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A Techno-Economic Study of a Hybrid PV-Wind-Diesel Stand-Alone Power System for a Rural Telecommunication Station in Northeast Algeria †

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Abstract: Telecommunication stations, particularly operating in rural areas are usually powered by diesel generators due to the lack of access to the utility grid. However, the growing cost of energy due to the constantly increasing fuel prices and the related greenhouse gas emissions contributing to the global warming have driven the telecom companies to seek for better energy management solutions. In this paper, we study the economic feasibility of an environmentally friendly power supply system for rural telecommunication station in the city of Skikda, northeast Algeria. The proposed system is a standalone hybrid PV-Wind system with pre-existing diesel generators and battery storage. Different system configurations are considered in the study: (a) Diesel generators only, (b) PV-Diesel-battery, (c) Wind-Diesel-Battery, (d) PV-Wind-Diesel-Battery, and lastly (d) PV-Wind-Battery, this helps to select the most optimal solution based on the lowest net present cost (NPC) and the cost of energy (COE) of each configuration. The optimization is performed using HOMER PRO software. The results showed that a hybrid system of 5 kW DG, 3.81 kW of PV capacity, 3 wind turbines and 14 battery bank is the best design for the proposed power system with an NPC of 85,673 $ and a COE of 0.214 $. The greenhouse gas emissions were considerably reduced to more than half making the proposed system a technically, economically and environmentally viable solution.

Keywords: telecommunication; hybrid system; PV; Wind; renewable energy; optimal sizing; Homer

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1. Introduction

The industrial development and rapid population growth have resulted in an increasing energy consumption in all sectors including telecommunications [1]. Most telecom stations operate in rural and remote areas using diesel generators (DGs) due to the unavailability of the utility grid or the high-cost investment of grid extensions. Although the initial cost of using generators is low, there are other issues related to their operation. On one side, DGs require high maintenance and fuel-consumption which results in high operating costs due to increasing prices of fossil fuels. On the other hand, they have a huge environmental impact because of the significant greenhouse gas emissions related to their operation which contribute to global warming [2,3]. Hence, searching for alternative power solutions that are reliable, cost-effective, and environmentally friendly is mandatory.

Renewable energy resources such as solar and wind are widely used as alternative energy solutions and are considered as a primary source for decarbonizing the energy sector. However, due to their intermittent nature, an energy storage system (ESS) is required to store the excess of electricity produced to enhance the system's reliability in meeting the load demand when there is no renewable power production [4]. For this end, batteries are commonly used as an ESS to store surplus energy during overflow periods.

Many studies in the literature have reported the problem of powering telecommunication stations and towers by implementing renewable energy as a main power source. R. Kaur, et al. [5] assessed the techno-economic feasibility of a PV-Wind based DC microgrid for a 3.5 kW telecom tower using NSGA II algorithm to find the optimal size. The main objectives of the study were minimizing the cost of energy (COE), the loss of power supply probability (LPSP) and the excess of energy (EE). The results showed that 100% reliable system (LPSP = 0) has a 35% lower COE than the conventional DG system and further increasing the LPSP value results in a COE lower than that of the grid power supply. In [6], the authors investigated the technical, economic and environmental performance of multiple hybrid power systems to power a remote telecom station using HOMER Software in order to find the best configuration which was the hybrid configuration of PV/Wind/DG/FC and which corresponded to the lowest net present cost (NPC) and COE. Kusakana and Vermaak [7] investigated the feasibility and the environmental impact of four different combinations of PV/wind/DG hybrid system as a primary source of energy to supply telecom base transceiver stations in three different rural regions of the Republic of Congo. In [8], the authors proposed hybrid PV/FC power system for a telecom base station in India. The results showed that the proposed system has a very low cost compared to the conventional power-based system. In a similar study [9], the author proposed the FC technology for the power supply of the Italian telecom stations as a sustainable and cost-effective solution. In [10], authors simulated three different renewable based system configurations to find the optimal power system design for powering a base transceiver station (BTS) in Sudan. The winning case was PV/DG/Battery with PV contributing to 97% of the power generation. In [11] proposed a PV/Wind/DG/Battery system for powering a remote telecom tower in Nigeria. The study revealed that PV/DG/Battery system has the lowest NPC and COE with a renewable fraction of 78% making it an economically viable and sustainable solution.

This study aims to reduce the operating costs and environmental impact of a diesel-based operating telecom station by replacing pre-existing diesel generators with a hybrid renewable energy system and batteries as an energy storage system. HOMER Pro (hybrid optimization model for multiple energy Resources) software is used to perform the techno-economic study of multiple configurations with different renewable fractions from 0 to 100%: (a) Diesel generators only, (b) PV-Diesel-battery, (c) Wind-Diesel-Battery, (d) Hybrid PV-Wind-Diesel-Battery, and lastly (d) PV-Wind-Battery to finally determine the optimal configuration that meets the technical, economic and environmental needs.

2. Methodology and System Modeling

HOMER Pro software is used to assess the techno-economic feasibility of the proposed hybrid system. The software has a three-stage process: Simulation in which different configurations are considered, optimization in which all the technically feasible solutions are sorted based on the lowest net present cost (NPC) and cost of energy (COE) and finally, the sensitivity analysis where different values for the same input parameter can be entered to see how the results can be affected. Homer is able to perform the simulation of one-year data and allows the evaluation of a large number of different design combinations using inputs such as technology options, power sources, unit costs, and so on and sort the results of the feasible configurations based on the lowest NPC. HOMER also displays simulation results in a wide variety of tables and graphs which helps to compare configurations and evaluate their economic and technical merits [12]. HOMER has been extensively used in literature for hybrid renewable energy system (HRES) optimization and various case studies due to its simple and quick analysis of the vast variety of different HRES. The main limitation of the software that it allows only one objective function for minimizing the NPC as such the multi-objective problems cannot be formulated [13].

The total NPC (or life-cycle cost) is HOMER's main objective function. It's the value by which HOMER ranks all system configurations of the optimization results, and the basis from which it calculates the total annualized cost and the levelized cost of energy (LCOE). The NPC of a system is the present value of all costs incurring throughout its lifetime, minus the present value of all revenues earned throughout the lifetime [14]. It can be expressed as:

$$C_{NPC,tot} = \frac{C_{ann,tot}}{CRF} \tag{1}$$

where $C_{ann,tot}$ is the total annualized cost ($/year) and CRF is the capital recovery factor expressed as:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{2}$$

N is the number of years and i is the annual real discount rate (%).

Another convenient economic metric by which systems can be compared in Homer is the levelized cost of energy (COE). However, Homer doesn't rank systems based on their COE which is another drawback of the software. It can be calculated as follows [14]:

$$\mathrm{COE} = \frac{C_{ann,tot}}{E_{served}} \tag{3}$$

where $C_{ann,tot}$ is the total annualized cost ($/year) and E_{served} is the total electrical load served (kWh/year).

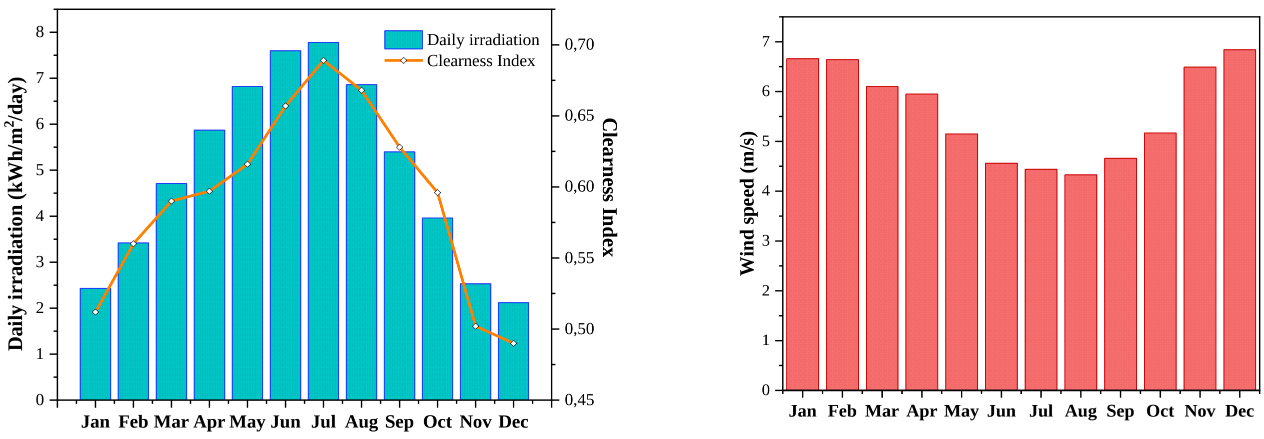
The upcoming section describes the location of the telecommunication station and the energetic potential of the site as well as the model of the proposed system.

2.1. Renewable Energy Potential and Telecom Load

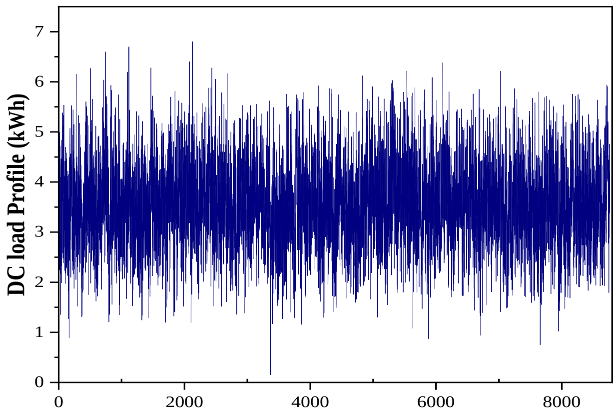
The telecommunication station is situated in a rural area in the city of Skikda, in the Algerian northeast. The coordinates of the location are 37°0.8′ N, 6°33.8′ E based on which the weather data of the site were obtained from NASA meteorology database [15].

2.1.1. Solar and Wind Energy

The monthly average irradiation and wind speed at the studied site are depicted in Figure 1a and Figure 1b, respectively. The location receives a yearly total radiation of approximately 1.74 MWh/m^2 with an annual average estimated at 4.75 kWh/m^2/day and a peak of 7.176 kWh/m^2/day in the month of July, while the annual wind speed is estimated at 5.58 m/s with the highest speed marked in December, estimated at 6.84 m/s.



(**a**) (**b**)



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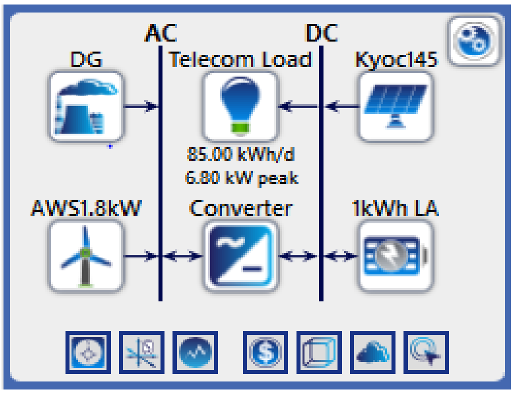

(**d**)

Figure 1. (**a**) Monthly average solar irradiation; (**b**) Monthly average wind speed; (**c**) Telecom load hourly profile; (**d**) Schematic of the proposed system in Homer Pro.

2.1.2. Electric Load Profile

The hourly electric consumption of the studied telecommunication station is shown in Figure 1c. It's a DC primary load with an average consumption of 85 kWh/day.

2.2. System Modeling

2.2.1. *PV* Array

Solar photovoltaic is a key technology in energy transition. The *PV* array power output can be calculated using the following equation [14]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right)\left(1 + \alpha_p\left(T_c - T_{c,STC}\right)\right) \quad (4)$$

where the Y_{PV} is the rated power of the *PV* array (kW), f_{PV} is the derating factor (%), G_T and $G_{T,STC}$ are respectively, the solar radiation incident on the *PV* array and the standard incident radiation (W/m²). α_p is the power temperature coefficient (%/C°). T_c and $T_{c,STC}$ are the *PV* cell and the standard temperatures in (°C), respectively.

The *PV* panel chosen in this study is flat plate Kyocera 145 SX-UFU series with a rated power of 145 W, a derating factor of 88% and temperature coefficient of −0.46. The lifetime of the panel is estimated to be 25 years for 80% output.

2.2.2. Wind Turbine

The wind turbine power output is calculated using a three-step process. Firstly, the wind speed at the hub height of the *WT* is calculated using the following power law [14]:

$$U_{hub} = U_{anem}\left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \quad (5)$$

where, U_{hub} is the wind speed at the hub height (m/s), U_{anem} is the speed at the anemometer height (m/s). Z_{hub} and Z_{anem} are the hub and the anemometer heights (m), respectively. α is the power law exponent.

After determining U_{hub}, we refer to the *WT*'s characteristic power curve to calculate the expected power output at that wind speed under standard conditions of temperature and pressure. Finally, to adjust to actual conditions, the predicted power output is corrected through multiplying it by the air density ratio as shown in the following equation:

$$P_{WT} = \left(\frac{\rho}{\rho_0}\right) P_{WT,STP} \quad (6)$$

where ρ is the actual air density in (kg/m³), ρ_0 is the air density under standard conditions (kg/m³). P_{WT} and $P_{WT,STP}$ are the wind turbine output power at actual conditions and at standard temperature and pressure (kW), respectively. For this study, AWS HC wind turbine with a rated power of 1.8 kW.

2.2.3. Diesel Generator

The diesel generator is typically used as back-up power generation in off-grid power systems. The fuel consumption of the diesel generator is calculated assuming the following linear relationship [14]:

$$FC_{DIESEL} = \alpha P_{DG} + \beta P_{DG,r} \quad (7)$$

where α is the generator fuel curve slope (L/kWh), β generator fuel curve intercept coefficient (L/kWh), P_{DG} is the power output of the diesel generator (kWh), and $P_{DG,r}$ is the rated power of the diesel generator (kWh). The diesel generator used in the study has a 15,000-h operating lifetime.

2.2.4. Battery

Due to the intermittent nature of solar and wind energy, battery storage to ensure the reliability and stability of the energy is a must. It is used to store the excess of electricity produced from *PV* and wind to be later used in shortfalls and peak loads. A generic 1 kWh Lead-acid battery bank with 12 V nominal voltage and 10 years lifetime was used in this study.

2.2.5. Converter

The wind and diesel generator outputs are AC while the load is DC. Hence, a rectifier is required for the power transfer. A power converter with 95% efficiency and 15 years lifetime was used in the system.

The proposed system model is shown in Figure 1d while the economic input parameters of each component are found in Table 1. The diesel generator search space was set to 0 kW, 5 kW and 10 kW with a fuel cost of 0.3 $/L while Homer optimizer was used to determine the exact optimal size of the other components.

Table 1. Economic parameters for the proposed system components.

Component	Capital Cost	Replacement Cost	O&M Cost	Lifetime
Diesel generator	500 $/kW	500 $/kW	0.03 $/op. hour	15,000 h
Kyocera KD 145	2500 $/kW	2500 $/kW	10 $/kW	25 years
AWS HC 1.8 kW	5500 $	4800 $	50 $/year	20 years
1 kWh Lead Acid	300 $	300 $	10 $/year	10 years
Converter	300 $/kW	300 $/kW	0 $/year	15 years

3. Results and discussion

The main aim of this study is to reduce the dependence on DGs and replacing it with renewable energy for a cost effective and a sustainable power supply. Homer software was able to simulate different configurations with different renewable fractions in order to find the optimal configuration. Table 2 represents the main technical, economic, and environmental findings for each configuration. The base case where only generators are used has the lowest initial capital but a high NPC because of the high operating costs making it an unfavorable solution, especially with the high amounts of CO_2 emitted. The other hybrid systems were economically acceptable except for the 100% RES which has the highest NPC due to expensive installation cost. The winning configuration is PV-Wind-DG-Battery with an NPC of 85,673 $ and a COE of 0.214 $ with a total electric production of 34,879 kWh/year in which *PV* contributes to 17.7% of the total production, 38.6% by WTs and 43.7% by DGs. The fuel consumption was decreased to more than half that of the base case. The optimal size of the different simulated configurations is represented in Table 3. It can be seen that the diesel capacity in DG combined configurations was reduced to half compared to the base case. The optimal size of the winning configuration is 3.81 kW of *PV* capacity, 3 wind turbines, 14 battery banks, and a 6.10 kW converter. Figure 2, shows how the pollutant emissions were considerably reduced in the optimal hybrid renewable energy system compared to the conventional one making it an environmentally friendly option. CO_2 emissions were reduced from 31,081 kg/year to 13,328 kg/year which is the lowest amount among the other DG combined renewable systems.

Table 2. Techno-enviro-economic comparative analysis for different configurations.

Configuration	NPC ($)	COE ($)	Initial capital ($)	Elec. Produced (kWh/year)	Unmet load (kWh/year)	Fuel (L/year)	CO_2 (kg/year)	RF (%)
DGs	123,240	0.307	6830	32,901	3.95	11,873	31,081	0
PV/DG/Batt	87,359	0.218	24,585	32,921	0	7322	19,167	27.1
WT/DG/Batt	85,923	0.214	23,663	33,803	8.76	6731	17,621	34.4
PV/WT/DG/Batt	85,673	0.214	34,169	34,879	0	5091	13,328	50.8
PV/WT/Batt	169,349	0.423	115,111	57,353	20.3	0	0	100

Table 3. Optimal sizing for the base case, optimal case and the rest of configurations.

Component	DG	Kyocera KD 145	AWS HC 1.8 kW	1 kWh Lead Acid	Converter
Base case: DGs	10 kW	-	-	-	4.85 kW
Optimal case: PV/WT/DG/Batt	5 kW	3.81 kW	3	14	6.10 kW
PV/DG/Batt	5 kW	6.35 kW	-	16	4.71 kW
WT/DG/Batt	5 kW	-	3	10	5.54 kW
PV/WT/Batt	-	16 kW	7	116	5.93 kW

The control strategy used in this study is the load-following strategy, this dispatch strategy is suitable for systems with high renewable penetration. The hourly energy management for a representative day is clearly shown in Figure 3. The DC load is primarily supplied by the electricity produced from *PV* and Wind turbines. The surplus is stored in batteries once there is an excess of power production. Whenever the renewable electricity produced is not enough to meet the load demand, the battery discharges to back up for the deficiency. If the battery reaches its minimum state of charge, then the diesel generator operates to generate enough power output to meet the load.

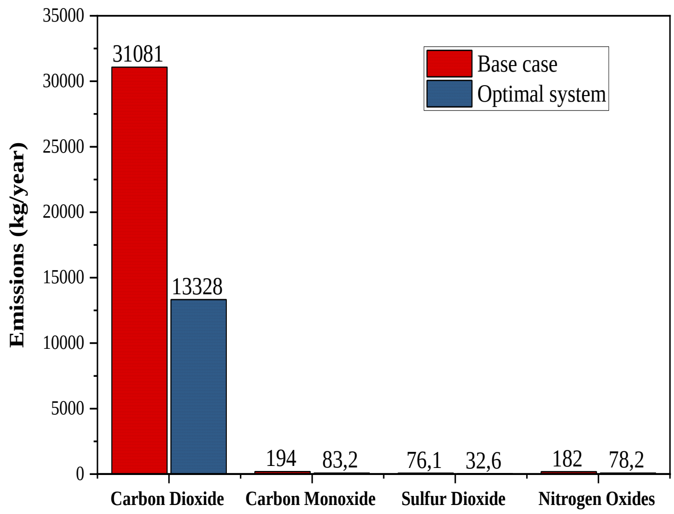

Figure 2. Pollutant emissions for the base and the optimal system.

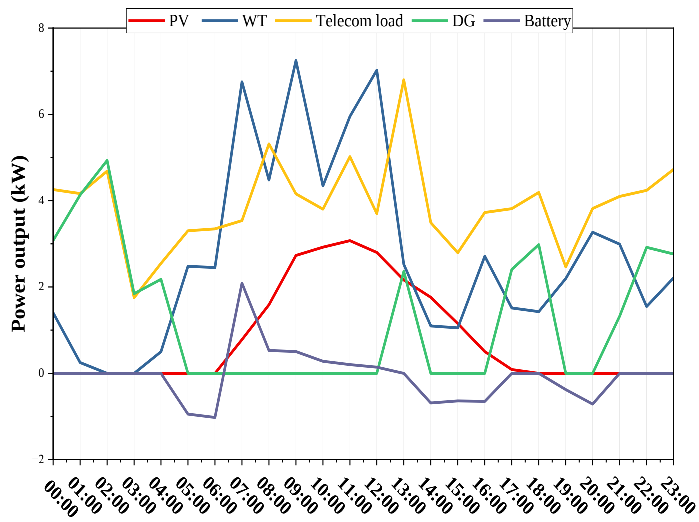

Figure 3. Hourly energy management of the optimal system.

4. Conclusions

Telecommunication stations operating in rural areas present several technical, economic and environmental issues that need to be addressed. This study investigated the feasibility of a hybrid PV-Wind-Diesel standalone system with battery storage to replace a DG-based power system for a rural telecommunication station located in the Algerian northeast. Homer software was used to perform the techno-economic and environmental analysis of the system. Different configurations were considered in the simulation in order to determine the optimal one which was the PV-Wind-Diesel-battery hybrid system. Economically, the system had the lowest net present cost 85,673 $, and a LCOE of 0.214 $/kWh while the DG-based power system had an NPC of 123,240 $ and a LCOE of 0.307%. Technically, the system to produce 34,879 kWh/year and was able to meet the annual load demand with 0 unmet-load. Environmentally, greenhouse gas emissions were considerably reduced to more than half since the dependence on DGs was reduced from 10 kW to 5 kW consuming 5091 L/year instead of 11,873 L/year. Overall, the proposed system was viable in every aspect making the transition towards a RE-based system an attractive option to make economics and decarbonize the telecommunication sector while maintaining a high operating reliability.

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