Technical, Economic and Environmental Analysis of Hybrid Energy Solutions for Rural Electrification in the Republic of Chad

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Abstract. The use of renewable off grid systems are being more common in the African rural communities. Especially hybrid systems have an important role to play on sustainable energy access for all. Different combinations are possible to ensure intermittent energy production far from the national grids. However, it is important to find the best hybrid combinations for each climate region.

This work focuses on the technical, economic and environmental analysis of a hybrid energy system (SEH), based on **solar-wind-diesel and batteries** applied in the three existing climatic regions of Chad, for the needs of a decentralized rural electrification. The sizing and optimization approach consisted in choosing for each climate region a representative site where the solar and wind potentials data are available. Using HOMER software (Hybrid Optimization Model for Electric Renewable), technical-economic analysis of energy solutions is made for four types of load profiles in each climate region. The system is applied to provide energy separately for domestic use, income generating activities and a telecommunication station all in rural areas. The main performance parameters in which focused the work are the net present cost (NPC), the cost of electricity (COE), the Green House Gases (GHG) emissions and the renewable fraction. The results show that in the Saharan region the best combinations are **PV-wind-diesel-battery** for domestic use, and **PV-diesel-battery** for both water pumping and telecom application. For income generating activities, a **PV-battery** system is the most interesting hybrid system in the Sahelian region. Finally, a sensitivity analysis shows that by increasing the renewable energies fraction in the system, the COE will decrease.

Keywords: Hybrid system · Rural electrification · Homer energy · Optimization · Sensitivity study · Climatic regions · NPC · COE

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1 Introduction

The global energy demand ceaseless increasing is one of the major constraint on the preservation of the environment. The satisfaction of this demand is largely based on the use of fossil fuels that have a huge negative impact on the world global warming and the degradation of the ozone layer. In addition, fossil energy resources are in limited quantities, thereby, the need to consider new ways of producing energy for the satisfaction of global demand is necessary [1]. In Africa, The electricity demand in some areas is conventionally supplied by small isolated diesel generators [2]. The operating costs associated with these diesel generators may be unacceptably high due to discounted fossil fuel costs and difficulties in fuel delivery and maintenance of generators [2]. Indeed, the CO_2 emission due to the use of these fossil fuels is one of the principal cause of greenhouse effect on the environment [3].

Renewable energies start playing an important role in the production of electricity in the world. Africa, particularly has a significant renewable energy resources that can help to emphasis energy access without compromising our environment. At the same, most of the African rural population are living far from the countries' national electricity grid.

In this situation, off-grid renewable energy sources, such as solar photovoltaic (PV) and wind turbine generator provide a realistic alternative to supplement diesel generators for electricity supply in rural areas. Indeed, the problem associated to the natural fluctuation of these resources can be partially overcome by combining them to make a hybrid energy system [4]. This is one of the most important systems for developing renewable energies at the moment. That is why we need strategies that are technically, economically and socially viable. Hybrid systems have greater reliability and lower cost than a stand-alone PV or a wind system. In order to have a cost-effective hybrid system, optimal sizing is necessary [5].

Several works have been done to size hybrid systems PV/wind associated with batteries and or diesel generator using different methods [6, 7]. Ramli et al. estimated the energy demand for domestic, industrial, agricultural in a remote village, identified the optimal option for RE based electrification and compared it to conventional grid extension using HOMER software [8]. The results show that a hybrid combination of solar-wind-hydro-battery is cost effective, sustainable, techno-economically and environmentally more viable compared to grid extension.

This paper studies the optimal combination of different energy sources for different load profiles in the three climate region of the republic of Chad. It is conducted for energy supply to the following applications in rural areas: domestic use, income generating actives like shops, telecommunication relay antenna and water pumping. The main elements of the system are solar PV, Wind energy, diesel generator and Batteries. For all the three sites and all the load profiles, the combination of all the components will be the basic system, and homer energy according to the techno-economical parameters gives the best hybrid solution for the different applications in each site. The objective of this paper is to produce a decision support tool for the Government of Chad in the energy sector.

2 Materials and Methods

2.1 Description of the Hybrid System

The photovoltaic array and the wind generator supplies DC phase connected to a bidirectional inverter. The power will be then distributed either directly to the consumers or to the battery bank, depending on the state of charge and state of demand.

The PV modules and the wind turbines work together to satisfy the energy demand. During the day, the renewable energy sources production is first directed to the grid to meet the daily energy needs. If the production from the wind generator and PV array is sufficient, then the other part of the generated power is provided to the battery bank up to its full charge. The batteries can then provide electricity for nocturne energy needs and during cloudy time. In case the batteries have low charge and the PV and wind generators cannot provide enough energy to the system, the diesel generator will be launched automatically to produce the necessary energy to satisfy the demand and charge also the batteries Fig. 1. Depending on the type of load profile and the energy potential in each site, the optimal hybrid system can be with fewer elements. The components not necessary to meet perfectly the demand will be removed from the system.

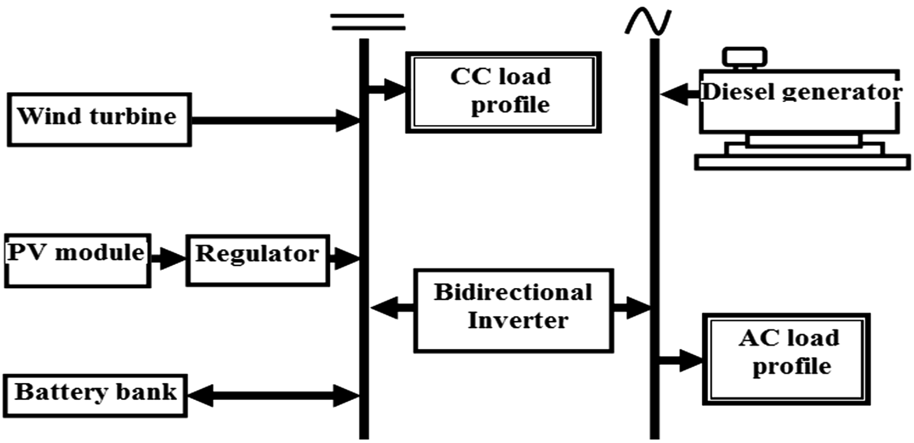

Fig. 1. Block diagram of the hybrid solar-wind-diesel system

2.2 Description of the Sites and Used Data

General Description

The territory of Chad is between 12° and 24° north latitude and 13° and 24° west longitude. Located in north-central Africa, Chad stretches for about 1,800 km from its northernmost point to its southern boundary. It is divided into three (3) major bioclimatic regions, namely the Saharan, Sahelian and Soudanian regions.

The Saharan region covers an area of 600,350 km^2 or 48% of the land area. Dry for nine months of the year, it receives 350 mm (13.8 in) or more of rain, mostly during July and August. The Sahelian region represents about 490,570 km^2. The climate in this transition region between the desert and the southern soudanian region is divided into a rainy season (from June to early September) and a dry period (from October to May). The Soudanian region, is the wettest part of the country. Between April and October, the rainy season brings between 750 and 1,250 mm of precipitation. Temperatures are high throughout the year. For this study we selected one village in each climatic region. The villages are located in the three cities described in Fig. 2.

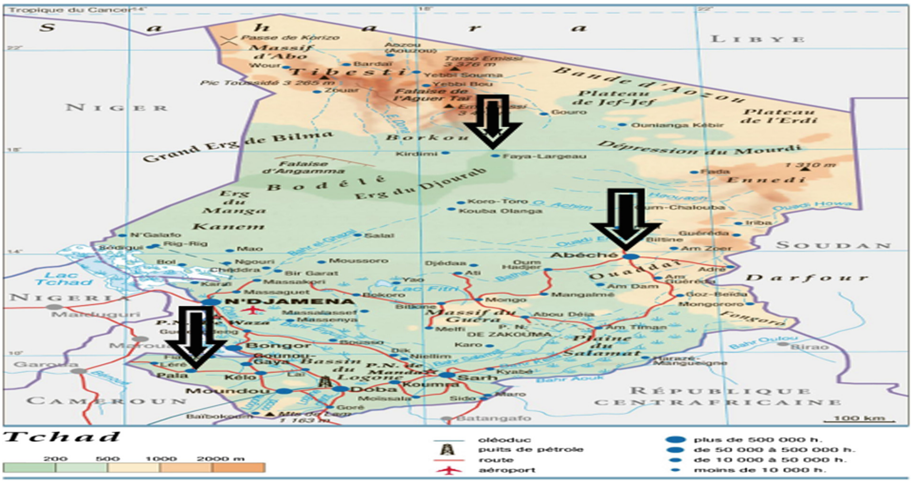

Fig. 2. Sites location

Renewable Energy Potential

Wind: Due to the lack of data from meteorological stations during a long period with a good time resolution, we used the MERRA (Modern-Era Retrospective Analysis for Research and Applications) satellite data from NASA. The wind data are sampled hourly and include wind speed, relative humidity, pressure, temperature and wind directions. It is for a period of ten years between 2005 to 2014 equal to 87648 records for each site. All the data are given for highs from 10 m and more.

Using Matlab for data treatment, the average wind speed variation for the three sites is represented in Fig. 3. It can be seen that for the three climatic regions, Saharan, Sahelian and Soudanian, the mean monthly wind speeds are between 2 and 7.3 m/s at a height of 10 m. Faya located in the north and in the Saharan climate region has more important wind speeds during all the year. The lowest wind speed is about 3.7 m/s, and it can increase up to 7 m/s during a long period of the year. For the two other sites, Abéché and Pala, the wind velocity is not very important. It sometime can attend

4.5 m/s but the yearly average wind speed is just about 3 m/s. Meaning that it is more useful to install wind turbines in Faya compared to the other sites.

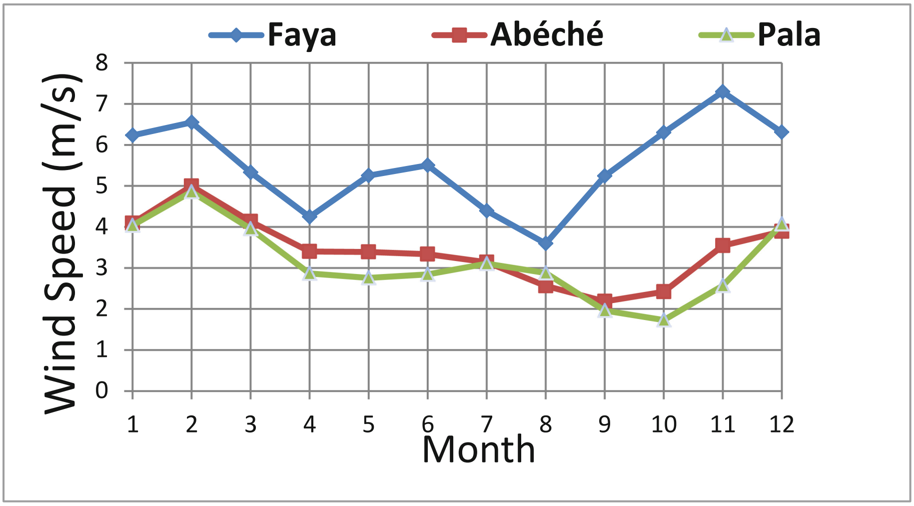

Fig. 3. Wind speed variation over the year

Solar: For solar potential assessment, the monthly average data used were downloaded from National Aeronautics and Space Administration (NASA) database [11]. The data obtained show that the chosen sites are characterized by a significant solar radiation. The average monthly radiation on a horizontal surface varies from 4.7 to 7.4 $KWh/m^2/d$. For the two sites Faya and Abéché, the lowest solar radiation months are January and December; while for Pala the lowest radiations are registered in June and August Fig. 4.

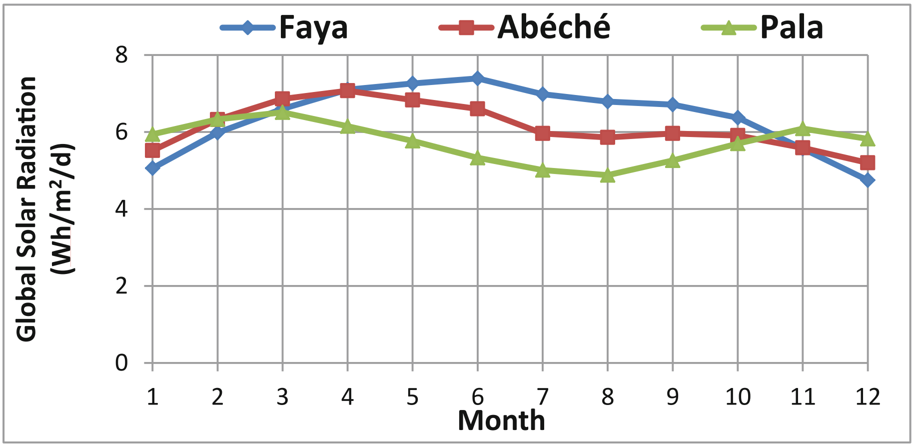

Fig. 4. Global solar radiation

2.3 Method of Analysis

HOMER Simulation Tool

Hybrid optimization Model for electric renewable (Homer) is one of the most used software for sizing and analyzing hybrid systems. HOMER simulation tool is used for the design of micro-power system and comparisons of various powers generating system. HOMER can design grid-connected and off-grid hybrid systems serving electric and thermal loads using different renewable and non-renewable sources along with power conditioning equipment [9]. Optimal system configurations suitable for the different application can be evaluated through this simulation tool. In pre-HOMER phase, physical modeling of hybrid renewable system or the various input parameters to model the system are the load profiles, selected energy components to generate electricity, different energy resources associated with the selected components and optimization constraints. HOMER simulates all possible system configurations that meet the required load demand for a given area under its available energy resources. HOMER simulates thousands of system configurations, optimizes for lifecycle cost, and generates results of sensitivity analyses on most inputs. In the optimization process, HOMER simulates many different system configurations, discards the infeasible ones, ranks the feasible ones according to net present cost and presents and the cost of electricity. Figure 5 shows the block diagram of the operating principle of the Homer software.

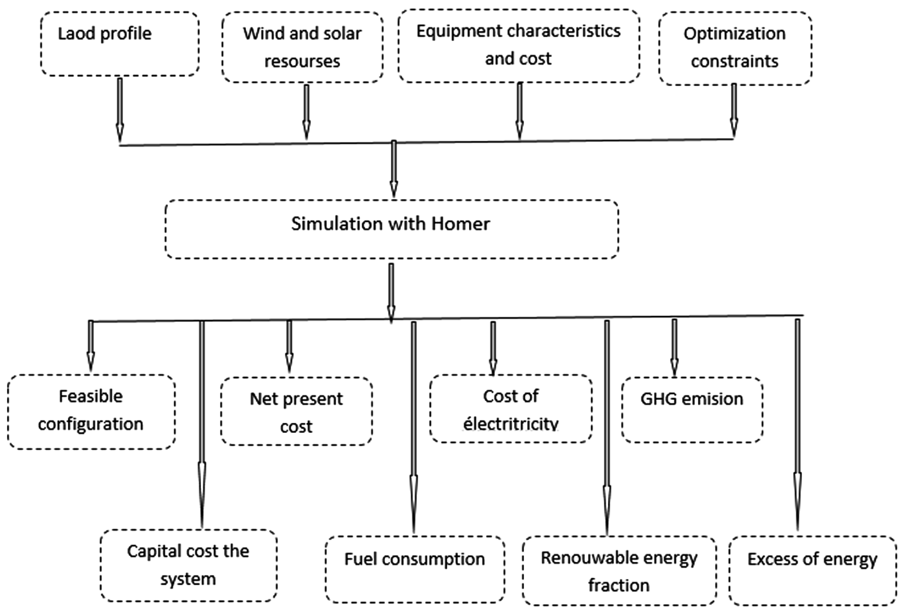

Fig. 5. Principle of operation of the Homer software

2.4 Energy Demand Analysis

For the analysis four of the most used application that needs energy in rural areas are selected. The load profiles represented in Fig. 6 describes the energy demand for domestic use, income generating actives, water pumping and telecommunication relay antenna.

For domestic load estimation, we assumed that all households in a village of 400 inhabitants use electricity. They use appliances like led light bulbs, radios, TVs, sometimes refrigerators and computers. In addition, this load profile takes into account other community infrastructure energy needs. The chosen village type has one health center, a primary school and a church. The total daily energy consumption is then 90 kWh/day for a peak of 7 kW.

The income generating activities consists of three shops, a mill and a sewing workshop. The different types of devices used are: lamps, fan, radio, refrigerator and a sewing machine. All the activities energy needs combined correspond 24.13 kWh/day.

The pump used specially for households' water needs and farming consumes about 5.62 kWh/day with a total power of 5.62 kW. And lastly the total telecom antenna has peak power demand of about 2 kW and the daily energy required is 4.6 kWh. The four energy demand profiles are represented in Fig. 6.

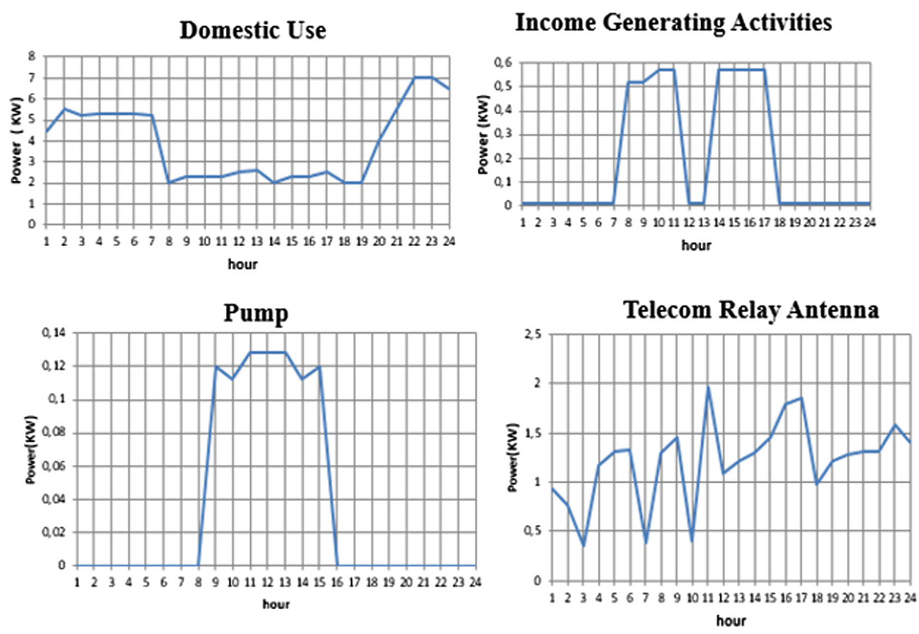

Fig. 6. Daily load profiles

3 Results and Discussions

After computing all the input data needed like load profiles, solar and wind potential, components sizes and costs, HOMER starts running the simulation. All possible systems configurations that can allow to satisfy the energy demand are then given and classified according to the cost of electricity obtained and the net present cost. The feasible solution with the lowest COE is in the top then come the other possible solutions ranked according to their COE. The results obtained for the three sites with the four load profile applications are presented in the following tables. The project life time is assumed to be 25 years.

3.1 Domestics Use

In all the climate regions, the best solution to supply the domestic energy needs is to combine all the basic component of the system. The optimal hybrid system with the lowest price of electricity between 0.264 USD in the Saharan region to 0.362 in the Soudanian region is PV-wind-diesel-batteries. The Sahalian region also has a COE of about 0.304 USD/kWh which is quite high but less compared to the COE in the Soudanian region. The CO2 emissions in the Saharan, sahalian and soudanian region for the hybrid system are respectively 1078 kg/year, 5946 kg/year and 8437 kg/year. In this case, using PV-wind-diesel-batteries hybrid system is more viable economically than using a standalone solar or wind system in all the three climate region. But it can clearly be noticed that the implementation of this hybrid system is economically more interesting in the Saharan climate region. At the same time, it has less impact on the environment. This is imperatively due to the fact that the solar and wind potential are more available in this region, thus, the diesel generator is not used so much. The results for the domestic application in the three climate region are summarized in Table 1.

Table 1. Optimal solutions for domestic use

Application	Energy Demand	System architecture	Saharian region	Sahalian region	Soudanian region
Domestic use	P = 13,56 kW E = 90 kWh/j	PV generator (KWc)	20	20	20
		Wind generator (kW)	10	10	10
		Diesel generator	4	8	6
		Battery bank (Ah)	25 920	25 920	2880
		CO2 emissions (Kg/year)	1078	5946	8437
		Renewable energy fraction (%)	98.6	90.2	81.5
		Net present cost (USD)	115,151	132,380	157,574
		Cost of electricity (USD)	0.264	0.304	0.362
		Optimal hybrid system	**PV/Wind/ DG/battery**	**PV/Wind/ DG/battery**	**PV/Wind/ DG/battery**

3.2 Income Generating Activities

The results for the income generating activities energy demand supply differ from a site to another. The optimal solution found for the Saharan region is just the use of a diesel generator. Compared to the other feasible solutions in this site it has the lowest COE, but in practical it does not fit to the objectives of this work. The aim of this study is to find feasible solutions with renewable resources that can replace diesel generator. A PV/battery and a PV/battery/DG are the two optimal systems for the Sahalian and Soudanian. It is normal that a wind generator is not needed in these two sites, the potential is very low. We can clearly notice that the COE obtained 0.830 USD/kWh for the Saharan region, 0.39 USD/kWh for the Sahalian region and 0.451 USD/kWh for the soudanian climate are quite high (Table 2).

Table 2. Optimal solutions for income generating activities

Application	Energy demand	System architecture	Saharian region	Sahalian region	Soudanian region
Income generating activities	P = 4.49 kW E = 24.1 kWh/j	PV generator (KWc)	0	2	1
		Wind generator (kW)	0	0	0
		Diesel generator	2	0	0.57
		Battery bank (Ah)	1440	1440	1440
		CO2 emissions (kg/year)	2144	0	415
		Renewable energy fraction (%)	0	100	79
		Net present cost (USD)	17,846	8,376	9,701
		Cost of electricity (USD)	0.830	0.390	0.451
		Optimal hybrid system	**Diesel**	**PV/battery**	**PV/DG/ battery**

3.3 Water Pumping

A PV/Diesel/Battery hybrid system is the most viable solution technical-economically in all the three climate regions. Two things can justify this result. In this case, energy is needed only during day time. Secondly the three regions have also an important solar radiation. Therefor the PV array can provide almost all the needed energy. The battery bank and the diesel generator have to supply the system during cloudy time and during a small part of the day. The COE are practically the same and there is also a very small difference in quantity of CO2 emitted per year. However, it should be noted that the costs and amount of CO2 emission are lower in the Saharan region. This is clearly because of its solar potential a little more important compared to the other two regions (Table 3).

Table 3. Optimal solutions for water pumping application

Application	Energy demand	System architecture	Saharian region	Sahalian region	Soudanian region
Water pumping	E = 5.62 kWh/j	PV generator (KWc)	1	1	1
		Diesel generator	0.3	0.3	0.3
		Inverter (kW)	0.5	0.5	1
		Battery bank (Ah)	1440	1440	1440
		CO2 emissions (kg/year)	452	480	525
		Renewable energy fraction (%)	81.6	79.7	76.6
		Net present cost (USD)	8,010	8,153	8,398
		Cost of electricity (USD)	0.372	0.379	0.390
		Optimal hybrid system	**PV/Diesel/ battery**	**PV/Diesel/ battery**	**PV/Diesel/ battery**

3.4 Telecom Relay Antenna

The optimal hybrid system in all the climate regions is a PV-wind-battery combination. For the telecom relay antenna, the needed power is always quite low, so even with quite low wind speeds a small wind turbine can participate to the energy generation to satisfy the demand. During the day, the wind and solar generators produce the energy needed by the antenna and charge also the batteries. When Sun sets, the wind turbine can still continue producing energy depending on the resources, but the most of the needed energy will come from batteries. Despite the fact that the optimal hybrid system is the same, the COE is lower in the Saharan region. As presented in Table 4 the COE are 0.293 USD/kWh, 0.303 USD/kWh and 0.321 USD/kWh respective for the Saharan, sahalian and soudanian region. This is because of the variation of the wind potential which is more important in the North. The impact of the system in the environment is negligible everywhere.

Table 4. Optimal solutions for the Telecom application

Application	Energy demand	System architecture	Saharian region	Sahalian region	Soudanian region
Antenna Telecom	P = 0.57 kW E = 4.6 kWh/j	PV generator (KWc)	10	10	10
		Diesel generator	1	1	2
		Battery bank (Ah)	8640	8640	8640
		CO2 emissions (kg/year)	241	494	241
		Renewable energy fraction (%)	98.9	97.5	98.9
		Net present cost (USD)	39,462	40,848	43,289
		Cost of electricity (USD)	0.293	0.303	0.321
		Optimal hybrid system	**PV/Wind/ battery**	**PV/Wind/ battery**	**PV/Wind/ battery**

4 Conclusion

The primary objective of this study was to find the optimal hybrid solution adapted to satisfy different energy demand profiles in the rural areas of the three climatic regions in the Republic Chad. The optimal systems also must have trifling impact on the environment. For the country's three climate regions, mainly the same hybrid system is found as optimal to meet perfectly the energy needs of different application. To bring energy for the rural households and some public infrastructure, it is more interesting to install a PV/Wind/Diesel/battery hybrid system in all the three climate regions. However, this hybrid combination is more useful in the Saharan region. The COE is low and the CO_2 emission is negligible.

A PV/Diesel/battery and a PV/Wind/battery hybrid system fits respectively more to a pump and Telecom Relay antenna in all the three selected regions. Unlike the other applications, meeting the energy demand for the identified income-generating activities requires different systems depending on the region. In the Saharan region, it has been found that economically it is more useful to use a Diesel generator for this type of load profile, but this will have important negative consequences in the environment. Using PV associated with batteries is the perfect solution in the two other sites, however a diesel generator need to be added in the Soudanian region.

The results of this study can be used as a decision making tool for deployment of stand-alone hybrid systems to supply cost effective electricity in rural areas in the Republic of Chad while protecting the environment. It might be conducted in other areas to support efficient use of hybrid off systems in remote areas.

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