantages of solar and wind energy systems are widely known, system designers have started looking at integrating them [17-18].

Although, in 2011, only 1% of the electricity produced in Algeria was from renewable energy sources (except hydro), renewable energy systems have been given some favourable attention by the authorities in recent years [19]. This was marked by the inauguration of the hybrid renewable power plant of Hassi R'Mel which consists of a 130 MW combined cycle; a 25 MW parabolic trough solar field that covers an area of over 180,000 m^2; a 10.2 MW wind farm connected to the grid in the province of Adrar and an experimental photovoltaic power plant of 1.1 MW in Ghardaia. Recently, the Algerian government has upgraded the production capacity of its projects for power generation from renewable energy sources to a load of 22,000 MW instead of the 12,000 MW set in 2001. This new programme was started this year carrying out projects with a power capacity of 318 MW; 53 MW of which are installed in the province of Adrar and use the photovoltaic technology [20]. The implementation of this programme will allow Algeria to achieve a share of renewable sources of nearly 27% in the national electricity generation balance by 2030.

2. Description of the case study

The location and electrification of Timiaouine and the availability of renewable energy sources for the town are presented in the following sub-sections.

2.1. Location and population

Timiaouine is one of the most remote areas located in the extreme south of the province of Adrar in Algeria. The location of this village in Algeria is shown in Figure 1. The village is located at 20° 26′ N latitude and 1° 47′E longitude, and consists of 200 households.

2.2. Load profiles and electrification

There are still problems with the supply of electricity to the town of Timiaouine. Electricity is provided for only six hours a day and usually at night using diesel generators. These belong to the municipality and not to the national society for electricity and gas “Sonelgaz”, as the town is not connected to the power grid. Fuel is often conveyed over a long distance from the province of Adrar with expensive transport costs. The maintenance of diesel generators is also difficult in a regional enclave that does not have enough qualified personnel. This was the motivation for this work focused on a study of the feasibility of utilizing hybrid solar photovoltaic/wind energy systems to supply electricity to the town. The electricity demand in Timiaouine varies according to the two seasons, namely winter and summer. The population is made up of a majority of rural dwellers with minimum comfort requirements and the main activity is breeding camels in the desert. In this study, we used a reference month for the power load in winter and a reference month in summer as models for the power demand for the town. Data corresponding to 2010 provided by the Timiaouine municipal council was used in our simulation. Monthly load profiles obtained by the synthesizing process of HOMER are shown in Figure 2. The average annual electricity peak load demand is 2.5 MWh/day and is the power that the electricity generation system is required to guarantee.

The study of the load curve is based on an analysis of the current load and the evolution of the electricity consumption load in Timiaouine. The isolated southern Algerian networks experience an annual growth of electricity consumption that exceeds 14% compared to a 9.6% increase for interconnected networks in the north [20]. This pronounced increase in electricity consumption is caused by the massive use of air conditioning during the hot months characteristic of the southern regions.

The load curve was obtained from the electricity consumption database registered by the current energy production system with diesel generators.

2.3. Availability of renewable energy sources

2.3.1. Solar radiation

Average monthly values of solar radiation for Timiaouine are shown in Figure 3. As seen from this figure, the solar radiation in the village reaches its maximum value of 7.52 kWh/m^2/day in June and is at its minimum value of 4.34 kWh/m^2/day in December. The average daily radiation for the whole year is 6.35 kWh/m^2/day.

The average monthly daylight hours are shown in Figure 4. The daily hours in this village reach a maximum value of 13.3h/day in June and a minimum value of 10h/day in December. The average value of daily hours for the whole year is 10.9 h.

2.3.2. Wind speed

The wind speed data used in this study was provided by the national society for electricity and gas "Sonelgaz", although, HOMER is capable of generating synthetic wind data if four parameters are defined by the user [21], namely Weibull k value, autocorrelation factor, diurnal pattern strength and the time of peak wind speed. Timiaouine is characterized by an average wind speed of 5.53 m/s at 50 m elevation, 6.14 m/s at 100 m and 6.52 m/s at 150 m. The lowest monthly wind speed is obtained in September and the highest one is obtained in January. Figure 5 depicts the monthly changes in wind speed over a year at 50 m, 100 m and 150 m elevations at the Timiaouine site. These data were obtained from reference [22] for the period 1983 to 2005. As this figure shows, the highest speed in a year is registered in December and January.

Over 24 hours the wind speed increases during the night reaches a maximum value and then decreases until it reaches its minimum value around 10h30 in the morning. This trend can be observed in Figure 6, which illustrates the changes of the wind speed on September 25th, 2003 at 50 m elevation. The wind speed increases and reaches a maximum value at night when solar energy is not available. Therefore, a hybrid system with integrated wind energy and solar energy could be more efficient.

3. Analysis of the power generation system in Timiaouine

To evaluate the extent to which the configuration proposed in this study is economic for Timiaouine and in order to explore the viability of improving its current power system, an economic analysis and a ranking of the feasible systems were performed using the Homer software. A hybrid power system formed by a wind turbine, a PV system and a generator diesel was used. The wind turbine is designed for low and moderate wind speeds and optimized for regions with low wind speed response.

3.1. System configuration

The implementation of real systems is usually preceded by a series of theoretical studies for technical feasibility. The HOMER software simplifies the task of evaluating the design of different power systems, i.e. off-grid and connected to network, for a variety of applications. It allows for the analysis and combination of different energy sources to arrive at an optimal display configuration.

The objective of the optimization process carried out in the present work was to determine the optimal value of each decision variable (PV, wind and generator size). The configuration proposed for the power system did not include a storage battery. The diesel generator supplies electrical energy when wind and solar energy are not available. The optimization process determines the best configuration of the system that satisfies the specified constraints at the lowest cost. Different initial configurations were proposed for the hybrid power system considered in this study and those that did not satisfy the constraints were rejected until a suitable configuration was encountered. In these configurations, a renewable energy penetration rate of over 90% was imposed in order to take advantage of the huge potential of solar and wind energy sources in the region under study. The schematic sketch of the system is shown in Figure 7. This figure also shows the specifications and configurations of all the feasible stand-alone systems for Timiaouine, simulated by HOMER for an assumed project lifetime of 25 years. Grid extension and connection costs are important factors for integrating renewable power sources into a future electricity network or for exporting the excess to the north of Mali.

3.2. Optimization results and discussion

Based on the optimization results obtained from HOMER, the most economic system in each category has been chosen as the representative of that category. Moreover, the selected representative systems from all categories are ranked in order from the most to the least economic. A summary of the results of this procedure is shown in Table 1.

Table 1 reveals that the most economically viable system, which is also the most affordable one among the feasible hybrid energy systems, is the wind–diesel–PV design. It consists of a Vestas V82 wind turbine of 1650 kW, a 150 kW diesel generator, a PV system of 10 kW and a 20 kW power converter. Total NPC is 1,331,999 U$ and COE is 0.176 U$ /kWh.

This first optimized configuration of the hybrid power generation system for the case study considered in the present work has the highest renewable energy penetration rate (96 %) and the lowest cost per kWh. Table 1 shows that the second most economically feasible system is also the second most affordable one of the feasible hybrid renewable energy systems and is composed of only two energy sources, i.e. a Vestas V82 wind turbine of 1650 kW and a diesel generator of 150 kW. Total NPC for this configuration is 1,267,190 U$ and COE is 0.179 U$ /kWh. Compared with the first configuration, the investment cost of this second configuration is 1,267,190$ as against 1,331,999$. This is because the photovoltaic sub-system is not used in the second configuration. A regards the maintenance cost, it is higher in the case of the second configuration because of higher use of the diesel generator. This in turn means that the renewable energy penetration rate is 1% lower than in the first configuration. The cost of electricity ($/kWh) is also higher for the second configuration. The third configuration reported in Table 1 is composed of three energy sources, namely a PV system of 20 kW, a Vestas V82 wind turbine and a 200 kW diesel generator. The investment cost of this configuration is the highest and the renewable energy penetration rate is 2% lower than that of the first configuration.

To compare the hybrid power configuration proposed with that of electricity generation using diesel generators, the hybrid power system was also analysed for performance and usefulness. To do this, parameters such as energy efficiency, pollutant emissions and saving in oil consumption were applied.

3.2.1. Wind energy conversion system

The wind turbine included in the present analysis is a Vestas V82 model [23] with a rated capacity of 1650 kW and an AC output of 220 V. This wind turbine is connected to the AC bus with obvious advantages regarding energy efficiency because the electricity produced can directly supply the load without being diverted through the DC bus. The cost of one unit of V82 wind turbine is 1,000,000 U$, with annual maintenance costs at 25,000 U$. The V82 wind turbine, whose characteristics given by the manufacturer were included in the optimization software, starts operating at a velocity of 4m/s, which is suitable for the wind velocity map of the region. Figure 8 shows the monthly power production of the wind turbine over a year.

3.2.2. Diesel generator

A diesel generator with a capacity of 150 kW was selected to provide electricity to the village when the solar and wind energy sources were not available. The operating reserve was set at 10 % of the hourly load. The production of the diesel generator, whose initial capital cost was assumed to be 100 U$/kW, is represented in Figure 9. Currently diesel price estimation for remote areas in some countries like Algeria is 0.135 U$/litre. This price is not the real price on the international market, as it is subsidized by the government [19]. The diesel price considered in the present work was higher because the cost of transport from the refinery located in the province of Adrar to Timiaouine was included. The distance between the two sites is 1,000 km.

3.2.3. Photovoltaic system

We included solar photovoltaic energy in the power generation system because of its high potential in the site under study and in Algeria in general. The cost of a 1 kWh of solar energy was estimated between 4000 U$ and 5000 U$. Because Timiaouine is located in the south of Algeria transportation costs are very high. Ten different sizes of PV array (10, 20, 30,…100 kW) were analyzed. The best configuration for the case study was that of 10 kW for which the monthly power production over a year is shown in Figure 10. The lifetime of the PV array was taken as 25 years and no tracking system was assumed for the PV system, also an optimal degree of inclination of 23.9° was calculated (Figure 11).

There are several parameters that influence the performance of a photovoltaic system for electricity generation. These parameters are related to the degree of inclination and the temperature of the solar panel. In this case study, we analyzed the optimal degree of inclination of the solar panel for each month taking into consideration that it can be monitored by means of a MPPT tracking system. Figure 11 shows the monthly optimal degree of inclination of the solar panel and an optimal degree curve throughout the year almost constant at a degree of 23.9.

Solar radiation improved considerably when the optimal inclination degree was applied to the photovoltaic system as shown in Figure 12. As can be observed in this figure, solar radiation in this village reaches values higher than 7.10 kWh/m^2/day all the year except in December, when its maximum value is 6.3 kWh/m^2/day.

Figure 13 shows the average monthly temperature over a year in Timiaouine. The maximum average monthly temperature registered was 45.3 °C in July and the minimum average monthly temperature was 22.3 °C in December, while the average temperature over a year was 31.9 °C.

3.3 Carbon emissions

This section aims to investigate how renewable energy sources can be used in Timiaouine and reduce pollutant gas emissions while keeping the system as economical as possible. The renewable share using the hybrid system proposed in this study is 96% (Figure 14). This means that CO_2 emissions to the atmosphere are reduced by 96%. Consumption of diesel fuel is also significantly reduced, as only 4% of the consumed electricity produced by the diesel generator is incorporated into the hybrid power system.

Electricity production using the proposed hybrid power system can annually reduce emissions to the atmosphere in 593.125 tons of CO_2. This makes it 96% ecological when compared with fossil fuel electricity production using diesel generators (Table 2).

The reduction of CO_2 emissions using the ecological hybrid power system proposed here is an indicator of the quality of the system. The initial investment cost is high compared to conventional power systems but the gains for environmental protection also have a high price [24].

It is worth mentioning that a battery bank was not considered for use here because the hybrid configuration proposed incorporates a backup power generation system consisting of a diesel generator. The excess electricity produced by the power hybrid system designed to cover the electricity supply to the population of Timiaouine could be used in other sectors like agriculture or exported to some regions of the north of Mali where the population still has no electricity supply. Figure 15 shows the energy balance between the hybrid power system and the utility power supply over the year. As can be observed in this figure, the balance between power production and utility power is higher in winter than in summer. This is because even wind reaches its highest speed in summer so this corresponds to the peak power demand resulting from higher cooling demand.

4. Conclusions

This study aims to show how interesting a hybrid power system is to supply electricity to the population of Timiaouine in the extreme south of Algeria. It assesses optimal design and operation strategy for hybrid stand-alone power systems, including wind turbines, photovoltaic and diesel generators but not the use of storage batteries. The optimization results predict that 100% of the electricity demand could be supplied to the town using the proposed hybrid power system and moreover, the excess electricity produced could be exported to the north of Mali or used in other activity sectors. The cost of the electricity generated by the system is estimated at 0.176 U$ /kWh. It is worth highlighting that the use of a hybrid power system could approximately reduce carbon emissions to the atmosphere in this small town in the south of Algeria by 593.125 tons/year. The proposed wind–PV–diesel system or even the wind–diesel system could, not only lower the expense, but also achieve a significant increase in the share of renewable energy sources used in the system. At the same time this could result in less pollution to the atmosphere. However, the photovoltaic panels to be used should support the high temperatures that characterize the south of Algeria without suffering a significant decrease in their efficiency. From all the scenarios studied, it is readily observed that in terms of both economic and environmental concerns, it would be beneficial if renewable energy sources were taken into account seriously and were given more importance when designing power systems.

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Figure 1: Geographical position of Timiaouine

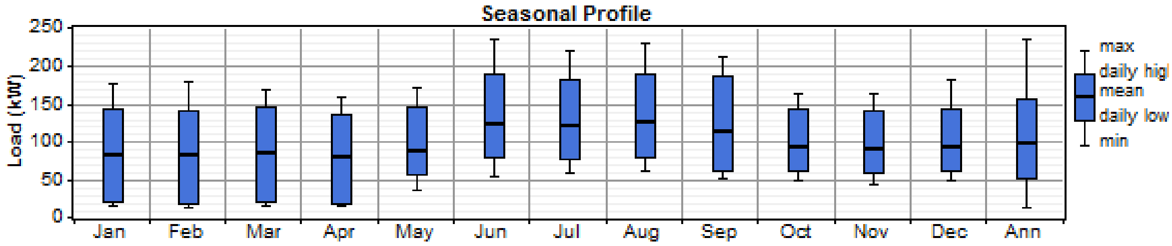

Figure 2: Monthly power demand of Timiaouine

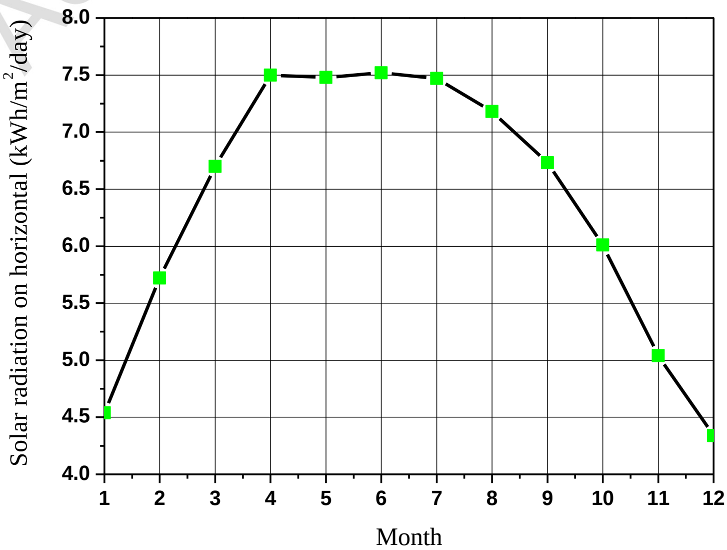

Figure 3: Average monthly solar radiation in Timiaouine

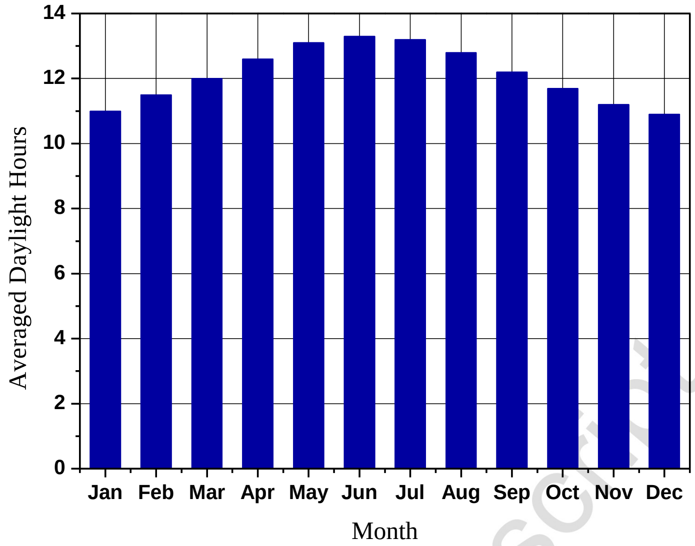

Figure 4: Average monthly daylight hours in Timiaouine

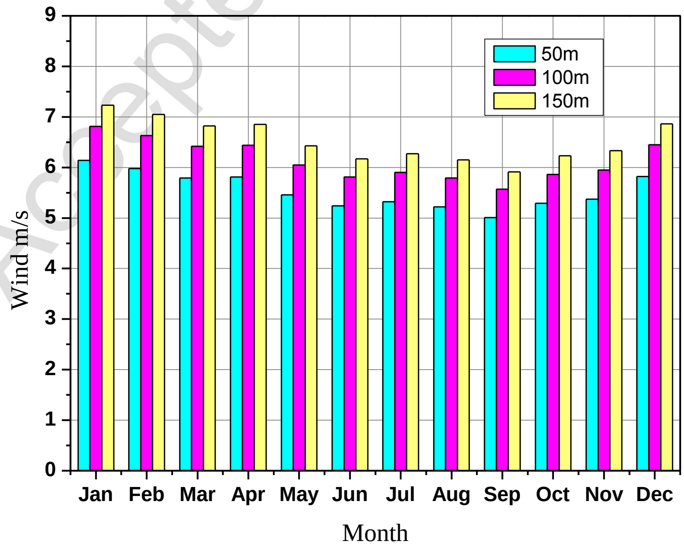

Figure5: Average monthly wind speed in Timiaouine over a year

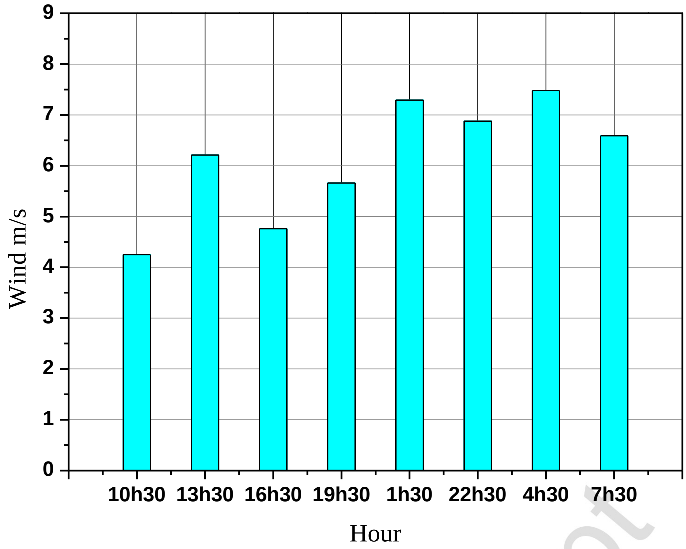

Figure 6: Wind speed changes in Timiaouine over a 24-hour day at 50 m elevation

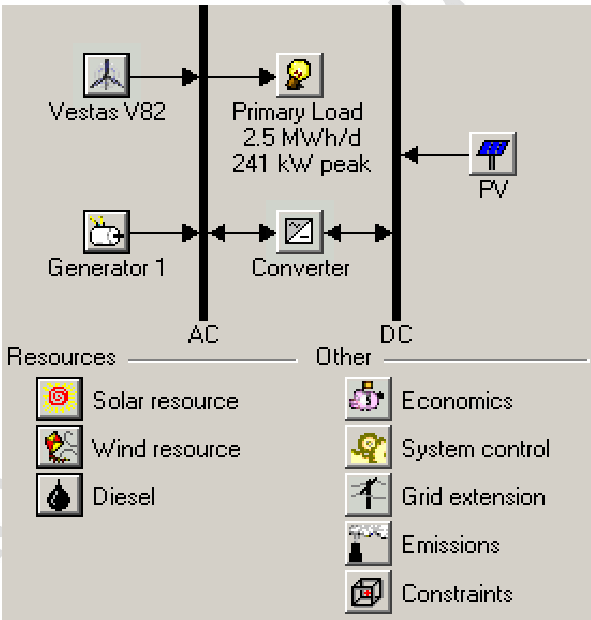

Figure 7: Configuration of the hybrid power system

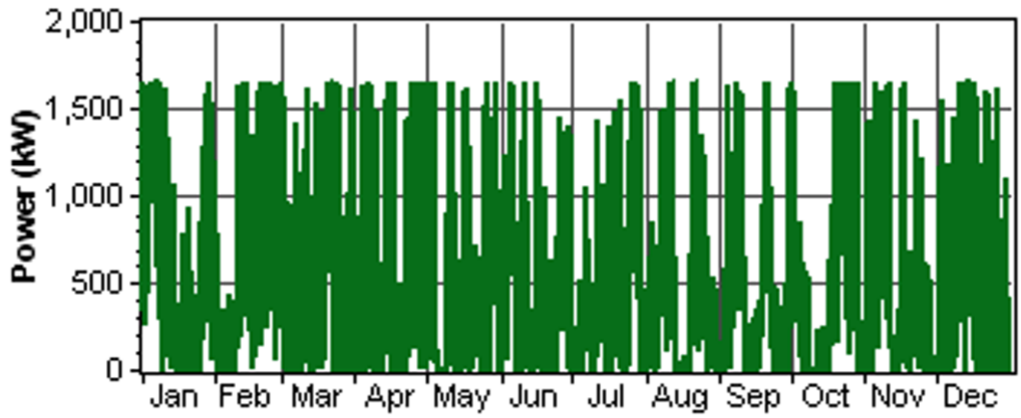

Figure 8: Power produced by the wind turbine (V82)

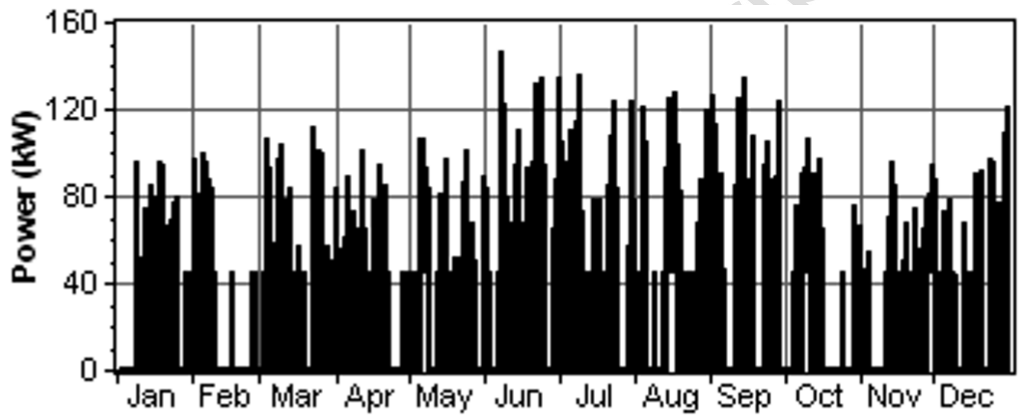

Figure 9: Power produced by the diesel generator

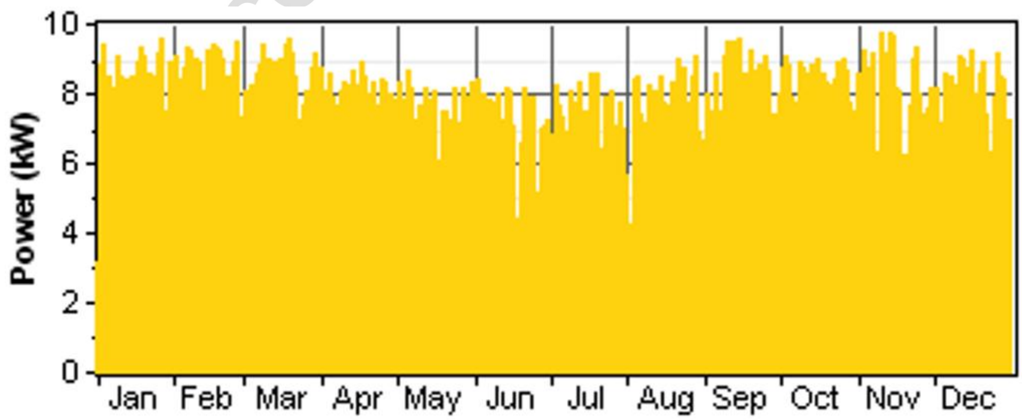

Figure 10: Power produced by the photovoltaic system

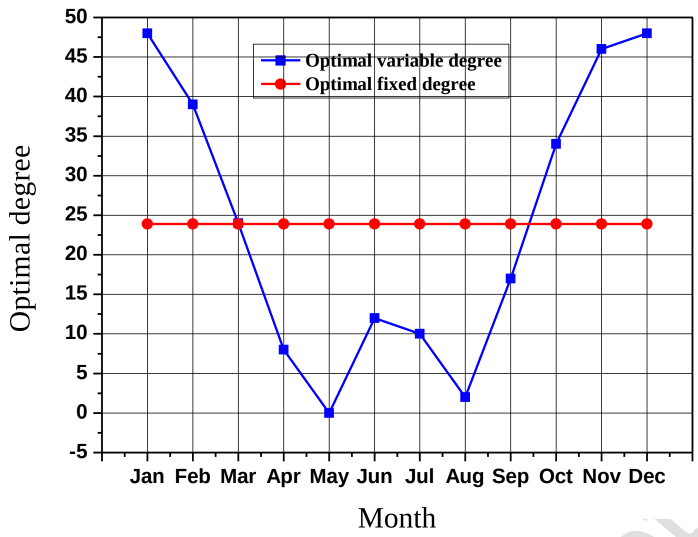

Figure 11: Variation of the optimal degree of inclination of the solar panel versus months

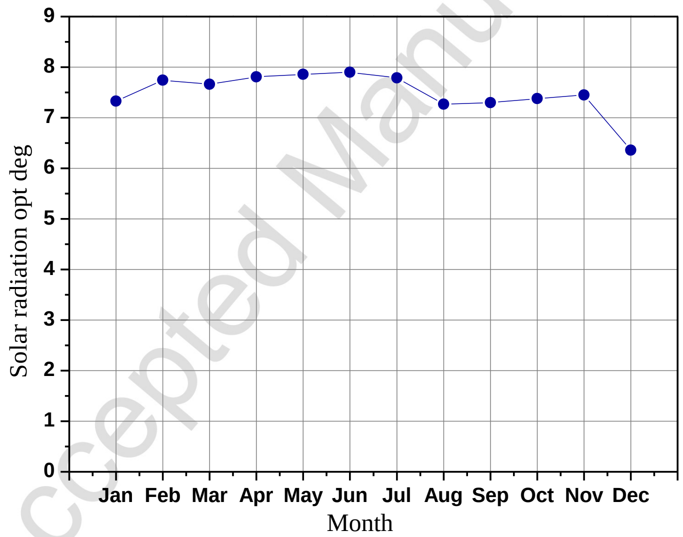

Figure 12: Solar radiation of the solar panel at the optimal degree of inclination

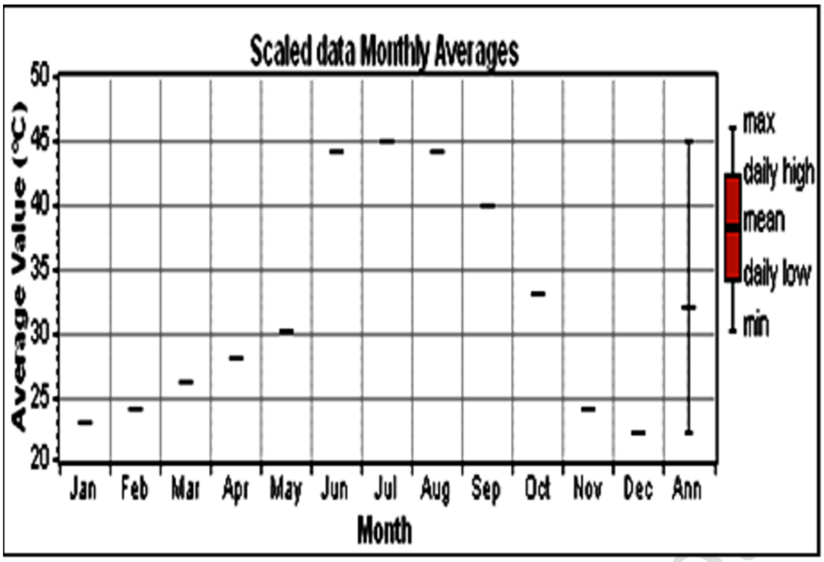

Figure 13: Average monthly temperature over a year in Timiaouine

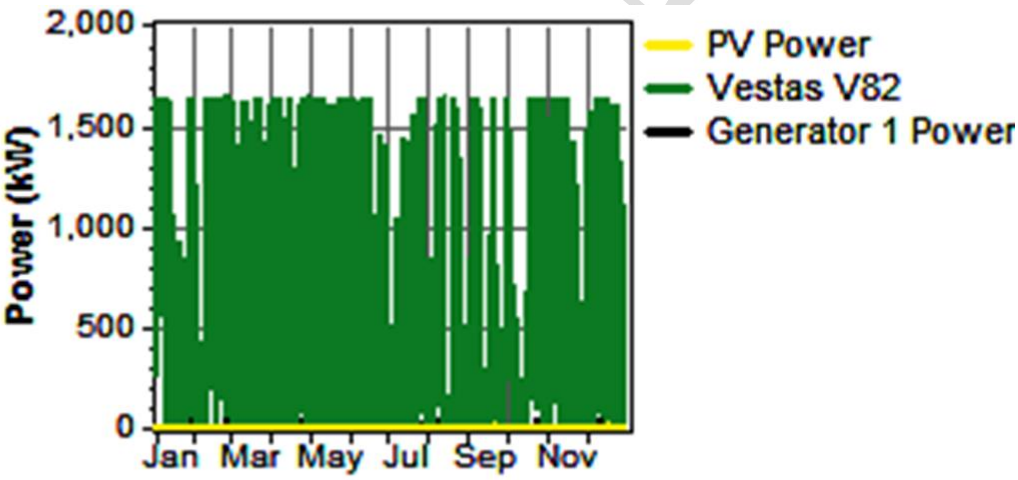

Figure 14: Electricity production by the hybrid system proposed for Timiaouine

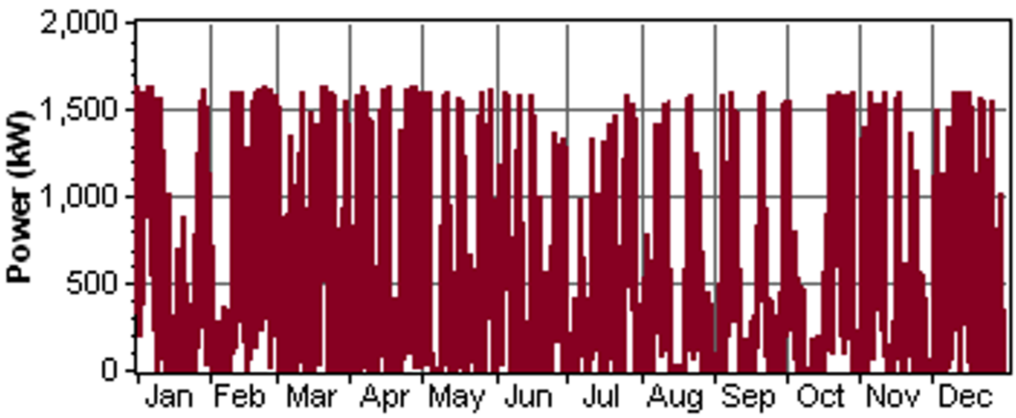

Figure 15: Excess of electricity production by the hybrid power system

Table 1: Categorized optimization results

Pv (kW)	Vestas V82 (1650 kw)	Generator (kW)	Inverter (kW)	Operating Cost (U$/year)	Total NPC (U$)	COE (kwh/U$)	Renewable Fraction
10	1	150	20	19,418	1,331,999	0.176	96
0	1	150	0	19,728	1,267,190	0.179	95
20	1	200	20	20,320	1,472,213	0.210	94

Table 2. CO_2 emissions with conventional and hybrid power systems

Type of electricity	Consumption (kWh/day)	CO_2 Emission (kg/kWh)	CO_2 Emission per year (Tons)
Fossil fuel Electricity	2,500 (100%)	0.65	593.125
Hybrid system	100 (4%)	0.65	23.725