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Flexible Design and Assessment of a Stand-Alone Hybrid Renewable Energy System: A Case Study Marrakech, Morocco

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Abstract- The main objective of this study is to propose an optimal 'hybrid renewable energy system' (HRES) destined to supply a group of typical houses in Marrakech-Morocco. The renewable hybrid system consists of a wind turbine, a photovoltaic field (PV), a diesel generator (DG), converters and batteries. Hybrid Optimization of Multiple Electric Renewables (HOMER) software has been used to assess the techno-economic feasibility. Four scenarios are evaluated and modeled by HOMER. A comparison of economic feasibility, renewable fraction, total emissions, and excess of electricity for all the scenarios is done. For an interest of 7%, the optimum hybrid system (PV/battery) has a levelized cost of energy (COE) of 0.236$/kWh, which is lower than the COE of the other hybrid systems (PV/DG/battery, PV/Wind/battery and PV/wind/DG/battery) which are respectively, 0.242, 0,270 and 0.274 $/kWh. The Sensitivity analysis was also investigated in the intent to present the impact of changing the interest rate, battery increase, solar radiation, and the load demand increase on the performance of the hybrid system. The sensitivity results elucidate that the PV/Battery hybrid system is still viable for all interest rates ranging from 7 to 10% compared to PV/DG/Battery and PV/Wind/DG/Battery that are also report good economic performance but still suffer from harmful emissions. The combination of PV and batteries together ensures a clean electricity production compared to the PV/DG/Battery and PV/Wind/DG/Battery. The latter present a total CO_2 emission of 5200 kg/year with an increase of the COE that achieves 50% for DG/battery system. Furthermore, the hybrid system combining PV with batteries gives a high renewable fraction compared to the second optimal system.

Keywords: HOMER pro software, hybrid system, off grid, optimization, sensitivity.

1. Introduction

Energy is considered as one of the main features of today's socioeconomic development. However, the world is still suffering of its reliance on the conventional energy based on fossil fuels (represented in natural gasses, coal and oils), which generally contributes to global warming and other environmental damages. This kind of energy represents many challenges such as price fluctuations, political conflicts, and effects on the environment [1][2][3][4]. In this context, various research works are focused on the development of renewable energy technologies for the sake of creating new opportunities that can reduce the harmful emissions [5], [6] and exploit local energy sources (e.g., wind solar and energy).

Recently, the development of the solar and wind energy has attracted a great deal of intentions due to their positive impact on the environment , low cost of energy (COE), and reduced water consumption unlike thermal energy, which necessarily needs freshwater for cooling [7], [8], [9]. In fact, according to the International Renewable Energy Agency (IRENA), compared to the cheapest fossil fuel-power generation option, the solar PV and onshore wind provide lower electricity price which is expected to be USD 0.055, 0.049 $/kWh in 2020 respectively [10].

Despite the benefits of solar and wind energies, they depend on different variables such as terrain, weather, and environment. In fact, days without wind or without high brightness can severely hinder the production of wind and solar energy [11], [12]. A hybrid system combining two or more resources of renewable energy comes to solve the mentioned problems by exploiting the intensity of one source to balance the weakness of the other. The mixing of solar and wind energies presents a good and viable alternative to energy systems based on fossil fuels [13] [14][15][16].

Geographic and climatic conditions make Morocco one of the most countries oriented to renewable energy. The Moroccan government has an ambitious strategy to develop solar/wind energy hybrid operation. The fossil energy will decrease from 61% in 2008 to 38% in 2030, while as illustrated in **Error! Reference source not found.**, the renewable energy (wind+ solar) will cover 14,3% of the electricity demand in 2030 [17], [18].

Morocco has 17 suitable regions for wind power generation. Their theoretical wind capacity is estimated at 2,645 GW [19][20]. This situation prompted Morocco to change its energy policy by adopting an ambitious program aiming to install a 2,000 MW wind farm by 2020 for an annual production of 6600 GWh. This corresponds to 26% of current electricity production. The development of new wind energy farms with a capacity of 850 MW are planned as follow: Boujdour (100 MW), Tangier (100 MW), Jbel Lahdid (200 MW), Tiskrad (300 MW), and Midelt (150 MW).

Moreover, Morocco's solar power generation potential is high, with an average daily solar radiation ranging from 4.7 kWh/m^2/day in the north to approximately 5.6 kWh/m^2/day in the south [21].

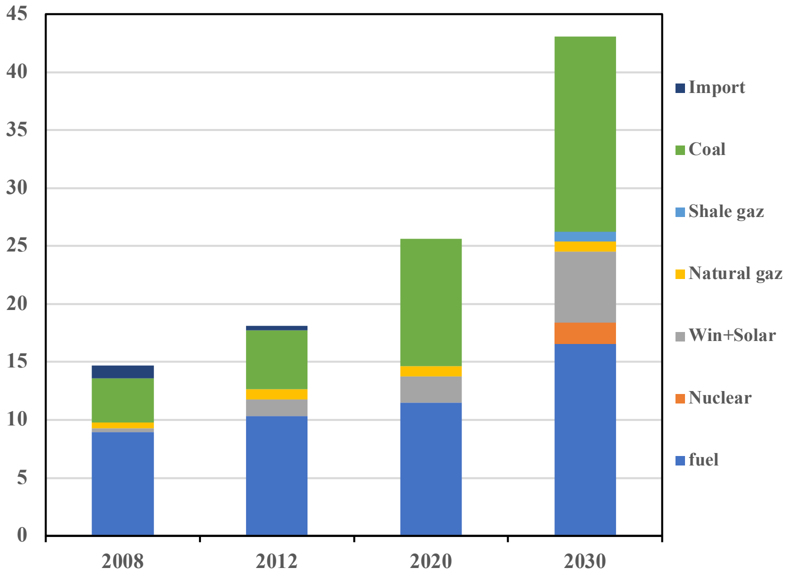


Fig.1. Electricity supply mix

Moroccan's solar plan aims to build new solar projects (based on PV and CSP technologies) with a total capacity of 2000 MW and a total investment around $9 billion, which allows saving 1 million toe and preventing 3.7 million tons of CO_2 emissions per year. The new sites will be located in Tata (300 MW of PV and 300 MW of CSP), Midelt (300 MW of CSP and 300 MW of PV), Tafilalt and Atlas (300 MW of PV), Laayoune and Boujdour (100 MW of PV), Ouarzazate (510 MW of CSP and 70 MW of PV) and solar power plants in the economic zones (150 MW PV) [21], [22].

Over the last decade, reviews of literature indicate that various studies have focused on hybrid renewable energy systems (HRES) in several countries around the world. These HRES are either grid-connected [[23]–[26][27]] or standalone with the use of storage systems such as battery banks and fuel cells [28] [29] [11] [30] [31]. In some cases, the diesel generators (DG) are used to fit the gap between the load demand and the generated power by the other energy resources [32][33][34][35][36]. The use of DG increases the reliability of the power plant, but it's not environmentally friendly. In order to assess the techno-economic feasibility of such systems, some indicators are usually used such as the (COE), the net present cost (NPC) and some environmental factors including the CO_2 emissions.

In order to promote renewable/clean energy generation, the Moroccan government established numerous legislative laws that demonstrate the country's willingness to invest in renewable energies. To accompany this vision, it is necessary to perform several techno-economic investigations for small scale projects. In fact, the ideal sizing of HRES increases meaningfully their economic and technical performances. In this context, optimization and sensitivity analysis need to be done in order to assess the techno-economic feasibility of HRES configurations. It should be also noted that to the best knowledge of the authors, there are no comprehensive works on the techno-economic assessment of such stand-alone systems that have been made for the electricity supply to a group of typical houses in Marrakech-Morocco. Thus, technical and economic feasibility of four hybrid systems based mainly on solar and wind resources will be discussed and compared by using HOMER pro software for this houses group. Having regard to the economic situation in Morocco due to the energy deficit, the present study will attempt to provide a clear perspective of various economic parameters like the TNPC and the COE. Furthermore, this study compares the COE in Morocco and other developing countries, with the aim of clarifying the final costs of renewable electricity.

The rest of this paper is organized as follows. Section 2 presents a detailed description of Marrakech's climatic specifications, load energy demand, and a presentation of Homer software. Section 3 discusses the planning and optimization of HRES by comparing the different possible combinations based on the main criteria including NPC, and electricity production. A sensitivity analysis is also provided to examine the effects of changes in load demand, the increase in the number of batteries and the interest rate on the COE over time. Finally, section 4 is devoted to the results and the conclusion.

2. System description

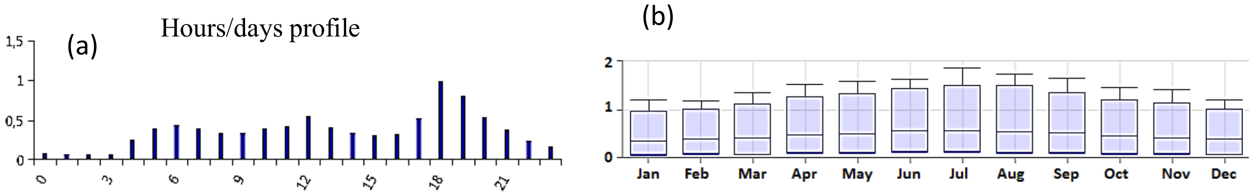
2.1. Geographic site specifications

Marrakech is the fourth largest city in Morocco, after Casablanca, Fez, and Tangier. It is the capital city of the region of Marrakesh-Safi. The average temperatures range from 12 °C (54 °F) in the winter to highs 48°C (100.4 °F) in the summer; the average wind speed at 2 mph is 3 km/h, while the humidity is about 26%. Its Elevation above sea level is 457 m. Fig shows the location of Marrakech. The total irradiation and wind capacity map in Marrakesh are illustrated in Fig.3 and Fig.4, respectively.

Fig.2. Map details of the studies site.

2.2. Load demand

The load demand in the selected area has a domestic aspect including the electricity supply of 50 houses. The estimated load profile includes washing machines, fluorescent lamps, computers, fans, televisions, dishwashers and fridges. As shown in Fig.1, the average daily electricity load is reported to be 208 kWh/day with a daily peak of 35.7 kWh. It can be clearly noted that the load profile has a peak in the evening due to usual evening activities (cooking, reading, watching, TV, and lighting). Fig.2 shows the monthly load demand with a peak load demand recorded in the summer season.



Yearly profile

Monthly profile

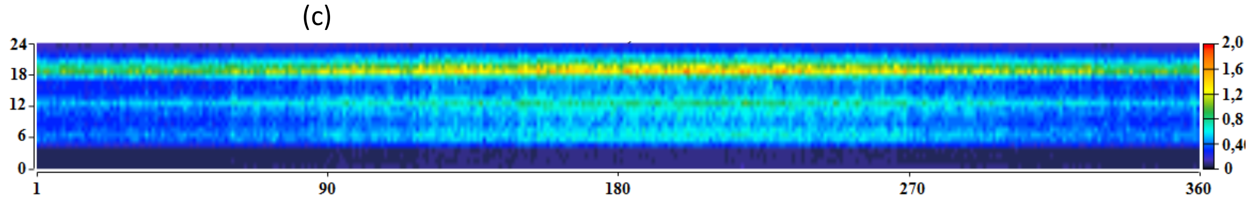


Fig.1. Load profile for one typical house (a: daily profile, b: monthly profile and c: DMAP of yearly profile)

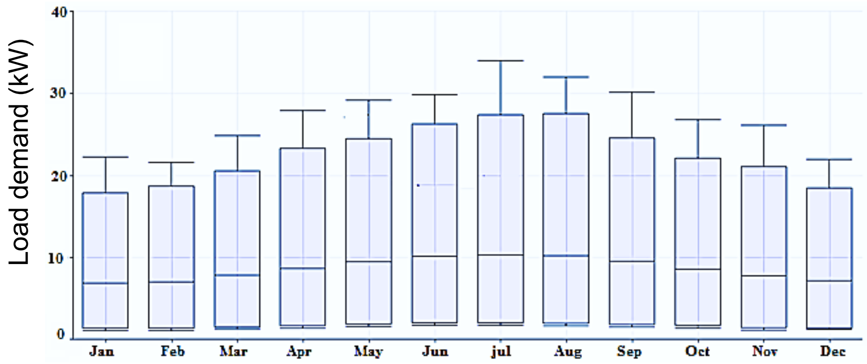


Fig.2. Total Monthly load profile

2.3. Solar Energy

Fig.3 and Table 1 show the monthly average of Global solar Horizontal Irradiance (GHI) data and clearness index (CI) in Marrakesh city. These data are obtained from the website of NASA. The annual average solar irradiation is 5.24 kW/m2/day [37]. As shown in Figure 9, an interesting amount of solar energy can be obtained due to its presence during the whole year.

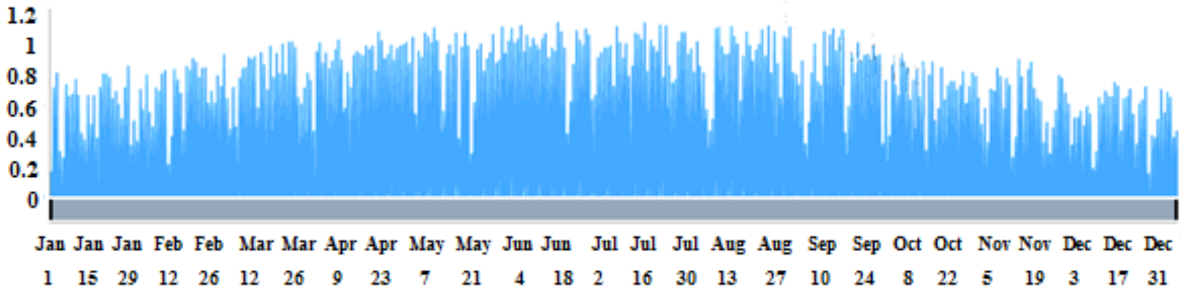


Fig.3. Daily solar radiation

2.4. Wind Energy

The monthly average of the wind speed in this location was given by NASA resource website [37]. The annual average of the wind speed is 5.77 m/s with an altitude of 457 m and anemometer height of 50 m. The average daily and monthly speed are illustrated in Fig.5. It can be noted that the period of [June - July - August] has the highest wind speed values, which allows to cover the increase in the load demand in the same period.

Table 1. Table Diagram of Daily Radiation and Clearness Index for the case study

Month	*Clearness index*	*Daily Radiation (kW/m2/day)*
Jan	0,595	3,360
Feb	0,602	4,160
Mar	0,613	5,270
Apr	0,622	6,310

May	0,618	6,870
Jun	0,620	7,110
Jul	0,604	6,800
Aug	0,620	6,490
Sep	0,601	5,470
Oct	0,603	4,460
Nov	0,598	3,540
Dec	0,581	3,050

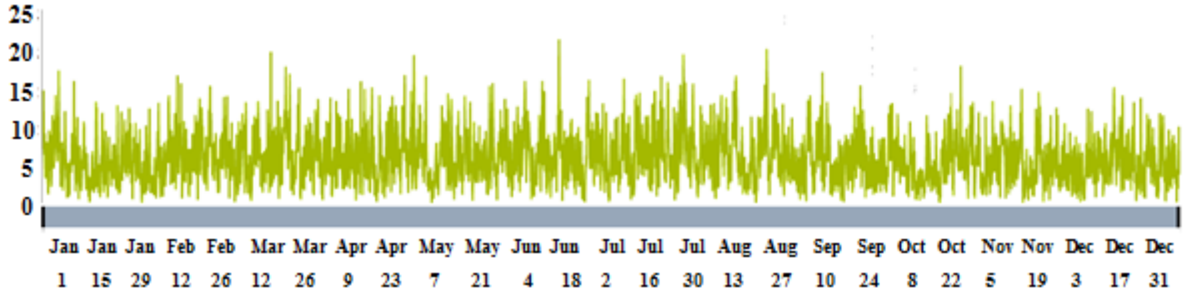


Fig.4. The average daily wind speed

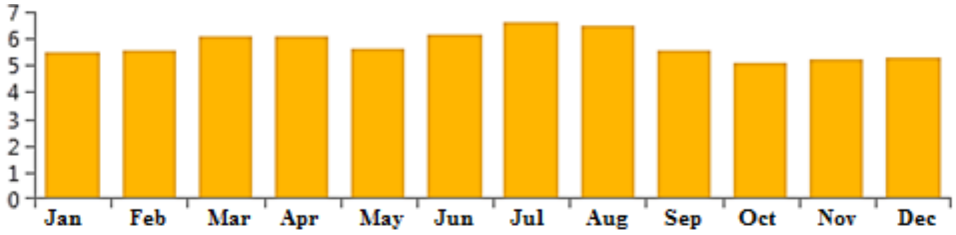


Fig.5. The average monthly wind speed

2.5. Diesel price

Fig.6 shows the DG prices in Morocco from 24-Jul-2017 to 30-Oct-2017, it can be noted that the DG price is in the range of \$0.91 and \$1.1/L. During this period, the average value is 0.96\$, which remains low compared to the world average value of 1.22\$.

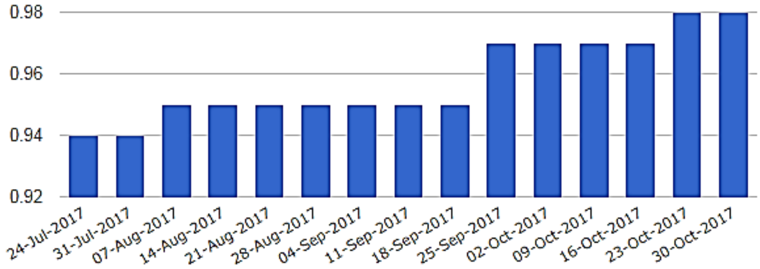


Fig.6. The average price of DG in Morocco

3. Homer software and system components

HOMER pro software is a powerful tool mainly used to size and optimize HRES. It performs three main tasks: simulation, optimization, and sensitivity analysis [38][39]. HOMER models the performance of a particular hybrid system configuration each hour of the year to define its technical feasibility and life-cycle cost. A feasible system is presented as a hybrid system configuration that can satisfy the required load. The optimization process is carried out to simulate several system configurations. In this stage, any technical specifications of hybrid energy system components as input are not required due to its embedding in its algorithm in generic form. Then, HOMER searches for the system that satisfies the technical and economic constraints at the lowest life-cycle cost. It should be noted that HOMER Pro has two optimization algorithms. The original grid search algorithm simulates all of the feasible system configurations defined by the Search Space. The new HOMER Optimizer uses a proprietary derivative-free algorithm to search for the least-costly system. HOMER then displays a list of configurations, sorted by net present cost (sometimes called life-cycle cost), that you can use to compare system design options.

In the sensitivity analysis process, different optimizations under a range of input values are performed with the intent to evaluate the effects of uncertainty or changes in the model inputs (e.g., changes in wind speed or DG price) [40][41]. In fact, when you define sensitivity variables as inputs, HOMER repeats the optimization process for each sensitivity variable that you specify. For example, if you define wind speed as a sensitivity variable, HOMER simulates system configurations for the range of wind speeds that you specify.

Figure 9 illustrates a simplified optimization and sensitivity flowchart of HOMER Pro.

The Homer pro software is based on general techniques in intent to model the different components of the HRES as follow [23]:

a- The PV array output is calculated by using the following Equation:

$$P_{pv} = H_{PV} * U_{PV} * \frac{V_T}{V_{T,STC}}\left(1 + \beta_P\left(T_C - T_{C,STC}\right)\right) \quad (1)$$

Where, H_{PV} represents the PV array output (kWh), U_{PV} is the derating factor of the photovoltaic generator (%), β_P represent the temperature coefficient, V_T is the incident solar radiation upon the PV array, $V_{T,STC}$ represents that of based standard testing conditions (kW/m^2). The T_C and $T_{C,STC}$ are the cell temperature and based standard temperature conditions(°C).

b- In regards to the wind turbine component, Homer pro is based on the equation (2) to determine the wind speed by using the power law based on 10m height.

$$\frac{W_2}{W_1} = (\frac{Y_2}{Y_1})^{\alpha} \quad (2)$$

Where W_2 and W_1 are the wind speed corresponding to the heights Y_2 and Y_1 respectively, while α represents the power law exponent.

c- The generator fuel consumption can be modeled by HOMER pro by adopting the following equation:

$$F = F_0 * Y_{gen} + F_1 * P_{gen} \quad (3)$$

Where Y_{gen} is the generator rated capacity(kW), P_{gen} represent the electric output(kW), F_1 is the fuel slope curve and F_0 is the fuel curve intercept coefficient.

d- At each time step, HOMER pro is started to calculate the maximum amount of energy that can be absorbed by the batterie. This maximum load power is used for decision-making, for example if the storage bank can absorb all of the excess renewable energy available or the amount of excess power that a charge generator per cycle has to produce. the state of charge of the battery as well as its recent history of charging and discharging practically influences, from one-time step to another, the maximum charging power. The following equations adopted by HOMER are performed under three major limitations (kinetic model, maximum charge rate and Storage Component's maximum charge current). The calculation the state of charge and the depth of charge can be expressed as follow:

- The state of charge

$$SOC = \frac{C_b}{C_m} \quad (4)$$

Where C_b is the capacity of batterie, while Cm represents its maximum capacity

- The depth of charge (DOC) is given by:

$$DOC = \mathrm{SOC} - 1 \quad (5)$$

- The batterie is protected from the deep charging and also the overcharging according to the equation bellow:

$$C_{min} \leq C_t \leq C_{max} \quad (6)$$

C_t is the instantaneous charge capacity of the battery, while the C_{max} and C_{min} represent the maximum and minimum capacity of batterie, respectively.

3.1.1. Environmental criteria

One of the indispensable parameters in any hybrid system design is the environmental issues that can be related to the amount of CO2 emissions. This amount can be calculated on the basis of equation (5).

$$tCO_2 = 3.667 * M_f * X_C * HV_f * CEF_f \quad (11)$$

Where, tCO2, M_f, HV_f, CEF_f and X_c are the total amount of CO2 emissions, the fuel quantity in (liter), the fuel heating value in (MJ/L), the carbon emission factor in (ton carbon/TJ), and the oxidized carbon fraction, respectively, while 3.667 of CO_2 generates 1 g of carbon.

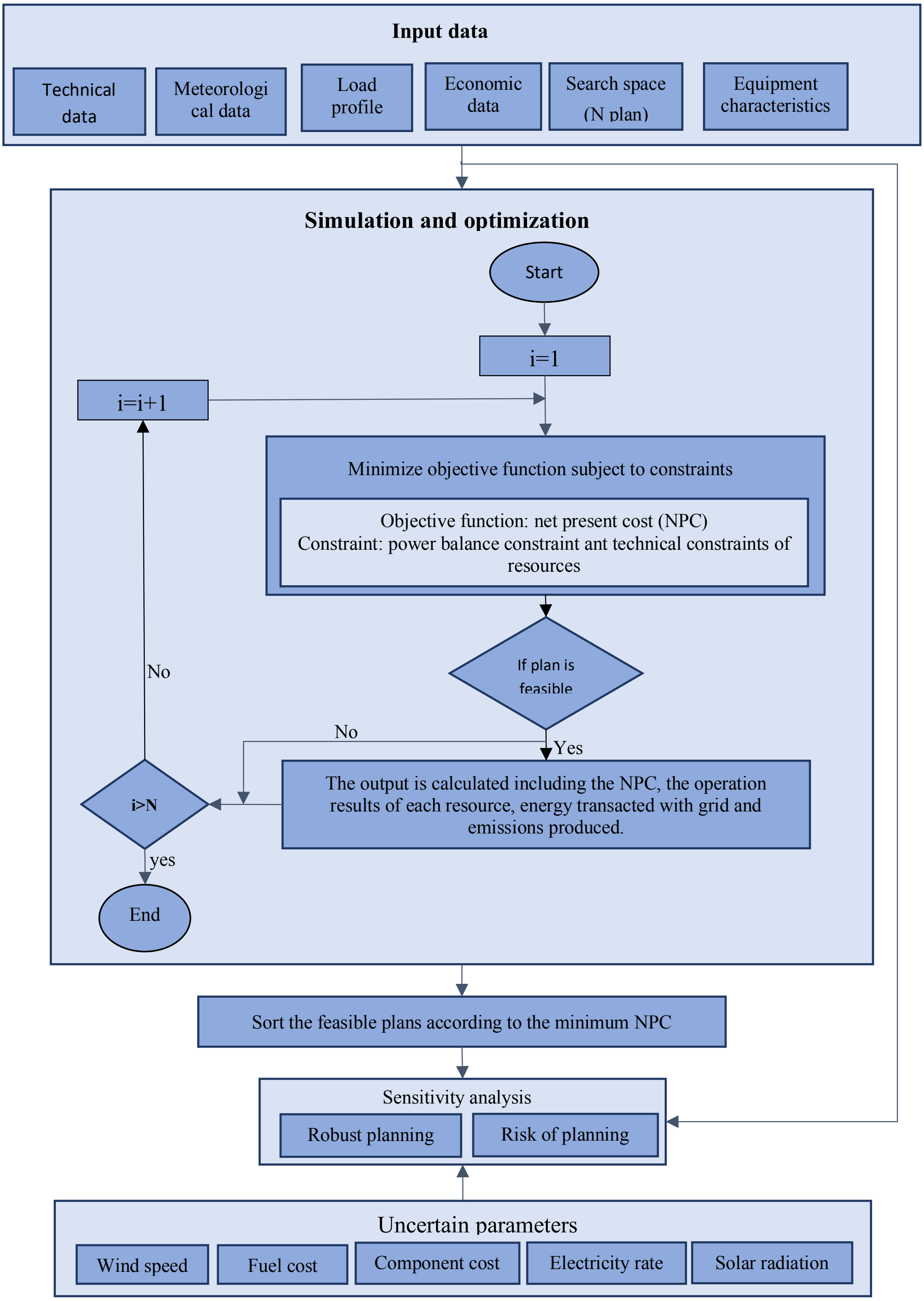


Fig.9. Optimization and sensitivity flowchart of HOMER pro

3.2. System components

3.2.1. PV array

The solar panel cost depends on many factors such as the size of the PV panel, the technology and the brand. A PV panel with 72 mono-crystalline cells is considered in this study. Its peak power is in the range of 305 and 315 watts[42]. The cost of PV panel in Morocco ranges from 0,6 to 0,9 $/kW, the PV panel's lifetime is defined to be 25 years. Moreover, the ground reflectance and the de-rating factor are considered as 90% and 20%, respectively.

3.2.2. Wind Turbine

The wind turbine XZERES 442SR (mentioned as Xzer 7.2 in Homer Pro) manufactured by Xzeres is employed in this study [43]. Its rated power is 10 kW with a hub height of 24 m. Fig.7 presents the wind speed versus the power output. The lifetime of the selected wind turbine is assumed to be 25 years.

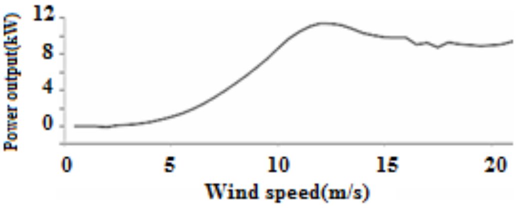


Fig.7. The curve of Xzer 7.2 wind turbine.

3.2.3. Battery

The batteries are used for backup purposes to cover the load demand in the absence of sufficient sunlight and wind levels and therefore to increase the reliability of the system. It is well known that the battery system is considered as the most critical element in any power system. This is due to its high cost and short lifetime compared to the PV panels and the wind turbine. In this study, the *Rolls Surrette 4KS25P* battery is used, its rated voltage is 4V with a nominal capacity of 1904 Ah. The battery efficiency is 80% with a replacement period of 10 years and a minimum state of charge of 20% [44].

3.2.4. Power Converter

In this study, a power converter system is required to ensure the energy flow between the AC and DC components in the proposed hybrid energy system. The capital cost of 1kW converter and also its replacement cost is considered as $300. Seven different converters size (20 kW, 30 kW, 40 kW, 50 kW, 60 kW, and 70 kW) are considered for the simulation analysis. Moreover, the lifetime of a unit is taken as 15 years with an efficiency of 90%[45].

3.2.5. DG generator

Generating sets are selected based on the electrical load they are intended to supply when the energy generated by wind, solar and batteries is not sufficient. In this study, the rated power of the DG is 10 kW, the complete specifications are shown in table 1.

4. Results and discussion

In this section, the technical and economic results for the studied Moroccan site are discussed. Homer allows simulating different possible combinations and optimizing them in order to provide the feasible ones in accordance with the lowest TNPC. In our case, the sensitivity analysis is devoted to show the impact of the interest rate and the increase of batteries. The relevant parameters of the different components used in this study are listed in Table 2.

Table 2. Technical details of input components

Equipment	Factor	Value	Equipment	Factor	Value
PV	**Rated power (Wp)**	**315**	**DG generator**	**Capacity (Kw)**	**10**
	Maximum Power Voltage (V)	37.1		Fuel	DG
	Maximum Power Current (A)	8.51		Fuel curve intercept(L/h)	0.480
	Open Circuit Voltage (V)	45.6		Fuel curve slope(L/h)	0,286
	Short Circuit Current (A)	9	**Converter**	**Inverter**	
	Derating factor (%)	80		Lifetime (Years)	15
	Temperature coefficient	- 0.41		Efficiency (%)	95
	Operation temperature (C)	44		**Rectifier**	
	Lifetime (Years)	25		Relative capacity (%)	100

	Efficiency (%)	16.2		Efficiency (%)	90
Battery	Nominal capacity (A h/Cell)	1500	**Wind Turbine**	Name	Xzer 7.2
	Nominal voltage (V)	4		Rated Power (kW)	10
	Nominal capacity	7.55		Alternator	3-Phase
	Maximum capacity(Ah)	1.89		Rotor Diameter (m)	7.2
	Capacity ratio (1/h)	0.254		Hub height (m)	24
	Round trip efficiency %	80		Lifetime (Years)	25

4.1. Optimization results

The optimal solutions obtained after several simulations considering a solar radiation of 5.24 kW/m2/day with 0.508 of clearness index, an annual scaled average wind speed of 4.57 m/s and a DG price of 0.9 $/L are presented in

Table 3. It is clear from this table that the PV/ Battery hybrid system is the most suitable hybrid system considering the COE, operating cost, initial capital and TNPC. The present study will focus on the first two hybrid systems, while the other suggested systems are omitted from this discussion.

Table 3: HOMER output sorted by the low cost of energy

PV	Wind turbine	DG	Battery	Converter	COE	TNPC	OC	Initial capital	RF	Capacity Shortage	Excess of Elect
66,5	0	0	54	31,7	0,236	169943	2967	140802	100	4,10	26,1
55,7	0	10	47	25,7	0,242	179052	5542	124612	92,4	0,94	15,3
61,6	1	0	56	33,3	0,270	194557	2929	165784	100	4,1	22,5
53,8	1	10	47	25,2	0,274	203350	5450	149818	92,8	0,92	15
0	0	10	20	20,7	0,482	348597	31904	35216	0	4,10	0

4.2. Power structure

a- PV/Battery

The configuration-based PV/Battery is shown in Fig(a). According to

Table , the optimization results of this configuration show that the PV/Battery is considered as an optimal solution due to its low COE fixed in 0.236$/kW and a TNPC of $169,943 compared to the other combinations. As shown in Table 4, the system's capital, replacement, O&M and salvage costs are 185023$, 55058.81, $19749.54, $33217.02 respectively with 25 years as a project lifetime. This system has a capacity shortage presenting 4 % of the total production. However, it's still having a high initial capital due to its large sizing compared to the second ranked hybrid system based on DG. The different components cost of this combination are given in Table 4. The optimal combination is composed of 63 kW_p of PV, a 10 kW Generic wind turbine, a battery bank with a nominal capacity of 1904 Ah (Surrette S4KS25P 24V) and a converter of 31 kW as rated power with dispatching strategy of cycle charging (CC).

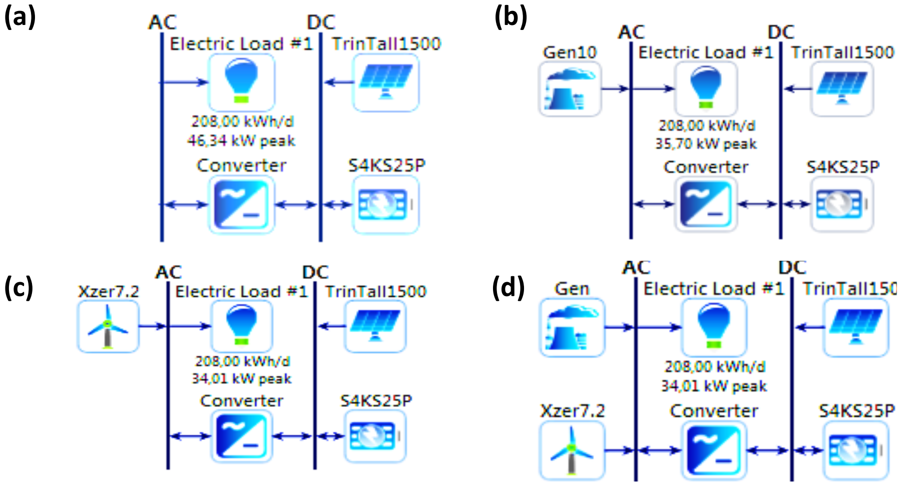


Fig.11. (a) PV/Battery (b) PV/DG/Battery (c) PV/Wind/Battery (d) PV/Wind/DG/Battery schematic diagrams.

On the other hand, HOMER pro software calculates the produced electricity, excess electricity, unmet load and the required power to supply the load. The simulation results presented in table 5 show that the total electricity production from PV is 113,656 kW h/year (100%) with an annual output of 43,816 kW/year assured by the batteries.

b- PV/DG/Battery

The system including PV and DG as well as batteries is presented in Fig(b). Homer ranked this system as the second optimal system that has the lower COE after the PV/battery system. This system presented the lowest initial capital cost due to the limited number of batteries fixed in 49 . Moreover, this system presents a low capacity shortage (0,9%) compared to other configurations (PV/Battery, PV/wind/Battery and PV/wind/DG/Battery). This is mainly due to the load continuity supply of this system assured by DG. As presented in Table 4, the system's capital, replacement, operation & maintenance and fuel costs are $128270 $35177, $9372 and $20648 respectively with 25 years as a project lifetime.

As presented in Table 5, the PV panels generate an amount of 100255 kWh/year (95,2%) followed by the DG generator that participates by 5031 kWh/year (4,8%). with Annual Throughput of 42 238 kW h/ assured by the batteries.

c- PV/Wind/Battery

The configuration of the PV/Wind/Battery system is shown in Fig(c). According to the optimization results, the PV/Wind/Battery is the third optimal system with a COE of 0.270 $/kW and a TNPC of $194557, with 56 batteries connected in a serial connection under an operating voltage of 24V. As shown in Table 4, the system's capital, replacement, O&M and salvage costs are $185023, $55058, $19749, $33217 respectively with 25 years as the project lifetime.

As shown in table 2, the PV/Wind/Battery hybrid system has a capacity shortage presenting 4.1 % of the total production and an excess of electricity lower than the PV/Battery. This system has a high initial capital because of the initial size that manifests itself in the price of the wind turbine. The cost details of this system are listed in Table 4. It can be observed from Table 3 that the PV participates with a large amount of energy (108632 kWh/year), followed by the wind turbine which produces only 5012 kWh/year, this represents only 2,44% of the produced energy.

d- PV/Wind/DG/Battery

Fig(d) shows the configuration of the PV/Wind/DG/Battery sized by HOMER, this latter calculates and optimizes the required power, electricity surplus and the unmet load. Table 2 shows the characteristics of the optimal configuration of the HRES. This configuration consists of 53 kW$_p$ of PV, one wind turbine of 10 kW, a converter group of 25.2 kW, DG generator of 10 kW that consumes a total of 1937 l/year and 47 batteries. The NPC of this system is $203350 and the COE is 0.247 $/kWh, more details about the different costs are presented in table 3. The PV/Wind/DG/Battery system presents the lowest excess of electricity (15%), with a renewable fraction of 92.8%.

4.2.1. Economic feasibility indicators

The simulation results of the major financial indicators based on the NPC and the COE are shown in Table 2-4. The PV/Battery system is the cost-effective energy source from an economic perspective. This system has the lowest total NPC and COE, while its initial capital cost is higher than the second hybrid system. The system's capital, replacement, O&M, operational and salvage costs are 191680, $52459, 21085 $ and 37735 $ respectively with 25 years as a project lifetime. For the annual cost, the system battery has a higher TNPC of 100 258$ followed by the PV array system (56968 $), whereas the wind turbine system, the DG generator, and the system converter cost 38706$, 23198$ and 14777$ respectively. PV/Battery had a cost advantage in the short term, but it has a high O&M costs. PV/DG/Battery has a relatively low initial capital in the short term, but the total NPC and COE are higher than the first ranked system with a TNPC of $179052 which represents an increase of 9.49%. PV/Wind/battery has a low initial capital investment, and the operation cost compared to the four systems. According to table 3, the PV array generated the large part of electricity followed by the wind turbine system, thus the optimization results show that the total annual electricity production of the optimized hybrid system is about 104 416 kWh/y. Hence, the electricity amount produced by PV array is 92,6% (96 692kWh/y), 4,8% (5012 kWh/y) of electricity is assured by wind turbine system followed by the DG system that generates 2,6% (2713 kWh/y) while 190 kWh/year is stored in the batteries

Table 2. Cost of different hybrid system components

Configuration	Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Fuel ($)	Total ($)
PV/Battery	PV array	64 442,14	0,00	6 879,05	0,00	0,00	71 321,19
	Battery	68 400,00	23 780,50	0,00	0,00	-1 786,58	90 393,92
	Converter	8 949,71	2 821,32	0,00	0,00	-435,61	11 335,43
PV/DG/Battery	PV array	56 843,79	0,00	6 067,95	0,00	0,00	62 911,74
	Battery	58 800,00	31 139,64	0,00	0,00	-8 547,57	81 392,08
	Converter	7 626,66	2 404,24	0,00	0,00	-371,21	9 659,69
	DG	5 000,00	1 633,65	3 304,91	20 648,01	-204,43	30 382,15
PV/wind/Battery	PV array	61 593,71	0,00	6 574,99	0,00	0,00	68 168,70
	Battery	67 200,00	23 170,11	0,00	0,00	-1 894,58	88 475,53
	WT	27 000,00	0,00	1 601,22	0,00	0,00	28 601,22
	Converter	9 783,63	3 084,21	0,00 $	0,00	-476,20	12 391,64
PV/wind/DG/Battery	PV array	54 823,57	0,00	5 852,29	0,00	0,00	60 675,86
	Battery	57 600,00	21 927,87	0,00	0,00	-65,34	79 462,53
	WT	27 000,00	0,00	1 601,22	0,00	0,00	28 601,22
	Converter	7 515,79	2 369,29	0,00	0,00	-365,81	9 519,27
	DG	5 000,00	1 663,54	3 359,35	20 675,16	-183,74	30 514,31

Table 3. Electricity Production generated by the different hybrid systems

	PV/Battery		**PV/DG/Battery**		**PV/wind/Battery**		**PV/Wind/DG/Battery**	
Production	(kWh/yr)	**%**	(kWh/yr)	**%**	(kWh/yr)	**%**	(kWh/yr)	**%**
PV array	113 656	100	100 255	95,2	108 632	97,6	96 692	92,6
WT	0	0	0	0	2 713	2,44	5 012	4,80
DG	0	0	5 031	4,78	0	0	2 713	2,60
Total	113 656	100	105 286	100	111 345	100	104 416	100

4.2.2. Fuel consumption and GHG emission

HOMER pro calculates the fuel cost by calculating the energy released per kg. The fuel consumption and its price fluctuation affect the PV/DG/Battery and the PV/Wind/DG/Battery hybrid systems. Fig illustrates the hourly fuel consumption for those two systems. As it can be seen, the DG mainly works in the period between [5h-9h] and [18h-23h]. This is due to the relative decrease of the produced energy by the renewable resources (absence of PV production and low values of the wind speed at night).

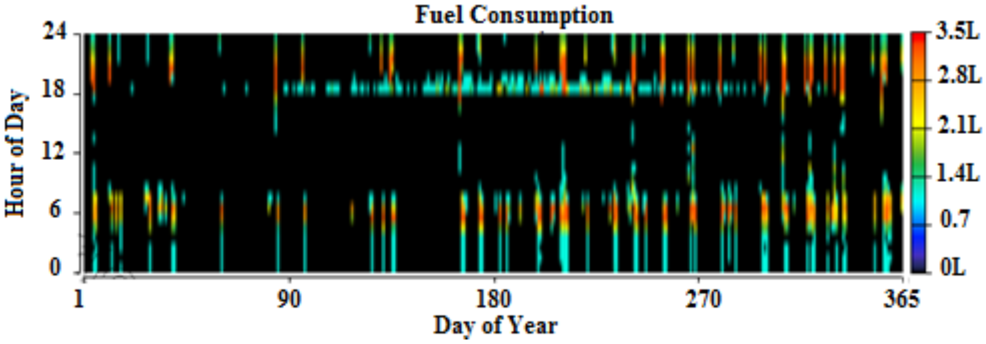


Fig.12. The hourly output of the DG generator through the year for PV/DG/Battery and PV/Wind/DG/Battery systems.

Both hybrid systems using DG generate polluting emissions, this represents a real threat to the environment. HOMER estimates the possible emission amount at the provided operation strategy. The carbon dioxide and pollutant emissions emitted by the PV/DG/Battery and PV/Wind/DG/Battery systems are shown in Table 4. As it can be seen from this table, the total emission is 5200 kg/year for each system. Those systems generate an amount of 5 053 kg/year carbon dioxide (CO2), 38.2 kg/year carbon monoxide (CO), 1.39 kg/year unburned hydrocarbons, whereas particulate matter, Sulphur dioxide and year nitrogen oxides (NOx) present 2.32 kg/year ,12.4 kg/year and 43.5 kg/year respectively. By adopting the first PV/Battery hybrid system, those emissions can be significantly removed.

Table 4. Total emissions of the based DG system

	PV/DG/Battery	**PV/Wind/DG/Battery**
Pollutant	**Quantity(kg/yr)**	
Carbon Dioxide	5 053	5 070
Carbon Monoxide	38,2	40
Unburned Hydrocarbons	1,39	1,39
Particulate Matter	2,32	2,32
Sulfur Dioxide	12,4	12,4
Nitrogen Oxides	43,4	43,5

The COE of some optimal configurations as reported in the literature is shown in Table 7. The proposed optimal system based on PV/Battery presents a competitive value of the COE compared to those reported in the literature particularly in remote areas.

Table 5. Summary of various obtained COE in the literature

References	**COE (\$/kWh)**	**References**	**COE (\$/kWh)**	**References**	**COE (\$/kWh)**	**References**	**COE (\$/kWh)**
[46]	**0.427**	[47]	**0.595**	[48]	**0.42**	[49]	**0.295**
[50]	**0.296**	[51]	**0.306**	[52]	**1.3**	[53]	**0.142**
[54]	**0.363**	[55]	**0.751**	[56]	**0.191**	[57]	**0.871**
[58]	**0.488**	[59]	**0.2**	[60]	**0.297**	[61]	**1.655**
[62]	**1.072**	[63]	**0.288**	[64]	**0.369**		

5. Sensitivity Analysis

After the selection of the optimal configuration, HOMER carries out the sensitivity analysis in order to assess the real effect of various sensitive variables such as the global solar radiation, the wind speed, the DG price and the interest rate. In our case, only the load demand, the interest rate, the capacity and the cost of resources (PV and Wind energy) are considered. Since that the system based on DG is not an environment-friendly system, the DG price is not considered as a sensitive variable.

5.1. Impact of the interest rate

The interest rate is a primordial parameter used in the calculation of the COE. Homer software uses Eq.(12) in order to calculate the real interest rate [65]:

$$\mathrm{i} = \frac{\mathrm{i'} - \mathrm{f}}{1 + \mathrm{f}} \tag{12}$$

Where i is the real discount rate, i' is the nominal discount rate and f is the expected inflation rate.

Table *6* presents the effect of the interest rate on the TNPC for the PV/Battery, PV/DG/Battery PV/Wind/Battery and the PV/Wind/DG/Battery hybrid systems. It can be observed from this table that the NPC increases when the real interest rate decreases, while the COE reduces as interest rate increases. In fact, for the PV/Battery and for an increase of the interest rate from 7% to 9%, the TNPC reduces from \$176823 to \$173050. Contrarily, the COE increases from 0,207\$/kW to 0,221\$/kW for the same interest rate change. According to the results given by the table 8, the PV/Battery hybrid system still economically the most suitable system under the all interest values ranging from 7 to 9% followed by the PV/DG/battery hybrid system.

Table 6. Interest rate's impact on the optimized PV/Wind/DG/Battery hybrid system with the DG price of \$0.9/L

	IR	PV (kW)	DG	WT	Battery	Converter (kW)	COE($)	TNPC($)	OC($)	RF	Initial capital($)	CS(%)
PV/battery	**9**	64	0	0	57	30	0,221	173050	2928	100	141792	4
	8	66	0	0	54	31	0,236	169943	2966	100	140802	4
	7	64	0	0	57	30	0,207	176823	3001	100	141844	4
PV/DG/ battery	**9**	55	1	0	47	25	0,242	179053	5542	92	124612	1
	8	57	1	0	49	25	0,229	184346	5253	93	128271	0,94
	7	60	1	0	50	26	0,216	190191	4908	94	132988	0,78
PV/Wind /battery	**9**	61	0	1	56	32	0,25	197637	3003	100	165577	4
	8	61	0	1	56	33	0,27	194556	2929	100	165783	4
	7	62	0	1	56	33	0,24	202182	3088	100	166193	4
PV/Wind/ DG/battery	**9**	53	1	1	47	25	0,27	203350	5450	92	149818	0,99
	8	54	1	1	48	25	0,26	208773	5324	93	151939	0,92
	7	55	1	1	48	25	0,24	214635	5306	94	152796	0,89

5.2. Impact of PV and batteries increase

The disadvantage of the off-grid system is that the surplus of electricity can't be sold to the grid. However, this excess can be absorbed by adding a battery bank. This latter is mainly used in off-grid systems in order to ensure high reliability especially if the hybrid system includes renewable resources. However, this solution has generally a great impact on the COE and increases also the O&M costs.

As clearly seen in Fig, the increase of the batteries number of an optimized PV capacity size (of 60 kW;) from 24 to 60 can reduce the excess of electricity from 50% to 14 %. Moreover, the adding of batteries presents another advantage towards stability problems due to the high renewable penetration.

It can be also noted that the hours of supply can be increased by an average of 3 hours after the batteries addition. However, the COE increased as shown in Fig.

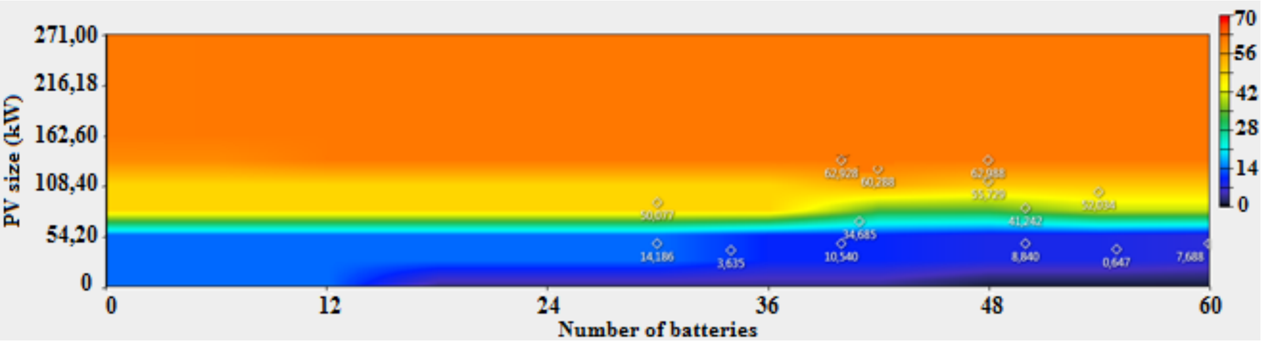


Fig.13. Sensitivity analysis of the impact of battery and PV capacity increase on the electricity excess.

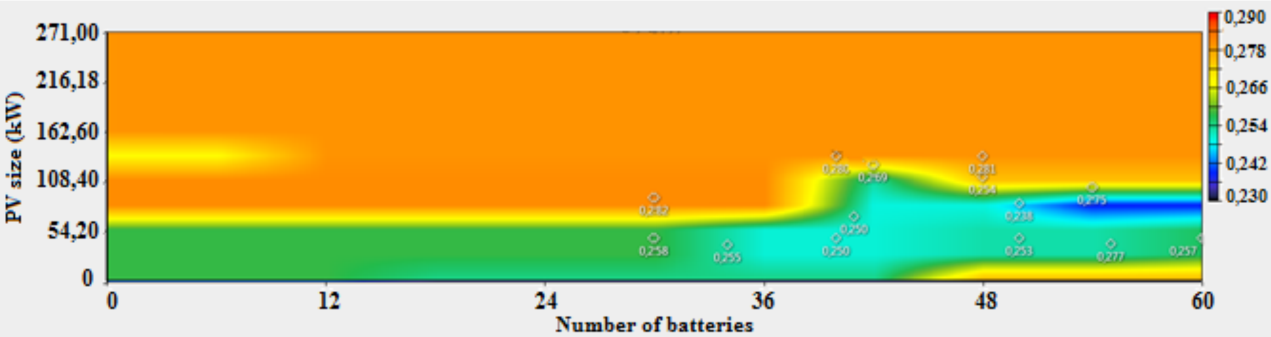


Fig.14. Sensitivity analysis of the impact of battery and PV capacity increase on the COE.

5.3. Impact of PV and batteries increase

Fig shows the result of the sensitivity analysis over changing the scaled load demand by 29% along with increasing the interest rate. As illustrated, HOMER pro sensitivity analysis shows that the combination including PV/Battery remains the optimal solution over an average load increase from 208 to 270 kWh/d. Furthermore, this solution presents the lowest COE along the changing of the load demand.

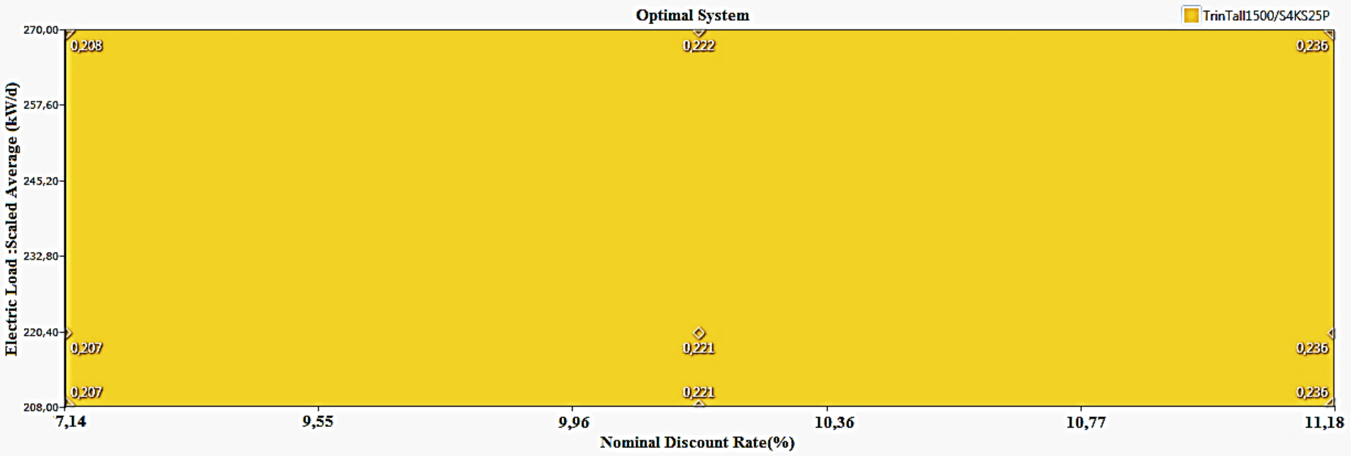


Fig.15. Impact of the load demand on the COE

It is clear that the batteries are hardly used during the period from February to April. This is due to the high demand and the relative lack of energy generated from the PV panels in this period. Thus, in this period the batteries have the minimum charging and the maximum discharging. As seen in Fig, the batteries frequency of use is generally in the range of 65 and 100% which mainly increases the lifetime of those batteries.

However, the maximum loads occur between May and August. During this period, we can observe that the batteries have the minimum charging and maximum discharging limits. Fig (c) clearly shows the high range of charging cycles. A maximum discharge of batteries can be observed in this period with a maximum discharge value of 45%.

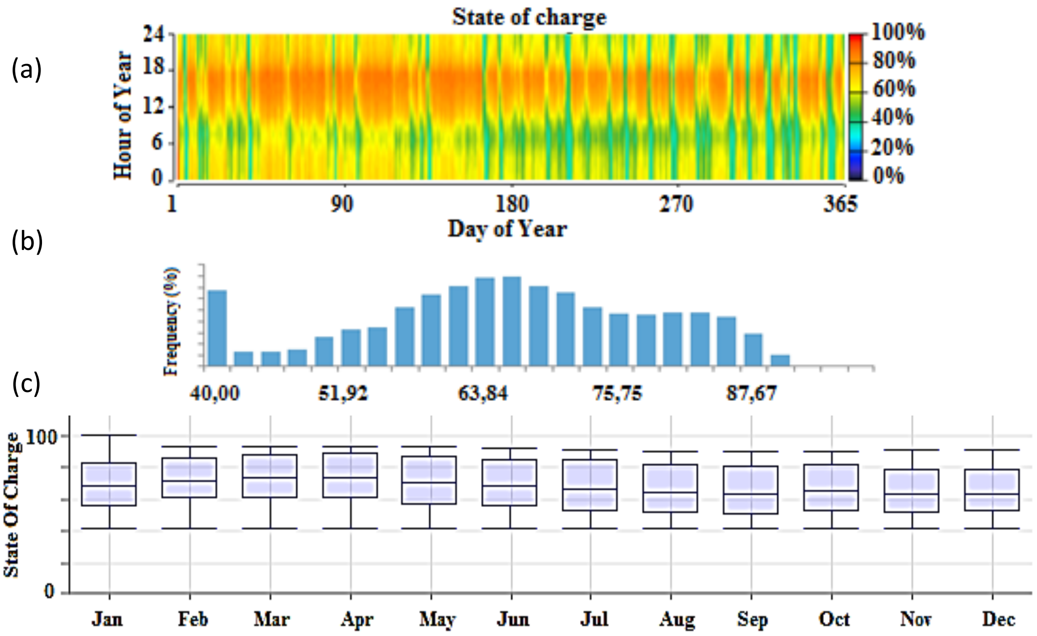


Fig.16. State of charge frequency and the battery maximum discharge.

5.4. Numerical results for the adopted hybrid system

The monthly distribution of the PV/Battery hybrid system is presented in Fig. As evidently observed from this figure, the PV is used to feed the load throughout the year with a PV participation of 100%. The

Fig(a) illustrates the hourly generated power from the optimized PV system, it can be observed that the solar irradiation remains over 12 hours in the summer season. According to the figure, the maximum power output of the PV system is 50.4 kW, mean output of 306 kW /day and a total production of 113 656 kWh/yr.

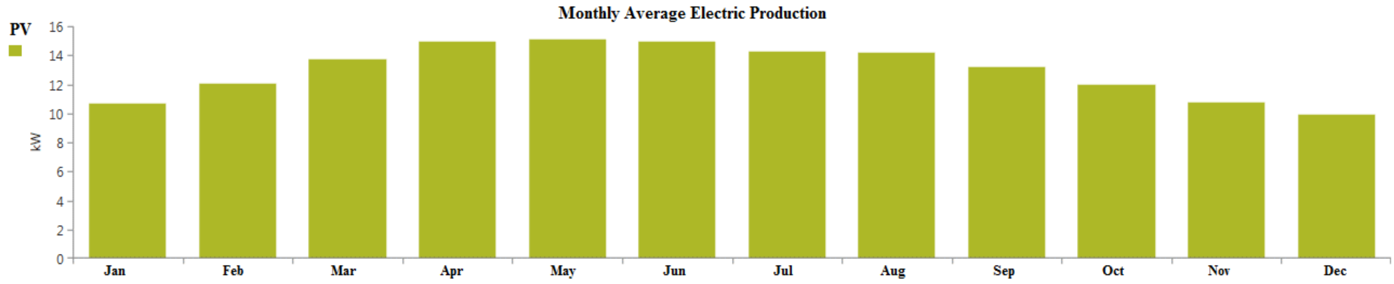


Fig.17. The monthly electric production of the PV/Wind/Battery hybrid system

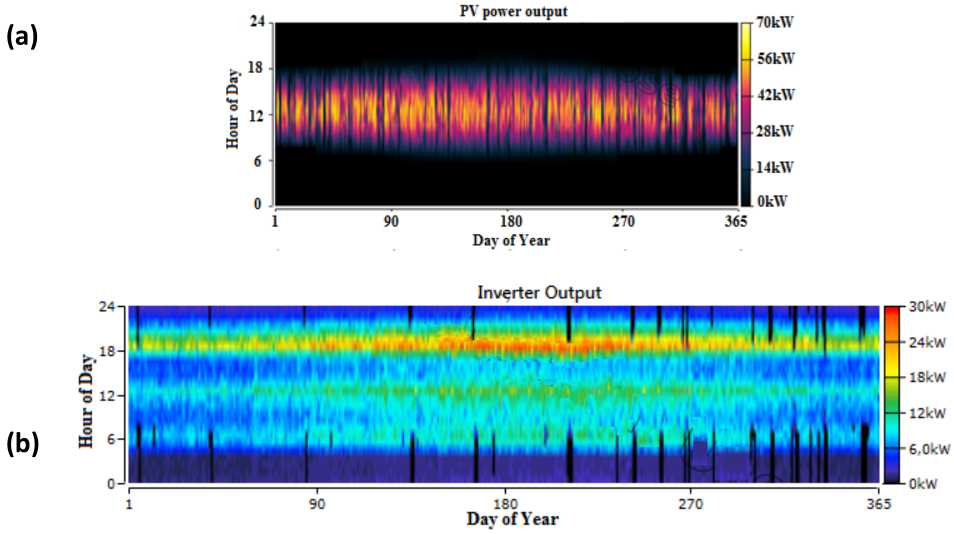


Fig.18. Dmap hybrid system diagrams

From

Fig(b), the inverter operates at its maximum in the evening with an amount of the converted power that can exceed 25kW to feed the load demand that knows its maximum in the evening. The period of [Jun to August], the transited amount of energy achieves 28 kW. The AC load demand and the total renewable energy production are presented in Fig(a-b). As seen in this figure, the energy demand increases in the summer season with a total consumption of 73 363 kWh/yr. According to Fig(c), it is clearly seen that the load demand is yearly covered with a limited unmet which does not exceed 255 kWh/yr (7.8% of the yearly load demand). Fig (d) shows that the maximum discharge of batteries has a maximum value (exceed 20%) between the period of September and December, which reveal the high demand of the stored energy. Those months reported the decreases in the numbers of solar hours. In contrast, the months from March to May reported the low maximum discharge, where the system tends to depend more on the wind and solar sources to meet the load demands.

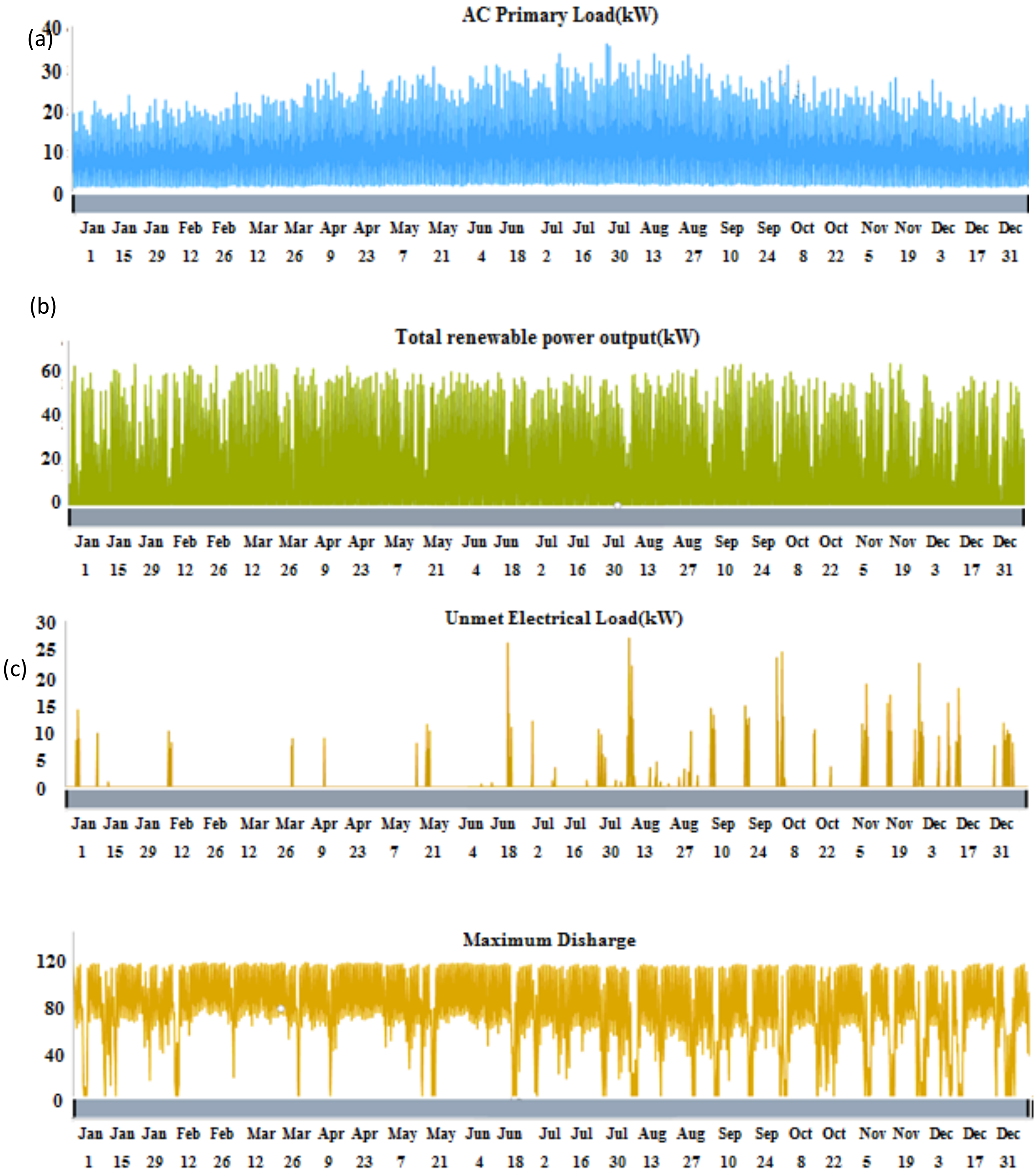


Fig.19. Load demand (a), RE output (b), unmet load(c) and the maximum discharge of batteries (d)

6. Conclusion

This study focused on the technical and economic feasibility of an autonomous hybrid system based primarily on solar and wind energy as renewable resources using HOMER pro software. The main objective of this facility is to provide electricity to a group of standalone houses in Marrakech, Morocco. the total load demand of those houses is 208 kWh/day with a daily peak of 35 kWh. Among the proposed configurations by Homer Pro, only four hybrid systems have been discussed and compared. The optimization results demonstrated that the PV/battery hybrid system is economically feasible. Meanwhile, the proposed system was sized with 66 kW of PV, 54 S4KS25P and a converter of 31 kW, which cover a TNPC of $169943 including a capital cost of $140802, the replacement cost of $ 30 265,45, and operation and maintenance cost of $ 7 515,90. In this respect, the cost of energy is 0,236$/kWh, which is the lowest compared to PV/DG/Battery, PV/WT/DG/Battery and PV/WT/DG/battery by 0,242, 0,270 and 0,274 $/kWh, respectively. The load demand (208 kW/day and 35.7 of peak) was supplied along the year. Moreover, the results of sensitivity analysis have proven that the hybrid PV/Battery system remains cost-effective for the different interest rates. In this respect, the COE ($/kW) for the interest rate ranging from 7% to 9% is 0.207, 0.236 and 0.221$/ kW respectively.

The sensitivity results showed the importance of batteries toward system efficiency. In fact, the addition of batteries reduces the excess of electricity and increases the reliability of the system. As a result, the addition of a string of 6 batteries increases the hours of the system availability by 3 hours and minimizes the electricity excess by an average of 5%. Moreover, the obtained results demonstrated that the PV/battery remains the most suitable hybrid system even if the load demand increases by 29,52 %, with a lower value of COE compared the other hybrid systems.

In term of environmental aspects, the inclusion of RF parameter has resulted in improving the system performance and minimizing the dependence on fossil fuel and harmful emissions as well. It demonstrated that the 100% of RF of the proposed system has no harmful gas emission (including CO2), which is in line with the Moroccan government vision. On the other hand, the HRES using a DG can be a competitive system. In fact, this latter has a significant reduction in the initial capital (from $140802 to $124612). However, this system could not be considered as clean, this is due to its generation of a total sum of 44,024.05 kg CO2, 123.39 kg CO, 13.471 kg UHCs, 9.16 kg PM, 90.52 kg SO2 and 1100.33 kg NOx.

7. References

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