Potential assessment of hybrid PV-Wind systems for household applications in rural areas: Case study of Morocco

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Abstract. Proper combination of wind and solar photovoltaic (PV) systems can result in optimal configurations that maximise the Annual Energy Production (AEP) while being economically attractive. This paper presents a typical approach to the design of a hybrid PV-Wind system for household applications in rural areas. Based on the capacity factor of the hybrid system components, a design methodology was developed to maximize the AEP and to minimise the investment cost. The electricity generated will be used to meet the load requirements of the user while the potential excess of the power will be stored in the battery system or dissipated in a dump resistor. This design methodology is suitable for household applications presenting limitations in the available roof area where the PV panels will be installed. Implementing the PV panels on the house's roof intends to eliminate the shadow over the panels, to avoid the material damage, and to prevent vandalism. Four different cities were selected to conduct the study. These are Tetouan, Essaouira, Dakhla, and Ouarzazate. For the present design approach, the installed cost of the hybrid system includes the price of the storage system.

1 Introduction

Hybrid PV-Wind Systems (HPWSs) are becoming an attractive energy sources that can be used for decentralized electrification in remote areas. Several methods and optimisation approaches have been developed for the design of HPWSs in a cost effective way. Erdinc and Uzunoglu have presented a summary of several sizing approaches that have been applied for the design of hybrid renewable energy systems [1]. Their literature overview includes methods based on the commercially available software (such as HOMER and HYBRID2). These tools are based on optimisation methods such as Genetic Algorithm (GA), Simulated Annealing (SA), Linear Programming, Particle Swarm Optimisation (PSO), Neutral Network, and iterative and probabilistic approaches. Predominant constraint in these methods is that the required PV power calculated does not take into consideration the available surface on the user's roof. The design methodology used in this paper is based on the Capacity Factor (CF) which is defined as the ratio of the actual annual energy production to the theoretical annual energy production. The optimum percentage of the hybrid system components will be determined such that the HPWS meets the load requirements while being able to adequately exploit the available resources of the given locations. The potential excess of the power will be stored in the battery bank or dissipated in a dump resistor (water heater or heating system of the house). The analysis in this paper is based on the following steps: at first, site-specific wind conditions of the selected locations was performed. Then, typical daily electricity consumption of a Moroccan household as well as the models used for the calculation of PV and wind systems are presented. In a third part, the hybrid system sizing procedure is given. Finally, the results are presented and discussed.

2 Wind and solar potential assessment

To ensure an appropriate level of efficiency and reliability for the HPWS design, wind and solar energy potential must be evaluated for the selected sites. Figure 1 shows the geographical locations of the sites that were selected for the analysis.
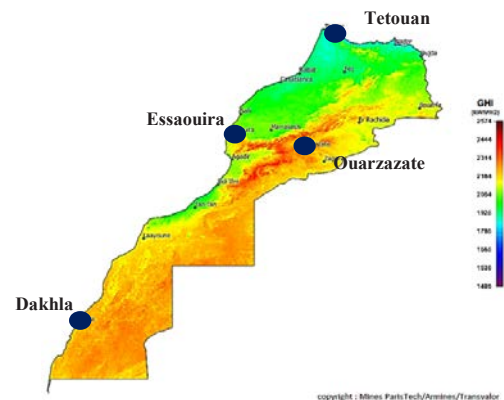

Fig. 1. Geographical location of the studied locations

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2.1 Wind potential assessment

Various mathematical tools have been used for the analysis of wind speed data. A convenient mathematical distribution function that has been found to fit well with wind data is the Weibull probability density function, whose probability density match in most of the times the actual wind speed measurements [2]. This function is mainly described using two parameters: the shape parameter, k, and the scale parameter, c. The general form of the Weibull distribution, for a specific wind speed, V, is given by the following equation [3]:

$$f(V) = \frac{k}{c} \times \left(\frac{V}{c}\right)^{k-1} \times e^{-\left(\frac{V}{c}\right)^k} \quad (1)$$

The value of the shape parameter varies usually between 1.5 and 3. If the values of these parameters, at the anemometer height, z_a, are c_a and k_a, then their corresponding values, at a higher level z, can be determined using the following equations [4].

$$C_z = c_a \times \left(\frac{z}{z_a}\right)^n \quad (2)$$

$$k_z = \frac{k_a \times \left[1 - 0.088 \ln\left(\frac{z_a}{10}\right)\right]}{\left[1 - 0.088 \ln\left(\frac{z}{10}\right)\right]} \quad (3)$$

The exponent, n, is given as:

$$n = \frac{[0.37 - 0.088 \ln c_a]}{\left[1 - 0.088 \ln\left(\frac{z_a}{10}\right)\right]} \quad (4)$$

Different methods have been developed to estimate the Weibull distribution parameters. The most widely used are the method of moments which was selected for wind data analysis in this study. Based on this method, the following equations give the values of the Weibull parameters [3]:

$$k = \left(\frac{\sigma}{V_{ave}}\right)^{-1.086} \quad (5)$$

$$c = \frac{V_{ave}}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (6)$$

Where Γ is the gamma function, which is given by [4]:

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt \quad (7)$$

To estimate wind speeds at various elevations, a vertical wind profile was used. The common power law that can be used to obtain the extrapolated values of wind speed at different heights is given by the following equation [4]:

$$V_{z2} = V_{z1} \times \left(\frac{z_2}{z_1}\right)^m \quad (8)$$

Where V_{z1} is the wind speed at the measurement height, usually taken as 10 m. V_{z2} is the height at which the wind speed estimation is required, and the parameter, m, is the power law exponent of the wind speed. The power law exponent, also called roughness coefficient, varies according to the roughness of the terrain. If there is no specific information, the International Electrotechnical Commission (IEC) standard for the design of small wind turbines (IEC 61400-2) recommends using a roughness coefficient of 0.2 [5]. This value corresponds to a roughness length of approximately 0.10 m (taking into account agricultural land with some houses and 8 m high hedges with spacing of approximately 1250 m).

The wind power density function is a parameter that gives the distribution of wind energy at different wind speeds. It is well known that the power of the wind that flows at speed, V, through a blade sweep area, A, increases as the cube of its velocity and is given by the following equation [4]:

$$P(V) = \frac{1}{2} \times \rho \times A \times V^3 \quad (9)$$

The parameter ρ is the air density which is taken as 1.225 Kg/m^3. The parameter A represents the wind turbine rotor swept area. Wind power density per unit area for a specific region (based on the Weibull probability density function) can be determined using the following equation [4]:

$$P = \int_0^\infty P(V) f(v) \, dv = \frac{1}{2} \times \rho \times c^3 \times \Gamma\left(1 + \frac{3}{k}\right) \quad (10)$$

For wind data analysis, a time series of daily measured wind speeds, recorded over a period of 20 years, were used for the statistical analysis of the wind speed and the wind power density. These wind data are given by the climatic data center of the National Oceanic and Atmospheric Administration (NOAA) [6]. Climate data provided by this center constitutes a reliable source for wind energy community, especially for pre-feasibility study of wind farm projects development. Table 1 summarizes the results of the wind potential assessment.

Table 1. Annual mean wind speed and Weibull distribution parameters of the four studied locations

Station	V_{ave} (m/s) 10 m	c (m/s)	k	V_{ave} (m/s) 24 m	Power density (W/m) 10 m
Tetouan	6.4	7.27	1.96	7.62	318
Essaouira	5.6	6.31	1.85	6.67	223
Dakhla	6.0	6.75	2.22	7.14	227
Ouarzazate	4.0	4.51	1.72	4.77	90

2.2 Solar potential assessment

The potential of solar energy is mainly determined by the solar irradiation which is defined as the amount of energy that reaches the ground surface over a stated

period of time, and expressed as Wh/m .day. The solar irradiation was assessed using the Photovoltaic Geographical Information System (PVGIS) [7]. This geographical information system, which has been developed by the Joint Research Centre (JRC), is the most commonly used GIS-based web application for estimating the performance of PV generation systems. Table 2 shows the annual average daily irradiation, I_{rr}, on an optimum tilted surface for the four studied locations (In°). The inclination of the solar PV panels is chosen such that power extraction from solar irradiations will be maximized. The solar panels will be mounted at an angle to point directly at the sun. The PV panels will be also oriented towards the south with a zero azimuth angle. The south facing modules increases the irradiance falling on the panels compared to the other orientations.

Table 2. Annual average solar irradiation for the four studied stations

	Tetouan In°(31°)	Essaouira In°(30°)	Dakhla In°(25°)	Ouarzazate In°(31°)
	I_{rr} (Kwh/m .day)			
Average	5.430	6.720	6.540	6.690

3 Daily electricity consumption

The residential electricity consumption was determined based on the needs of the household appliances that include water pumping systems for irrigation. The load demand was assessed using the following steps:

a) Determination of typical household appliances in rural areas: this is based on the acquisition rate of household appliances. This is defined as the ratio of the number of households owning the appliance at the total number of households involved in the survey. This step is based on the results of the national survey of households' standard of living (HCP 2014) which is the latest available report on the household's standard of living in Morocco.

b) Determination of the daily electricity consumption of a typical household: the dimensioning of the HPWS is strongly dependent on the overall daily energy consumption of the selected appliances. Based on this statistical approach, the daily electricity consumption of a typical Moroccan household in rural areas is 103.637 kWh/day. This value is relatively high due to the fact that the needs of the majority of the pumping systems in Morocco have an average Total Dynamic Head (THD) of 80 m with a daily water flow of 300 m³. This need corresponds to the water required to irrigate 5 hectares of agricultural area in a typical farm.

4 Wind/PV power assessment and capacity factors

4.1 Wind power assessment and capacity factor

Based on a typical household's daily electricity consumption of 103.637 kWh, equation (11) gives the required electrical power of the wind power system [8].

$$P_{wa} = \frac{E_{Load}}{C_{ptot} \times 24hour} \qquad (11)$$

C_{ptot} is the total efficiency of the wind turbine conversion system which is taken as 40% [8]. This total efficiency includes the efficiency of the drive train, the generator (assuming an overall transmission efficiency of 90%), and the aerodynamic losses. From equation (11), an electrical power generation of 10.8 kW is deduced. This power represents the required power output to meet all the load requirements when the wind generation system is used alone. This is because the power calculation given above assumes the wind power system will meet all the user's daily needs.

Productivity of the wind power system is usually evaluated using a quantity known as capacity factor:

$$AEP_w = C_{fw} \times 8760 \times P_{rated} \qquad (12)$$

P_{rated} is the rated power of the wind turbine. The capacity factor of the wind power system is determined using equation (13) [9]. This model describes the capacity factor as a function of the Weibull distribution and the wind turbine parameters.

$$C_{fw} = \frac{e^{\left[-\left(\frac{V_c}{c}\right)^k\right]} - e^{\left[-\left(\frac{V_r}{c}\right)^k\right]}}{\left(\frac{V_r}{c}\right)^k - \left(\frac{V_c}{c}\right)^k} - e^{\left[-\left(\frac{V_f}{c}\right)^k\right]} \qquad (13)$$

Parameters V_c, V_r and V_f are respectively the cut-in wind speed, the rated wind speed, and the cut-out wind speed of the wind turbine. Typical values of 3 m/s for V_c, 12.5 m/s for V_r, and 25 m/s V_f were used. The wind energy system will be assessed for a hub height of 24 m. This typical tower height is usually proposed by the wind turbine manufacturers for commercially available small wind turbines.

4.2 PV power assessment and capacity factor

The required power output of the PV generation system is obtained by the following mathematical equation:

$$P_{va} = \frac{E_{Load}}{I_{rr} \times \eta_{tot}} \qquad (14)$$

Where I_{rr} is the annual average daily irradiation of the geographical location and η is the total efficiency of the PV system. By considering the PV panels reduction factor and the efficiencies of the cables, the controller, the battery, and the inverter, the total system efficiency is found to be 60% [10]. With an annual average daily irradiation of 6.34 kwh/m .day (average value of the four studied stations), a required power of 27.24 kW_p is deduced for the PV generation system. Similarly, the calculated power represents the required power output to meet all the load requirements when the PV generation system is used alone. The capacity factor of PV generation systems is defined as the ratio of the actual annual energy production to the annual energy the PV system would produce if it operates at its full rated

power. This can be determined using the following equation:

$$C_{fv} = \frac{AEP_v}{8760 \times P_{rated}} = \frac{H_{tot} \times PR}{8760 \times P_{rated}} \tag{15}$$

AEP_v is the actual annual energy production of the PV generation system. H_{tot} is the total amount of solar energy received by the PV panels in one year which is given by:

$$H_{tot} = 365 \times (I_{rr} \times S_v \times \eta_P) \tag{16}$$

S_v is the total area covered by the solar PV panels (in m) and η_p is the PV panel efficiency. P_{rated} is the rated power of the PV panel (peak power). The parameter PR is the performance ratio which defines the total losses in the system (optical losses, array losses, and system losses). A typical value of 80% was used for PR in the present analysis [11].

5 Optimal sizing methodology

The objective function of this nonlinear optimization problem is defined as the ratio of initial investment cost to the total AEP of the hybrid system which is multiplied by the unit price of kilowatt hour (kWh) of electricity. The flow chart given in figure 2 summarizes of the steps of design methodology.
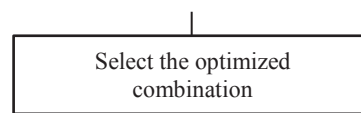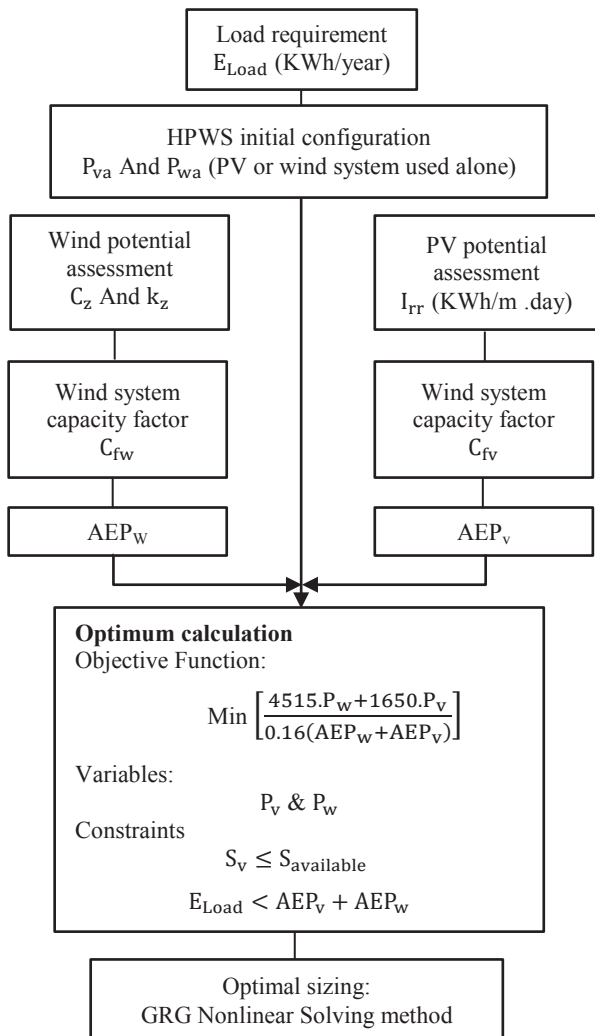

Fig. 2. Flow chart of the design methodology

The optimal hybrid configuration corresponds to the minimum of the objective function with the adequate values of installed powers of PV and wind turbine systems. For the wind generation system and according to the World Wind Energy Association (WWEA), the average worldwide installed cost of small wind turbines, in 2016, is about 4515 USD\$/kW. The average installed cost of PV systems in 2016, is about 1650 USD\$/kW$_p$. The installed cost of both wind and PV systems include the price of the battery bank. Therefore, the initial cost of an optimum design of the hybrid PV-wind system is given by:

$$Cost_H (USD\$) = 4515 \times P_w + 1650 \times P_v \tag{17}$$

The analysis was conducted for surface areas of 50 m , 100 m , and equal or more than 200 m . The contribution of the system to the payback period corresponds to the net cash flow saved from not being connected to the grid utility. For the calculation of the pay-back periods, the price of unit kilowatt (kWh) of electricity is fixed to 0.16 USD\$. The optimal sizing results for the considered available surface, S$_{available}$, are given in table 3.

Table 3. Results of the design methodology

	Tetouan		
S$_{available}$	**50 m**	**100 m**	**≥200 m**
Need (kWh/year)	37820		
Total AEP (kWh/Year)	37 820	37 820	37 820
P$_w$ (kW)	8.16	4.87	0
P$_v$ (kWp)	6.86	13.73	23.91
Capital cost (USD\$)	31 419.19	31 419.19	31 419.19
Cash-flow-20 years (USD\$)	108 364		
Payback period (year)	8	7	6
Percentage of contribution in total AEP (%)	**Wind : 71% Solar: 29%**	**Wind : 43% Solar: 57%**	**Wind : 0% Solar: 100%**
	Essaouira		
S$_{available}$	**50 m**	**100 m**	**≥200 m**
Need (kWh/year)	37820		
Total AEP (kWh/Year)	37 820	37 820	37 820
P$_w$ (kW)	9.07	4.07	0
P$_v$ (kWp)	6.86	13.73	19.32
Capital cost (USD\$)	35 133.71	33 298.48	31 816.42
Cash-flow-	108 364		

	50 m	100 m	≥200 m
20 years (USD$)			
Payback period (year)	9	7	5
Percentage of contribution in total AEP (%)	**Wind : 64%** **Solar: 36%**	**Wind : 29%** **Solar: 71%**	**Wind : 0%** **Solar: 100%**
Dakhla			
$S_{available}$	**50 m**	**100 m**	**≥200 m**
Need (kWh/year)	37820		
Total AEP (kWh/Year)	37 820	37 820	37 820
P_w (kW)	9.19	4.33	0
P_v (kWp)	6.86	13.73	19.85
Capital cost (USD$)	52856.78	42231.96	32763.69
Cash-flow-20 years (USD$)	108 364		
Payback period (year)	9	7	5
Percentage of contribution in total AEP (%)	**Wind : 65%** **Solar: 35%**	**Wind : 30%** **Solar: 70%**	**Wind : 0%** **Solar: 100%**
Ouarzazate			
$S_{available}$	**50 m**	**100 m**	**≥200 m**
Need (kWh/year)	37820		
Total AEP (kWh/Year)	37 820	37 820	37 820
P_w (kW)	16.41	7.42	0
P_v (kWp)	6.86	13.73	19.41
Capital cost (USD$)	70 758	56 196.62	32 029
Cash-flow-20 years (USD$)	108 364		
Payback period (year)	15	9	5
Percentage of contribution in total AEP (%)	**Wind : 65%** **Solar: 35%**	**Wind : 30%** **Solar: 70%**	**Wind : 0%** **Solar: 100%**

The design methodology gives the optimal combination of the PV and the wind power systems that meet the load requirements of the users for all the studied stations.

For all studied cases, the hybrid system tends to exploit the available surface for PV system. This finding is not surprising given that the average installed cost per kilowatt of the PV system (1650 USD$/kW$_p$) is very low compared to that of the wind generation system (4515 USD$/kW).

The capacity factor of the HPWS components (PV and wind systems) has a significant effect on the economic performance (payback period) of the hybrid system. This can be easily noticed in the results obtained for the case of Ouarzazate. This location presents the highest investment cost which is mainly due to the lower capacity factor of the wind system component. Therefore, the HPWS in this location is not economically viable because of the relatively high payback periods. On the contrary, the case of Tetouan and Essaouira presents the lowest investment cost, and hence relatively short payback periods. This is mainly due to the highest capacity factors of the both PV and wind generation systems.

The available surface for the PV panels has a significant effect on the cost effectiveness of the HPWS. For the case of Ouarzazate, the hybrid system is not economically effective as the pay-back period is more than 10 years. The minimum required surface that makes the HPWS cost effective in Ouarzazate is 142 m. However, for the sites of Tetouan and Essaouira, $S_{available}$ does not have a major effect on the cost effectiveness of the system. This is mainly due to high wind potential at these locations. Therefore, the system tends to compensate the limitations in the available surface with small wind power systems.

When $S_{available}$ is equal or more than 200 m, all the electricity needed to meet the load requirements comes from the PV system. This is normal since the design approach tends to minimize the initial cost of the HPWS by exploiting all the available surface area for PV generation which offers the advantage of very low costs per kilowatt installed.

6 Conclusion

An optimal design methodology for hybrid PV–wind systems was presented in this paper. This practical approach present a solution for complex nonlinear problems by taking into account the surface availability for the PV panels as a design constraint. The variables of this optimization exercise are the installed power of both the PV and the wind turbine system. The objective function consists in minimizing the ratio of the initial investment cost to the total AEP multiplied by the price of unit kilowatt hour (Kwh). It was found that the sites with high wind and solar potentials (Tetouan and Essaouira) provide configurations with less investment costs and short payback payments. However, a decrease in the wind energy potential (low wind capacity factors) in the site of Ouarzazate affects the economic feasibility of the HPWS (high investment costs and very long payback periods). For all studied locations, the design methodology demonstrates its ability to provide an optimal HPWS configuration without using commercial software.

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