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Modeling, Optimization, and Techno-Economic Assessment of a Hybrid System Composed of Photovoltaic-Wind-Fuel Cell and Battery Bank

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ABSTRACT

Decentralized electricity production from renewable energy sources offers greater security of supply to consumers while respecting the environment. However, the random nature of these sources requires us to establish rules for the sizing and use of these systems in order to make the best use of them. Hybrid renewable energy sources can effectively meet the electric energy needs of the University of Skikda's various structures. This study examines the financial viability of a hybrid renewable-based system that is off the grid and proposed to supply several campuses of the University of Skikda in Algeria with the electricity they need. In order to achieve this, HOMER software is used to optimize and simulate the system under consideration. The results obtained recommend using a system made up of a wind turbine, solar panels, a battery bank, and a fuel cell that can produce electricity at a levelized cost of 0.193 €/kWh.

1. INTRODUCTION

Algeria's electricity market is based on conventional energy sources such as petrol and natural gas. These resources are exhausted. Moreover, the use of such resources has a negative impact on the environment. Hence, using renewable energy sources (RESs) as viable alternatives to fossil energy [1] and finding benign solutions to environmental issues when producing electrical energy remain necessary [2]. The intermittency of RESs is an inherent issue that can decline the efficiency of single-source RESs. However, the concept of hybrid renewable energy sources (HRESs) can solve this problem to a great extent. Furthermore, HRESs are frequently used in conjunction with backup systems and technologies for storing energy, including batteries, fuel cells, and diesel generators [3]. However, among these backup systems, FC can provide a sustainable and environmentally friendly solution when the required hydrogen is obtained through renewable means [2]. Using HRESs to provide the required electrical energy at an effective cost is a great challenge. Otherwise, optimization and techno-economic feasibility studies have to be performed.

The hybrid Optimization Model for Electric Renewables (HOMER) tool, developed by the National Renewable Energy Laboratory (NREL), has been extensively employed to conduct simulation, optimization, and sensitivity analysis studies [4]. Eroglu et al. [5] investigated, for a mobile house, the effectiveness of an HRES composed of a PV generator, a wind turbine, fuel cells, an electrolyzer, and batteries. The system converted enough electricity to meet the load demand. However, the authors did not address the economic feasibility of the system. Gangwar et al. [6] studied the economics and reliability of a grid-independent PV-wind-PEMFC-battery HRES to feed a technical institute lecture hall using the software HOMER. The PV-wind-battery hybrid system was considered to be the most cost-effective system under the studied load. However, in the case of an unsatisfied low load, the hybrid system composed of PV-wind-FC-battery is more reliable. Kalinci et al. [7] examined the technological and economic aspects of a standalone HES with H_2 storage on Turkey's Bozcaada Island utilizing the HOMER tool. The findings demonstrated that the best HRES contained a PV module, a wind turbine, a converter, FC, an electrolyzer, and an H_2 tank to carry the main load. Furthermore, while technically feasible, the HRES with FC is prohibitively costly in Turkey. Sebbagh and Zaatri [8] and Karthick et al. [9] used HOMER to perform a techno-economic study of a mix of PV-wind-battery and an internal combustion engine as a backup, considering the electrical utility of health care buildings as loads in Algeria and India, respectively. To determine the suitable mix of a group of sources composed of solar, wind, biogas, biomass, fuel cells, and batteries, Vendoti et al. [10] used HOMER software to assess a techno-economic analysis of four configurations to find the optimal HRES able to meet the load required by a village in India. In another study, Babatunde et al. [11] analyzed the adoption of an HRES for the building of an institution in Nigeria. The HRES was designed using HOMER and a single criterion (total present cost (TPC)).

The current paper deals with the techno-economic assessment of an HRES composed of a PV generator, a wind turbine generator, a fuel cell, an electrolyzer, and batteries. The hybrid system is intended to feed the new extension of the University of Skikda, Algeria. The logiciel HOMER is used for optimal system sizing and economic evaluation.

This study presents a new contribution in order to identify the best combination to ensure energy supply continuity at the lowest possible cost. There is no other published publication –

to the knowledge of the authors- that used the hybrid system PV-wind-FC-Storage for this location.

The rest of the paper is organized as follows: Section 2 discusses about the system design of the hybrid system configuration and the study area. Additionally, it displays the available energy resources and load profiles for the location under consideration. The modeling of system components is presented in Section 3. Section 4 demonstrates the formulation of the optimal combination to ensure energy supply continuity at the lowest possible cost. Section 5 discusses the selection of the proposed optimal hybrid system for serving the load and the paper is concluded in Section 6.

2. METHODOLOGY

The primary goal of this work is to feed a university campus with electric energy converted from renewable sources. The HOMER Pro software is used to simulate, optimize, and analyze the system's economics. The proposed system comprises a PV system, wind turbine generator, fuel cell, electrolyzer, hydrogen tank, battery bank, and a converter. It consists of one AC and one DC load bus. The power converted from the wind generator is connected to the AC bus; whereas the power converted from the solar system and fuel cell is connected to the DC bus. When the battery's surplus power exceeds the load used by the electrolyzer, it energizes it and produces hydrogen (H_2), which is stored in hydrogen tanks. During energy shortages from other sources, the stored power is utilized to power the fuel cell generator, which supplies the necessary loads. Figure 1 depicts a schematic of the proposed system.

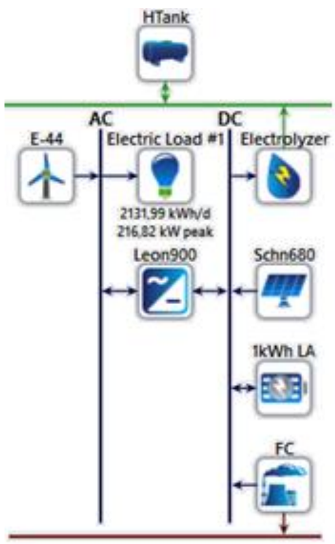

Figure 1. Schematic representation of the considered system

2.1 The study area

Skikda is located to the east of Algeria's coastline (36° 53' N, 06° 54' E). It has a population of 804.697 people and covers a land area of 4.137.68 km^2 with 130 km^2 of coastline. The Mediterranean Sea limits it to the north, and it borders the states of Annaba, Constantine, Guelma, and Jijel.

Strengthening the university card in Algeria, the university of August 20th, 1955-skikda is an institution of higher education. It consumes a significant amount of electricity, particularly during the day.

2.2 Estimation of the required energy

The load profile is the load input that specifies the electric demand served by the system in that specific place. The considered loads are shown in Figure 2.

According to Figure 2, electric consumption on the campus varies over the day. We note that the energy consumption is about 2132 MWh/d with a 216.82 kW peak.

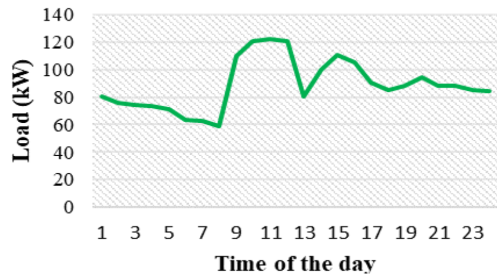

Figure 2. Daily average consumption in 2019

2.3 Estimation of the energy sources

RESs such as solar and wind are potentially available in this study area. The availability of average irradiance, average wind speed, and mean values of ambient temperature specifics for the research site were acquired from the NASA Prediction of Worldwide Energy Resource website [12], utilizing the study area's latitude and longitude (36.8467179° and 6.8877492°). These data play an important role and are required before simulating the system.

Through the specified latitude and longitude, the required meteorological data were downloaded using the HOMER simulation tools and then used to calculate the ideal system size.

The wind speed, irradiance, and temperature monthly mean values are shown in Figure 3.

Figure 3 shows that solar irradiance is crucial from March to September and has its maximum value in July at 7.08 kWh/m^2/day. The maximum wind speed was reached in March at 5.48 m/s. The mean values of the ambient temperature vary between 7.82°C in January and 28.4°C in July.

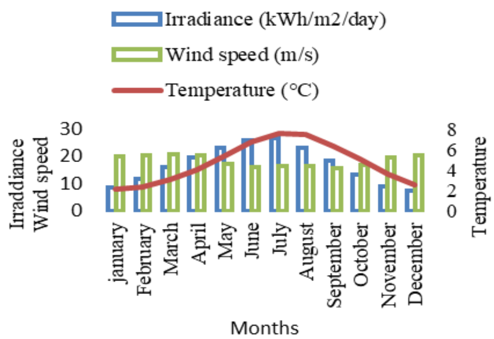

Figure 3. Monthly average variation of irradiance, wind speed, and ambient temperature for El-Hadaiek city [12]

3. MODELING OF SYSTEM COMPONENTS

3.1 PV system

The photovoltaic effect used in solar cells allows the direct conversion of the bright energy of the solar rays into electricity by means of production and transport in a semiconducting material of positive and negative electrical charges under the influence of light. Several electrical models were offered to represent the photovoltaic cell; one of them is given by [13-14]:

$$I = N_p I_{PH} - N_P I_S \left[\exp\left(\frac{q}{kT_C A} * \left(\frac{V}{N_S} + \frac{I_{RS}}{N_P} \right) \right) - 1 \right] - \frac{1}{R_{SH}} * \left(\frac{N_P V}{N_S} + IR_S \right) \quad (1)$$

where, I_{PH}: Photo current; N_P: Number of parallel cells; I_S: Cell saturation current; q: Electron charge. q=1.6×10-19C; k: Boltzmann's constant. k=1.38×10^{-23} J/K; T_C: Cell operating temperature; A: Ideal factor which is dependent on the PV characteristic; R_{SH}: Parallel resistance; R_S: Series resistance; I_{RS}: Reverse saturation current of the cell; N_P: Number of parallel-connected cells; N_S: Number of cells connected in series.

The following formula can be used to calculate the energy produced by solar panels [1, 15]:

$$E_{ph} = P_r \times F_0 \times \frac{G_{eff}}{G_0} \times P_C \quad (2)$$

where, P_r: Performance index; F_0: Loss factor; G_{eff}: Annual incident effective irradiance; G_0: Irradiance under STC (standard test conditions); P_C: Peak power.

The effectiveness of the PV system is greatly influenced by weather factors like temperature and solar radiation. PV output can be determined by using (3) [16]:

$$Ppv = \eta_{pv}.A_{pv}.G_t \quad (3)$$

where, A_{pv} is the PV generator's area in square meters, G_t is the amount of solar radiation in square meters, and pv is the PV efficiency, which is defined as:

$$\eta_{pv} = \eta_r.\eta_{pc}.(1 - \beta(Tc - Tref)) \quad (4)$$

where, η_r is the reference module efficiency, η_{pc} is the power conditioning efficiency, which is equal to 1 if a perfect maximum power tracker (*MPPT*) is utilized, and β is the reference module efficiency. For silicon cells, has a range of 0.004 to 0.006 per (°C) for the temperature coefficient of power (T_c) [16], where T_c is the cell temperature and T_{ref} is the reference cell temperature.

$$Tc = Ta + ((NOCT - 20)/800).Gt \quad (5)$$

where, T_a represents the outside temperature in degrees Celsius and *NOCT* the nominal cell operating temperature.

3.2 Wind turbine system

Wind turbines convert kinetic wind energy to mechanical energy, which is subsequently converted to electrical energy by an electrical generator. A wind turbine's energy output may be calculated using the following formula:

$$E_{wind} = \frac{1}{2} C_P \times \rho \times S_T \times V^3 \quad (6)$$

where, E_{wind}: the Energy converted by the wind turbine, C_P: Efficiency of the wind turbine; ρ: Density of the air (=1.225 kg/m^3); S_T: Rotor surface area=$\pi.R^2$/R is the length of a blade); V: Speed of the wind (m/s).

3.3 Fuel cell system

A fuel cell is an assemblage of basic cells, consisting of two electrodes (anode and cathode) loaded in a catalyst, separated by an electrolyte, which facilitates ion migration from one electrode to another due to the impact of the produced electrical field [17].

The global potential of fuel cell PEMFC is estimated by the following formula [18, 19]:

$$V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \quad (7)$$

where, E: Nernst voltage; V_{act}: Loss of activation polarization (V); V_{ohm}: Ohmic polarization loss (V); V_{conc}: Loss of concentration polarization (V).

The FC's power is expressed as:

$$P_{FC} = V_{FC} \times I_{FC} \times N_{FC} \quad (8)$$

where, V_{FC}: Output voltage of FC (V); I_{FC}: Output current of FC (A); N_{FC}: Number of cells in the FC stack.

Equation (8) [20] computes the overall efficiency of the fuel cell as follow:

$$\eta_{fc} = \eta_e.\eta_t.\eta_{reac} \quad (9)$$

where, η_e, η_t and η_{reac} are electric, thermal and the reaction efficiencies of fuel cell, respectively.

3.4 Electrolyzer/hydrogen tank

PEM Electrolyzers are used to produce hydrogen to supply fuel cells and maximum charges. The DC flows from the anode electrode to the cathode electrode within the medium (H_2O), resulting in the decomposition of oxygen and hydrogen. According to some research, the hydrogen tank is supplied by electrolyzers with direct coupling, as shown by the equation below [21]:

$$P_{elec-reservoir} = P_{ren-elec}.\eta_{elec} \quad (10)$$

where, $P_{elec-reservoir}$: is the power transmitted from the electrolyzer; $P_{ren-elec}$: is the renewable system's energy delivered to the electrolyzer; η_{elec}: is the electrolyzer's efficiency.

Furthermore, the energy derived from the hydrogen tank is stated as:

$$E_{H_2,tank}(t) = E_{H_2,tank}(t-1) + \left[E_{H_2,tank}(t) - \frac{E_{FC,tank}(t)}{\eta_{storage}}\right].\Delta t \quad (11)$$

where, $E_{FC,tank}(t)$ and $\eta_{storage}$: are fuel cell production and hydrogen tank efficiency.

The hydrogen mass is estimated by:

$$m_{tank}(t) = \frac{E_{tank}(t)}{HHV_{H_2}} \quad (12)$$

where, HHV_{H_2}: is the maximum heating value of the stored hydrogen, which is considered to be 38.89 kWh/kg [22].

3.5 Battery

Lead-acid batteries are used as a storage method. They are characterized by deep cycling [23].

The battery's state of charge is constrained by the following:

$$SOC_{max} \geq SOC(t) \geq SOC_{min} \quad (13)$$

where, SOC_{max}: maximum state of charge. It is equivalent to the total nominal capacity of all accumulators(C_n), and is proportional to the total number N_b, the number of batteries connected in series N_{bs} and the unit capacity C_b as shown in [24]:

$$C_n = C_b\left(\frac{N_b}{N_{bs}}\right) \quad (14)$$

SOC_{min}: is the lowest permitted storage capacity, it is dependent on SOC_{max} as:

$$SOC_{min} = (1 - DOD) \times SOC_{max} \quad (15)$$

where, DOD: is the depth of discharge of the battery.

3.6 Converters

One important component in the proposed system is the converter. Its primary role is to provide electricity from the DC converters to the load. This device's size is determined by its maximum and minimum energy levels [25].

The inverter and rectifier mathematical models are depicted below [26].

$$Pinv = (Ppv + Pfc).\eta inv \quad (16)$$

$$Prec = Prec\_in.\eta rec \quad (17)$$

where, $Pinv$, Pfc and $Prec$ are the output power of inverter, fuel cell and rectifier, respectively, $Prec\_in$ is the input power of the rectifier and ηinv and ηrec are the efficiencies of inverter and rectifier that equal to 96 (%) and 94 (%), respectively.

4. OPTIMIZATION PROBLEM FORMULATION

We intend to provide electrical energy to the institution using a multi-source renewable energy system comprised of a wind turbine, a PV system, and a fuel cell. As a backup, the system includes storage batteries. The issue to be solved is determining the best combination to assure energy supply continuity at the lowest possible cost.

The objective function and constraints included in the problem formulation are as follows:

4.1 Objective function

This problem is concerned with minimizing the hybrid system's Total Net Present Cost (TNPC). The formula (19) calculates the TNPC as follows [27]:

$$TNPC = CC_{syst} + RC_{syst} + O\&M_{syst} \quad (18)$$

where, CC_{syst} is the system's capital cost and is determined as the sum of the capital costs of all subsystems, RC_{syst} is the replacement cost of the system and is calculated as the sum of all system component replacement costs; $O\&M_{syst}$ is defined as the total system's operating and maintenance cost and is calculated by summing the O&M of all system components.

The TNPC and the Cost of Energy (CEO) are used to analyze the HRES.

4.2 Constraints

The optimization problem is solved under the following constraints:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (19)$$

$$N_{PV} \geq 0, N_{wind} \geq 0, N_{bat} \geq 0 \quad (20)$$

$$(N_{PV}, N_{wind}, N_{bat}) = interger \quad (21)$$

where, $SOC(t)$, SOC_{min}, and SOC_{max} are the instantaneous, min, and max battery state of charges, respectively; N_{PV}, N_{wind}, N_{bat} are the number of PV panels, wind turbines, and batterie, respectively.

5. RESULTS AND DISCUSSIONS

The main objective of the current study is to optimize the size and cost of the off-grid HRES proposed to supply the study area with the required energy demand. The proposed system was built using HOMER Pro software. It can design and simulate the system at optimal conditions under the expected constraints. When designing the system, besides the meteorological data required as inputs to the subsystems, the economic data have an important role before the economic analysis. Hence, the capital cost per kW of a PV module is around 300 €, with an annual maintenance cost of 10 €. Without a tracker, the PV system's lifetime is estimated to be 25 years, its efficiency is 17.3%; its derating factor is 96%; and its ground reflectance is 20%. A wind turbine with a capital cost of 150000 €, a replacement cost of 13000 €, and an annual operating and maintenance cost of 25 €. A PEMFC fuel cell with a capital cost of 3000 €, a replacement cost of 2500 €, and an O & M cost of 0.01 € / op.hr is being considered. The FC's lifetime is estimated to be 50000 hours. The capital cost of an electrolyzer per kW is approximately 2000 €, and a replacement cost of €2000 is expected with no maintenance cost. Their lifespan is estimated to be 15 years, and their efficiency is approximately 85%. For this study, a generic hydrogen tank is used, with capital and replacement costs estimated at 800 € and 0 €, respectively. The annual O&M cost is estimated to be 40 €. A "generic 1 kWh Lead Acid" battery is used. The rated voltage of such a standard is 12 volts, and the nominal capacity is 83.4 Ah. The capital and replacement expenses are considered to be 300 euros per unit, with a maintenance cost of 10 €. Finally, a Leonics MTP-4117H 300kW converter with a 10-year estimated lifetime, an inversion efficiency of 96%, and a rectification efficiency of 94% is being investigated. The inverter capital cost per kW, replacement cost, and maintenance cost are 300 €, 300 €, and 0 €, respectively.

The annual real discount rate is taken as 5.88%, the nominal discount rate is 8% and the expected inflation rate is 2%. The lifetime of the project is selected to be 25 years.

After running the calculation, 2702 solutions were simulated, of which 985 were feasible. Out of many, the optimal and sensitive solution is illustrated in Table 1.

Table 1 depicts the distribution of renewable resources for meeting the needed energy requirements in the research region, which includes wind turbine generators, solar PV, and fuel cells. The dimensions of the system's various components are as follows: 10 kW, 359 kW, 3, 3 kW, 974 strings, 10 kg, and 189 kW for the fuel cell, solar PV, wind turbines, electrolyzer, battery, hydrogen tank, and converter, respectively, while the yearly energy required is estimated at 723 072 kWh/yr.

Table 1. HRES architecture

Components	Name	Size/Unit
FC	Generic Fuel Cell	10,0 kW
PV	Schneider ConextCoreXC 680kW with Generic PV	359 kW
Storage	Generic 1kWh Lead Acid	974 strings
Wind turbine	Enercon E-44 [900kW]	3
System converter	Leonics GTP519S 900KW 700Vdc	189 kW
Electrolyzer	Generic Electrolyzer	3,00 kW
Hydrogen tank	Hydrogen Tank	10,0 kg

Figure 4 illustrates the overall cost overview of all components.

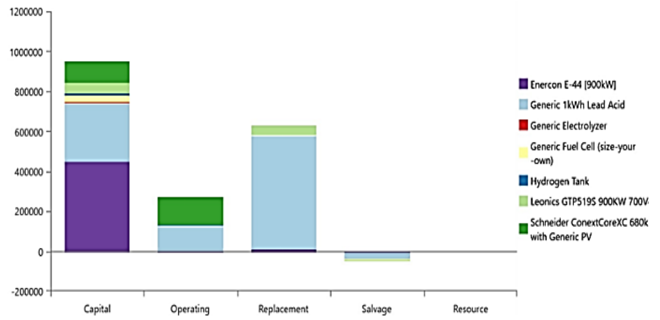

Figure 4. Costs summary

The TNPC of the system is estimated as 1 800 760,00 €. Indeed, out of all components, the batteries offer the highest TNPC with 951433 €, and the electrolyzer has the lowest TNPC with 8067 €.

Since the solar radiation data is the most uncertain variable, A sensitivity analysis is done for the proposed system, the scaled annual average value was varied by ± 25%. The results show that the effect of a slight variation of the solar radiation is neglected on the Systems' TNPC.

The proposed HRES can produce 3 270 792 kWh/yr of renewable energy at a Levelized cost of energy of 0,193 €/kWh. The wind turbine generator produces 81.8% of the yearly generated energy, the PV system can convert 18.2%, and the fuel cell produces less than 1%, as depicted in Figure 5.

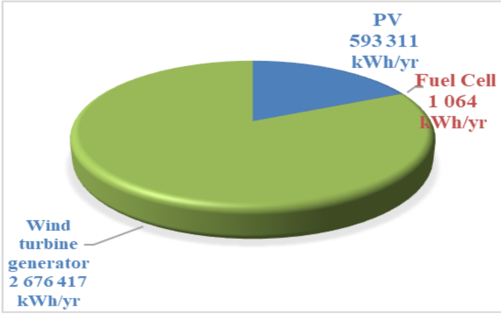

Figure 5. Yearly energy production per different components

6. CONCLUSIONS

The main objective of this study is to estimate the appropriate size of a stand-alone photovoltaic, wind, or diesel hybrid with a storage battery to guarantee the energy autonomy of the typical remote consumption at the lowest energy cost. The procedure is based on using the process for verifying the viability of a stand-alone HRES capable of meeting load requirements using HOMER software. Proper design is critical to ensuring the system's feasibility at the desired low cost. Several combinations were simulated, and NPC and COE were used to rank the possible configurations.

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