Techno-economic Assessement of Hybrid Energy System for a Stand-Alone Load in Morocco

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Abstract- The use of renewable energy is growing faster because it is green, it enables a long term energy supply, easily available and is therefore very advantageous in remote areas. However, the renewable energy sources are intermittent. This is why, a multi-source or hybrid energy system (HES), is actually widely used because it is usually more efficient than a single-source system in terms of cost, efficiency, reliability. But the hybrid energy system (HES) presents many technical challenges especially; the choice of the optimal sizing or the best combination of sources which is the most reliable, the most economical and the most sustainable.

The purpose of this paper is to investigate the techno-economical feasibility of PV/WindTurbine/Battery hybrid system feeding a domestic house in seven geographical locations in Morocco. The HOMER software is used in order to compare the hybrid system cost, the cost of a PV/Battery system and the cost of a wind/battery system. The aim of this study is to assess different configurations of hybrid system in order to further promote renewable energy generation in Morocco by providing a road map for those who want to design and implement successfully renewable energy systems in different locations in Morocco. In fact, the other studies investigated the most economical hybrid system in only one location in Morocco.

The simulation results from HOMER show that under different climatic conditions, the PV/Battery system is the most economically feasible configuration for powering a stand-alone domestic load in the seven selected geographical locations in Morocco.

Also, a Pearson Correlation based on SPSS software was used in order to determine if there is a relationship between the cost of the PV/Battery system and the solar radiation in each city. The results show that the level and standard deviation of solar radiation impact the system cost..

Keywords Hybrid energy system, Wind Turbine, PV, Battery, HOMER, Pearson correlation.

1. Introduction

The use of renewable energy is growing faster. Among them, wind energy and solar energy have made rapid and significant development over the last ten years [1]. And this, because they enable a long-term energy supply without adverse impact on climate, they are easily available [2-10]and are therefore very advantageous in remote areas where the cost of extension of the electric power grid as well as that of fuel supply are high [11]. But, in order to further promote the use of renewable energy sources, the intermittent and irregular nature of their production needs to be overcome [12] [13]. The solution to be retained is the coupling between several sources, for example wind turbines and photovoltaic panels [14-16].This coupling, called a multi-source or hybrid energy system (HES) which consists of two or more sources of energy production of which at least one is renewable [17-18] , is more efficient than a single-source system in terms of cost, efficiency, reliability and has therefore become increasingly attractive and widely used as an alternative source for fossil fuels [19]. The hybrid energy system may or may not be connected to the power grid. But generally it is independent of large centralized power grids and is used in remote rural areas

[20]. The off-grid or stand-alone system requires a high capacity of production and storage in order to ensure the load supply. A grid connected system requires smaller storage capacity and can supply both the load and the grid but it is essential to control voltage, frequency and harmonics with electronic power converters.
Besides energy sources, we can find in a hybrid renewable energy system, a storage system, converters and inverters, fillers and load management control or supervision system [21]. All these components can be connected in different architectures: DC architecture where the different sources are connected to DC bus as shown in Fig.1 , AC architecture where the different sources are connected to AC as shown in the Fig. 2 and the DC/AC bus as shown in the Fig. 3 below [22-29].

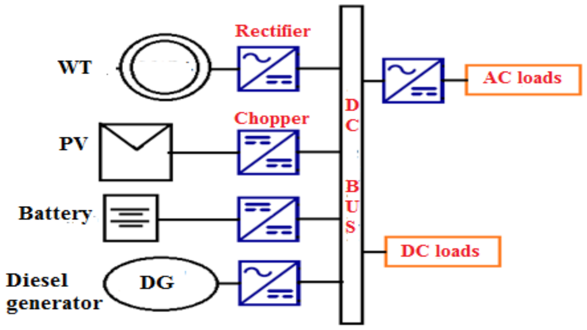

Figure 1. Architecture DC of Hybrid energy system

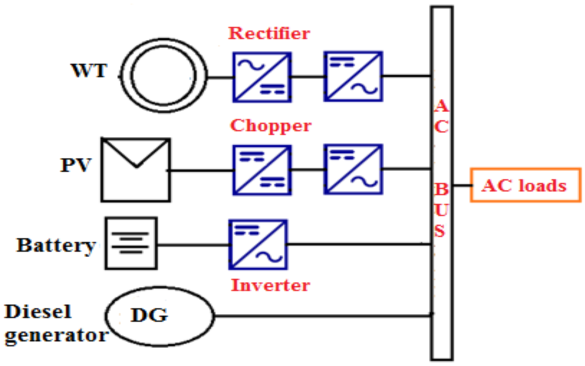

Figure 2. Architecture AC of Hybrid energy system

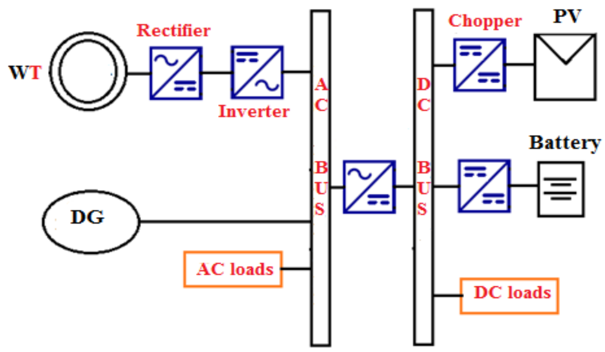

Figure 3. Architecture AC/DC of Hybrid energy system

The following hybrid systems are distinguished: PV / diesel, wind / diesel, PV / wind / diesel, PV / fuel cell, wind turbine / fuel cell, PV / wind turbine / fuel cell, etc.
According to the literature, about 90% of the studies deal with the design and economic aspect of HES. The papers [30] and [31] deal with the optimization of the design of the PV / Diesel system. The optimization of the structure of the Wind / Diesel system is treated in the papers [32-34]. The papers [35-36] present an optimization of the PV / Wind / Diesel system based on loss load probability, a minimum system cost, minimum climate-damaging emissions and a minimum unmet load. The works [37-38] concern the hybrid PV / Wind / Storage system optimization according to various criteria: loss load probability, minimum cost of kilowatt-hour produced, or a combination of several optimization criteria such as minimizing loss power probability, unused energy produced and the cost of kilowatt-hours produced.
However, a limited number of works deals with the control of the HES. Chedid and Rahman [30] presented the design of a controller for a stand-alone system or connected to the grid. The control device determines the energy available by each component of the system and the developed model can give the production cost, the unsatisfied energies, the losses of load and the battery discharge. In addition to its various benefits, hybrid energy system (HES) presents many technical challenges. Indeed, it is essential to choose for a given site, the best combination of sources that is the most reliable, the most economical and the most sustainable. Graphic construction methods, linear programming, and probabilistic approach are few examples of optimization techniques that have been developed for techno-economically optimum hybrid renewable energy system for both types [39].
An optimal sizing of the hybrid system is based on numerous parameters such as technical parameters and economic parameters. The technical parameters criteria as system efficiency, environmental Objectives (Reduction in the emissions of harmful substances to the environment) and reliability to fulfill the load demand (loss load probability method, the loss power probability method (LPSP) and the least squares method [40]. The loss power probability (LPSP) can be defined as the long-term average fraction of the total load not fed by the autonomous system. A zero value probability means that the demand for the loads will be satisfied while a probability equal to one means that the demand will never be satisfied [41]. For a power generation system, the optimization based on the least squares approach aims to minimize the sum of the squares of the deviation of the available power from that required.
The economic criteria for optimal sizing include minimization of per unit cost of energy (levelized cost of energy), total net present cost (TNPC) and other cost-linked optimization.
There are several simulation tools for optimizing a hybrid system. HOMER, found to be the most widely used for the problem of cost-effectiveness assessment of hybrid renewable energy systems [42].
HOMER (Hybrid Optimization Model for Electric Renewable) developed by National Renewable Energy Laboratory (NREL), is a renewable-energy-based system

optimization tool that facilitates the design of electric power system either for off grid or grid-connected application. HOMER sizes up the system specifications (load profile, wind resources, solar resources, diesel price, system control parameter, constraint parameter, and technical and economics details) and through simulation, it presents the optimal configuration based on the lowest NPC.

The NPC or total cost includes the initial cost, the maintenance cost, and the cost of renewing the system components.

The initial cost includes the purchase cost of the wind turbine, the photovoltaic panels, the batteries, the charge controller and the inverter, and the cost of installation, wiring, control and protection against lightning and over current of these components. The latter cost, also known as an ancillary cost (balance of system cost (BOS), is generally equal to the sum of 25% of the wind turbine cost and 50% of the PV module cost.

The annual maintenance cost is generally the sum of 5% of the wind turbine purchase price and 1% of the PV module purchase price. The annual discount rate for these values is generally equal to 8% [39].

The components renewing cost is the cost of replacing the battery and the inverter over the system lifetime.

In order to evaluate the best configuration obtained in terms of its cost, we use HOMER software to compare between PV/WT/Battery hybrid system cost, the cost of a PV/Battery system and the cost of a wind/battery system for seven geographical locations in Morocco which are: the northeast region, the northwest region, the north central region, the west central region, the central region, the south east and the south regions. These regions have different climate condition and this study will enable to show the feasible renewable system in all Morocco.

2. System Modeling

2.1. PV Model

A photovoltaic system is composed of a number of solar cells in series/parallel to generate power from solar irradiation. This power is determined from the following equation (1) [40, 41]:

$$P_{pv} = P_{pv-rated} \times \left({}^{G}/_{G_{ref}} \right) \times [1 + K_T(T_c - T_{ref})] \quad (1)$$

Where P_{pv} is the power output of the PV cell, $P_{pv-rated}$ is the PV rated power at reference condition, G is solar radiation (W/m2), G_{ref} is the solar radiation at standard temperature condition (G_{ref}=1000 W/m2), T_{ref} is cell temperature at reference conditions ($T_{ref} = 25°C$), K_T is temperature coefficient of the PV module. The cell temperature is $T_c = T_{amb} + 0.0256 \times G$, where T_{amb} is ambient temperature.

The annual energy output of solar PV system is estimated as in the following equation (2):

$$E_{pv-out} = \sum_{i=1}^{8760} P_{pv}(i) \quad (2)$$

2.2. Wind Turbine Model

A wind turbine is an energy system that produces electrical energy from the mechanical energy obtained from the wind energy.

There are different models for wind turbine. We can distinguish between models based on wind power equations and models based on power curve of the wind turbine.

The first model is obtained from the following formulas presented in the equation (3) and equation (4). The equation (3) enables to calculate the mechanical power over an area A of wind turbine rotor while the equation (4) presents the formula for calculating the wind turbine electrical power [41] [42].

$$P_m = \frac{1}{2} \times \rho \times A \times V^3 \quad (3)$$

$$P_w = \frac{1}{2} \times \rho \times C_p \times A \times V^3 \times 10^{-3} \quad (4)$$

Where ρ is the air density (1.225 kg/m3), and V the wind speed (m/s) and C_p is the power coefficient.

For the second type of models, the equation (5) below presents one of them called model based on linear power curve. However, this model lacks of precision because the power curve is rarely linear.

$$\begin{aligned} P_w &= 0 \ \text{pour } v < v_{ci} \\ P_w &= P_{rated} \frac{v - v_{ci}}{v_n - v_{ci}} \ \text{pour } v_{ci} < v < v_n \\ P_w &= P_{rated} \ \text{pour } v_n \le v \le v_{co} \\ P_w &= 0 \ \text{pour } v > v_{co} \end{aligned} \quad (5)$$

Where v_{ci} is the cut in wind speed, v_n is the nominal wind speed, P_{rated} is the rated power of wind turbine and v_{co} is the cut out wind speed.

2.3. Battery Model

Because renewable energy is intermittent in nature and generally not available in the consumption's peak hours, it is necessary to store the excess of energy produced in order to use it later. There are several energy storage systems. The most popular and the most used are the Batteries.

For modeling a battery, it is essential to determine its capacity (kW) and this is by using the most popular formula in the equation (6) bellow:

$$C_b = (E_L \times AD)/(\eta_{inv} \times \eta_{Batt} \times DOD) \quad (6)$$

Where E_L is the average daily load energy (kWh/day), AD is the battery's days of autonomy (typically 3-5 days), DOD is battery depth of discharge (80%), while η_{inv} (95%) and η_{Batt} (85%) represent the inverter and battery efficiency respectively.

3. PV/ Wind/Battery Hybrid System Characteristics

3.1. System Architecture

In this study, the hybrid energy system chosen is an off-grid system which contains alternative electric load, PV, wind turbine, battery, and inverter (Fig. 4). We have chosen this architecture because it is more efficient than other configurations. In fact, it presents higher overall efficiency, smaller sizes of the power conditioning unit while keeping a high level of energy availability [21].

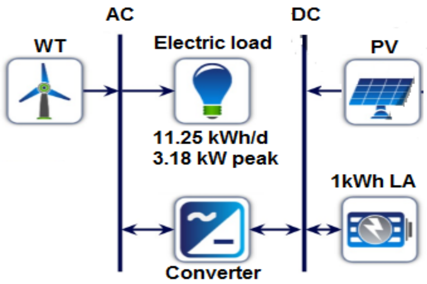

Figure 4. Hybrid energy system architecture

3.2. Technical And Economic Data Of The System Components

The technical and economic parameters for the PV, Wind turbine, battery and inverter are represented in Table 1 and were taken from HOMER database because there is not an available database for the costs of hybrid system components. The currency of all costs is the American dollar ($). As shown, a Generic Wind turbine 3 kW, a Generic Flat Plate PV 1 kW, a Generic Lead acid 1 kWh and a Generic inverter 1kW were considered. The only component which requires an operating and maintenance cost is the wind turbine and this is because it consist of mechanical and electrical components and also components in rotation. The choice of theses components' sizes was based on data available in literature for stand-alone houses.

Table 1. Technical and economic data of the hybrid system components

Component	Type	Rated capacity	Life-time	Initial cost ($)	Operating cost ($/year)
PV	Generic Flat Plate	1Kw	25	2500	10
Wind turbine	Generic	3Kw	20	18.000	180
Battery	Generic lead acid	1 kWh	10	300	10
Inverter	Generic	1 kW	15	300	00

4. PV/Wind turbine/battery System Components

4.1. Implantation sites

In this study, seven geographical locations in Morocco were selected. The northeast region (Nador city), the northwest region (Tangier city), the north central region (Fez and Khenifra cities), the west central (Essaouira city), thecentral region (Ouarzazate city), the south east (Figuig city) and the south region (Tantan city).

4.2. Load Demand

The first step in designing is to find out the total power of all loads that need to be supplied by the hybrid system. In this study, an off-grid domestic load has been considered for energy provision in each of the selected cities. The domestic house is supposed to be equipped with required household appliances (refrigerator, lighting, computers, television, washing machine and air conditioner). Generally in Morocco, the peak hours of electricity consumption are typically between 6 p.m and 11 p.m. also, there is no centralized air-conditioning.

The yearly load profile is represented in the Fig. 5. As shown, electricity consumption is higher in July, August, December and January because air conditioners are used in these months. Also, the total monthly load profile is shown in the Fig. 6, where we can observe that the consumption peak is in summer and winter due to use of air conditioning.

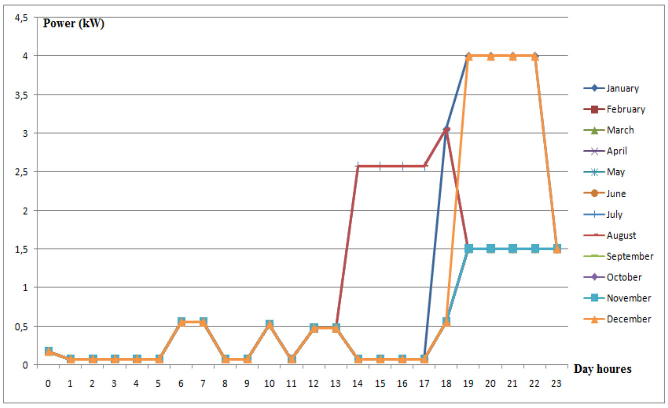

Figure 5. Yearly load profile of an off-grid domestic house

4.3. Resource Assessment
4.3.1. Solar energy
The monthly solar insolation data were taken from the NASA database available in Retscreen software. The solar radiation and the clearness index for the eight cities are shown in the Fig. 7, Fig. 8, Fig. 9 and the Fig. 10. The daily solar radiation is expressed in kWh/m2.

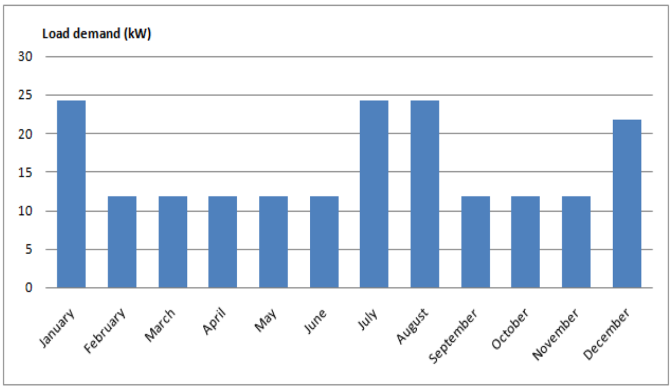

Figure 6. Total monthly load profile of an off-grid domestic house

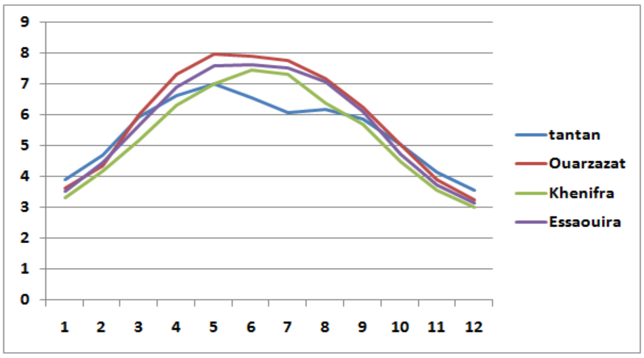

Figure 7. Solar radiation for the first four cities

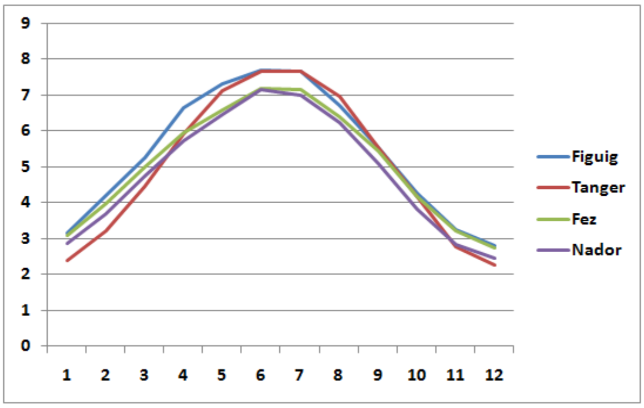

Figure 8. Solar radiation for the second four cities

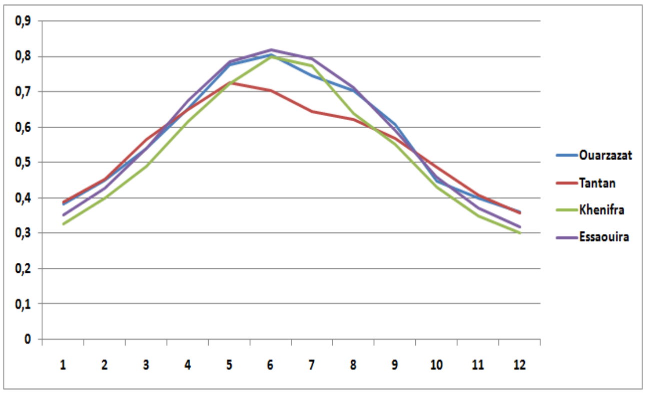

Figure 9. Clearness index for the first four cities

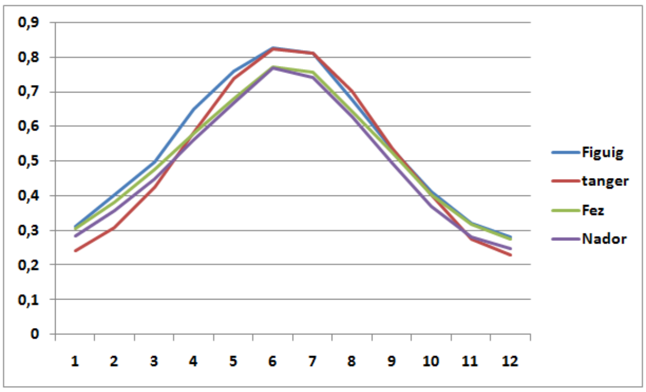

Figure 10. Clearness index for the second four cities

4.3.2. Wind energy

The monthly average wind resource data were collected from the NASA database available in Retscreen software.

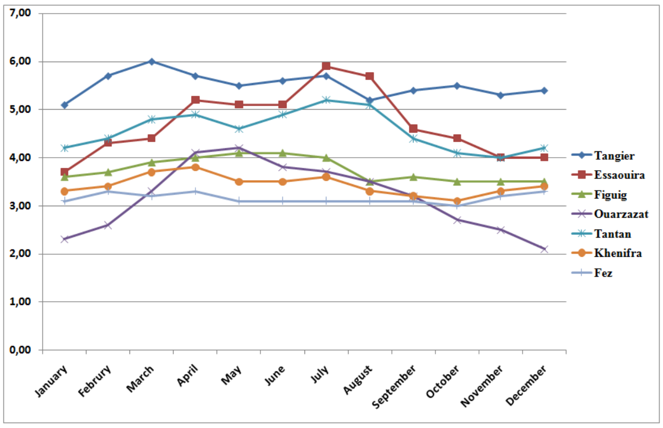

Figure 11. Wind speed for the eight cities.

The monthly average wind speed for the eight cities is shown in the Fig. 11 above.

5. Results and discussion

The Homer simulation results are illustrated in the Table 2 below. The results present the NPC of all the feasible system configurations (PV/WindTurbine/Battery, PV/Battery and WindTurbine/Battery) considered for implementation of hybrid power system in the selected cities. The table also shows the number of components selected for all the feasible configuration.

From the NPC results, we can observe that for all selected cities, the stand-alone PV/battery system has the lowest NPC among the two others configurations: PV/WindTurbine/Battery and WindTurbine/Battery. This is because Morocco is a sunny country with an unsatisfactory wind speed so wind system is not the best option. These findings meet the results of the paper [43] where it was found that the PV system is more economically feasible solution for Marrakech city in Morocco. Also, a wind system presents an initial cost higher that PV system and a maintenance cost is required contrarily to PV system. Khenifra city present the lowest NPC for the optimal solution (62,363 $) followed by Tantan city (78,016 $) and Essaouira city (82,695 $).

In order to investigate the relationship between NPC and the level of solar radiation, we use a descriptive method (Pearson correlation) where the variables are NPC value, annual mean value of solar radiation of each city and the standard deviation of solar radiation. The data of these variables which is represented in the Table 3, was analysed using SPSS software.the Table 4 shows the results of this analysis. These results show that there is a correlation between NPC and the standard deviation of solar radiation because the Pearson correlation is equal to 0.672 (there is a correlation if the Pearson correlation is between 0.5 and 1). That is to say, if the standard deviation increases, the NPC value increases. So, we can dedude that if the standard deviation of the yearly solar radiation decreases, the NPC decreases.

Also, we admit that there is a negative correlation between the NPC and the mean value of solar radiation because the

Perason correlation is equal to -0.542. That is to say, if the mean value increases, the NPC decreases. So, as we can observe from the table 3, the cities which present the lowest NPC for the optimal solution (Khenifra, Tantan, Essaouira and Ouarzazat), have a lowest standard deviation and highest mean value of yearly solar radiation. We can also observe that even if Tangier city present a yearly solar radiation mean value bigger than Nador city, it present a higher NPC for optimal solution. This is because Tangier city present a higher standard deviation compared to Nador city.

Table 2. Homer economic results of different configuration for the eight cities

Cities		Number of PV	Number of WT	Number of LA	Number of converter	NPC	Operting cost	Initial cost
Nador	Optimal solution	16.9	0	77	5.6	97,463	2,349	67,101
	solution pv/wt	16.5	1	71	5	114,976	2,547	82,050
	solution wt	0	12	184	11.2	399,639	9,675	274,563
Tangier	Optimal solution	20	0	69	5.53	100,306	2,157	72,418
	solution pv/wt	18.9	1	69	5.31	120,095	2,518	87,544
	solution wt		4	91	6.26	153,761	4,068	101,177
Fez	Optimal solution	15.2		78	5.65	93,467	2,359	62,972
	solution pv/wt	14.7	1	78	6.83	115,510	2,737	80,123
	solution wt	0						
Essaouira	Optimal solution	12.6	0	72	5.33	82,695	2,165	54,712
	solution pv/wt	12.9	1	65	5		2,345	71,250
	solution wt		12	68	8.03	321,986	6,434	238,810
Ouarzazat	Optimal solution	12.5		76	5.74	85,262	2,278	55,815
	solution pv/wt	11.3	1	81	5.31	107,909	2,774	72,044
	solution wt	0						
Khenifra	Optimal solution	9.69	0	52	3.3	61,363	1,589	40,819
	solution pv/wt	9.5	1	49	3.54	81,498	1,855	57,513
	solution wt		13	112	6.68	373,241	8,017	269,604
Figuig	Optimal solution	14.6		79	5.65	92,790	2,382	62,002
	solution pv/wt	13.8	1	76	6.02	111,544	2,667	77,071
	solution wt	0	8	204	7.06	319,809	8,702	207,319
Tantan	Optimal solution	10.4		74	5.13	78,016	2,196	49,628
	solution pv/wt	9	1	68	5.8	93,604	2,395	62,640
	solution wt	0	6	108	16.7	214,845	5,370	145,422

We can also observe from the Table 2, that the hybrid system PV/WindTurbine/Battery enables to minimize the number of the required batteries compared to PV/ battery or WindTurbien/Battery. This is very advantageous in terms of protecting the environment. In fact, many researches point out the environmental impacts of batteries which are severe and sobring.

Table 3. Standard deviation and annual mean value of solar radiation of the eight cities

Cities	Tantan	Ouarzazat	Khenifra	Essaouira	Figuig	Tangier	Fez	Nador
Standard deviation	1,15	1,77	1,59	1,68	1,82	2,06	1,60	1,68
Mean value	5,46	5,87	5,31	5,66	5,36	5,02	5,06	4,84

Table 4. Pearson correlation between NPC, mean value and standard deviation of the solar radiation of the eight cities

		Mean	NPC	Standard deviation
Mean	Correlation de Pearson	1	-0.542	-0.179
	Sig. (bilaterale)		0.165	0.672
NPC	Correlation de Pearson	-0.542	1	0.628
	Sig. (bilaterale)	0.165		0.095
Standard deviation	Correlation de Pearson	-0.179	0.628	1
	Sig. (bilaterale)	0.672	0.095	

6. Conclusion

This paper presented a techno-economic study in order to assess the feasibility of a hybrid renewable system for feeding a stand-alone domestic load located in eight cities in different Moroccan regions. This study, first of its kind, to consider all locations in Morocco that represent different climate conditions. The simulation results showed that for all the Moroccan regions, the PV/Battery system is the most economically feasible configuration for powering a stand-alone domestic load in the seven selected geographical locations. And this is because Morocco is a sunny country with an inadequate wind speed for using wind turbines. Also, we observed that by using a hybrid system, the number of required batteries decreases which is very advantageous in terms of protecting the environment.

In the other hand, the Pearson correlation through SPSS software was used in order to determine the relationship between NPC of PV/Battery system for the eight cities and the annual mean value and the standard deviation of the solar radiation. That is to say, derterming if the yearly mean value and the standard deviation of solar radiation impact the NPC. The results showed a positive correlation between the NPC and the standard deviation and showed a negative correlation between the NPC and the annual mean value. That is to say, if the standard deviation increases NPC increases and if the annual mean value increases, NPC decreases. So, the cities which represent the lowest NPC for the PV/Battery system are those having the highest solar radiation mean value and lowest solar radiation standard deviation.

Abbreviations

PV Photovoltaic
HES Hybrid energy system
WT Wind turbine
NASA National aeronautics and space administration
Homer Hybrid Optimization Model for Electric Renewable
BOS Balance of system cost
LPSP Loss power probability method
TNPC Total net present cost
SPSS Statistical package for the social sciences
NPC Net present cost
AD Autonomy days
DOD Battery depth of discharge
LA Lead acid
Sig Significance

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