Methodology to Size a Hybrid Energy Systems for Remote Regions: Technical-economic Analysis, Minimizing LCoE and CO2 Emissions

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ABSTRACT

This paper presents a methodology for optimizing the design of standalone hybrid energy systems. Firstly, technical-economic analysis based on the annual monthly average and on the average of the worst month of total energy are used. Secondly, genetic algorithm is employed to achieve the optimization by minimizing both Levelized Cost of Energy (LCoE) and CO_2 emissions. All the proposed methodology are applied to a remote region in Mahajanga, Madagascar, utilizing local solar radiation, temperature, and wind speed data. The performance of the system management strategy is evaluated, and a Pareto optimal front is generated. The optimal number of system components, LCoE, and CO_2 emissions are determined for each solution, allowing for a comprehensive analysis of the system's behavior under different load operating conditions.

Keyword: *- hybrid system, management strategy, optimization, genetics algorithm*

1. INTRODUCTION

Remote regions traditionally rely on diesel generators for electricity, resulting in high costs and significant CO_2 emissions. Hybrid systems integrating PV, wind, diesel, and battery technologies offer a promising alternative. While individual renewable sources often prove insufficient due to high costs and storage limitations, combining them with conventional power generation creates a more viable solution [1] [2].

Knowing the random nature of renewable energy sources, it is important to do the sizing in order to guarantee at all times, the satisfaction of the load of an autonomous system with a minimum possible cost. Indeed, the sizing in this case, consists in determining a number of materials (photovoltaic panel, wind turbine and battery) necessary in relation to the meteorological data and the daily consumption profile. This triplet is considered as the most important elements because of their high cost occupying the majority of the entire cost of the system [3] [4].

Previous research has explored hybrid system optimization, often focusing on minimizing the Annualized Cost of System (ACS) through iterative methods or genetic algorithms. However, these studies typically neglect crucial factors such as Loss of Power Supply Probability (LPSP) and CO_2 emissions. Additionally, they often overlook essential system components like regulators and inverters [5] [6].

This paper contributes by proposing a methodology to optimize hybrid PV/wind/diesel/battery systems, minimizing both Levelized Cost of Energy (LCoE) and CO_2 emissions [7]. The methodology is applied to a remote location in northwestern Madagascar using real-world meteorological data. By considering all system components and evaluating the diesel generator's impact, this research offers a comprehensive approach to designing optimal hybrid systems [8].

The methodology developed in this work was applied using the solar radiation, the temperature and the wind speed collected in remote site located in the northwestern coast of Madagascar. Further, firstly, the study by the worst month method and by the annual monthly average method for optimal configurations will be done [9] [10]. Secondly, influence of a diesel generator on the optimal sizing structure will be presented [11] [12]. The decision variables included in the optimization process are the number of PV modules, the number of wind turbines, the number of batteries, the number of solar regulators, and the number of inverters, all with one diesel generator [13] [14].

In the section 2, material and methods are presented. In which, the hybrid energy system is defined and is modeling as well as its architecture. The used strategies are explained for the sizing and technical-economic analysis of the hybrid system with battery, and for the purpose of Levelized Cost of Energy (LCoE) strategies. Results and discussions are delighted in section 3. Finally, in the last section, conclusions are given.

2. MATERIAL AND METHODS

A hybrid solar-wind-diesel system coupled with a battery bank comprises PV modules, a wind turbine, a diesel generator, a solar regulator, a battery bank, and a bidirectional inverter (Fig. 1) [1]. The PV modules and wind turbine collaborate to meet load demands. Excess renewable energy charges the battery bank. When renewable generation is insufficient, the battery discharges to support the load [2].

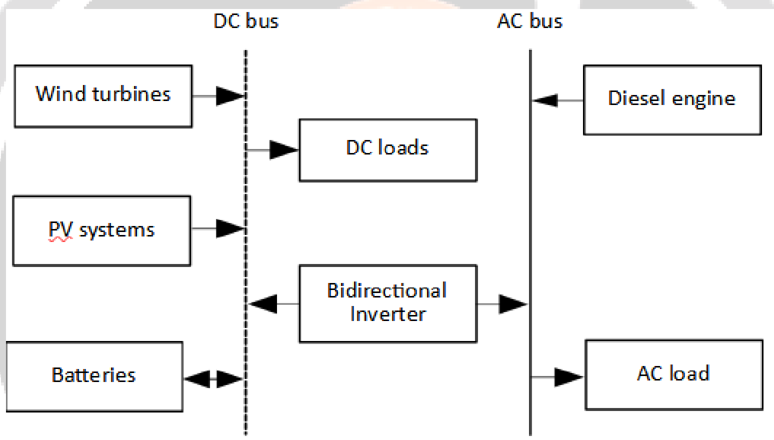

Fig. 1: Hybrid energy systems architecture

The diesel generator operates as a backup, supplying power when both renewable sources and battery storage are depleted.

2.1. Mathematical modeling

This paper focuses on the technical-economic analysis [3] and the Levelized Cost of Consumed Energy (LCoE) [5], which represents the average cost of electricity delivered to the end-user. Unlike traditional LCoE calculations that consider the total energy generated, our approach disregards energy losses. This is particularly relevant for remote areas where a significant portion of generated energy might be wasted due to excess production or battery inefficiencies.

2.1.1. Model of PV module

The power calculation method of PV module is given by equation 1.

$$P_{pv} = V_{oc}.I_{sc}.FF \quad (1)$$

Where: I_{sc} (A) and V_{oc} (B) are the short circuit current and open circuit voltage of a solar photovoltaic module, *FF* (dimensionless) is the fill factor. It is the ratio between the nominal and maximum power standard.

2.1.2. Model of wind turbine

Equation 2 gives the average of the output power from a wind turbine.

$$P_{wd} = P_r \cdot \left\{ \frac{\exp\left[-\left(\frac{V_{cin}}{A}\right)^k\right] - \exp\left[-\left(\frac{V_r}{A}\right)^k\right]}{\left(\frac{V_r}{A}\right)^k - \left(\frac{V_{cin}}{A}\right)^k} - \exp\left[-\left(\frac{V_{cou}}{A}\right)^k\right] \right\} \quad (2)$$

Where, A (m/s) is scale parameter, k is shape parameter (dimensionless), V is the wind speed (m/s), V_{cin} , V_r and V_{cou} are the cut-in speed, rated speed and cut-off speed given in (m/s).

2.1.3. Model of regulator

It is dimensioned according to its input current, given by the equation 4:

$$I_{rg} = \frac{N_{pv}.P_{pv}}{N_{pvs}.\eta_{rg}.U} \quad (4)$$

Where N_{pv} is the total number of PV modules, N_{pvs} is the PV modules number in series, η_{rg} (%) is the efficiency of the regulator and U (V) is the nominal system operating voltage [4].

2.1.4. Model of diesel generator

Energy generated by diesel generator in an hour t is defined by the equation 5:

$$P_{OG} = P_{NG}.N_{dg}.\eta_{Gr} \quad (5)$$

Where P_{NG} (kW) is the nominal power of diesel generators, N_{dg} is the total number of the diesel generators P_{OG} is the output power from diesel generators and η_{Gr} is the efficiency of diesel generators [5].

2.1.5. Model of Inverter

The inverter, a power electronic device, converts DC current from the system's DC bus to AC current for powering AC loads. The power delivered by the inverter to meet demand is calculated using equation 6.

$$P_{in} = \frac{P_{ch}}{\eta_{in}} \quad (6)$$

Where η_{in} is the inverter efficiency specified by the manufacturer (%), P_{ch} is the hourly demand *(W)*.

2.1.6. Model of battery bank

The battery nominal capacity is modeled by using equation 7 [6]:

$$\varphi_r = \frac{N_{bt}}{N_{bs}}.\varphi_{bt} \quad (7)$$

Where N_{bt} is the batteries total number, N_{bs} is the batteries number in series, ϕ_{bt} is the unit nominal capacity (Ah) of a battery.

The minimum state of charge, by [7], of the battery bank (SOCmin) can be expressed as Eq.8:

$$SOC_{\min} = (1 - DOD).SOC_r \quad (8)$$

Were *DOD* (%) is the depth of discharge and SOC_r is the rated state of charge of battery bank. The input/output battery bank power $P_{bt}(t)$ can be calculated according to the strategy in [8].

2.2. Sizing and technical-economic analysis of the hybrid system with battery

In this sizing study, two methods are used: one is based on the annual monthly average and the second is based on the average of the worst month of total energy.

2.2.1. Method of annual monthly averages

For this method, the size of the GPV and the wind generator are taken from annual average values of each contribution named E_{pv} and E_{el} (for one month). Similarly, the load is represented by the annual monthly average value [9]. Thus, the surfaces of the two PV and wind generators are given by the relations below

$$A_{pv} = f \cdot \frac{E_L}{E_{pv}} \tag{9}$$

$$A_{el} = (1-f) \cdot \frac{E_L}{E_{el}} \tag{10}$$

2.2.2. Worst month method

For this method, the sizing of the system components (GPV and wind power) is done based on the most unfavorable month [10]. The surfaces required for the two generators are expressed by:

$$A_{pv} = f \cdot \max\left(\frac{E_{L,m}}{E_{pv,m}}\right) \tag{11}$$

$$A_{el} = (1-f) \cdot \max\left(\frac{E_{L,m}}{E_{el,m}}\right) \tag{12}$$

In our case, E_L is constant.

2.2.3. Battery Sizing

The size of the storage battery is determined from the maximum requested load $E_{L,max}$ (maximum monthly load) [3]. The storage battery capacity can be expressed as:

$$C_{bat} = \frac{E_{L,\max}}{V_{sys}} \cdot \frac{\Delta t}{N_m} \tag{13}$$

Or V_{sys} is the system voltage; N_m is the number of days of the most unfavorable month; Δ_t represents the duration in days relative to the requested autonomy, which is defined by the designer.

2.2.4. Determining the overall initial cost of the autonomous hybrid system

The total system cost represents the sum of the initial costs of all components, operations and maintenance costs, and replacement costs [4]. For this economic analysis, only component costs will be taken into account. The total cost of the system will be given by:

$$C_{total} = C_{pv} + C_{éol} + C_{bat} \tag{14}$$

The local prices including tax of these components are given below:

- A Polycrystalline photovoltaic module is worth 92.78 *€* for a surface area of 1.31 m^2.
- A wind generator with complete kit costs 1,381.44 *€* for a surface area of 7.06 m^2.

2.3. Purpose of Levelized Cost of Energy (LCOE)

The objective function seeks to minimize both the Levelized Cost of Consumed Energy (LCoE) [5] and pollutant emissions [6], measured in kilograms of CO_2, a primary contributor to the greenhouse effect.

2.3.1. Economic model

The Levelized Cost of Energy (LCOE) for the studied hybrid system comprises three primary components: levelized capital cost (C_{acap}), levelized maintenance and operation cost (C_{amain}), and levelized replacement cost (C_{arep})

[7]. Equation 15 defines the LCOE in euros per kilowatt-hour (*€/kWh*).

$$LCE = \frac{J(x)}{E_{annual}} \tag{15}$$

E_{annual} is the annual consumed energy (*kWh/year*), $x = [N_{pv}, N_{ag}, N_{dg}, N_{bt}, N_{rg}, N_{inv}]$ is the variables decision vector. Where N_{pv}, N_{ag}, N_{dg}, N_{bt}, N_{rg}, and N_{inv} are the numbers of PV module, wind turbine, diesel generators, batteries, solar regulators and inverters. And $J(x)$ is the Levelized Cost of system given by Eq.16:

$$J(x) = C_{acap}(x) + C_{amain}(x) + C_{arep}(x) \tag{16}$$

C_{acap}, C_{amain} and C_{arap} are the levelized capital cost, levelized maintenance and the levelized replacement cost of the system.

2.3.2. Pollutant emissions

This study quantifies pollutant emissions in kilograms of CO_2, a primary greenhouse gas contributing significantly to fuel combustion emissions [8]. To assess the environmental impact of the hybrid system, we calculate the annual CO2 emissions produced by the diesel generator.

The diesel generator's fuel consumption, which influences CO_2 emissions, is directly linked to its output power and is determined by Equation 17.

$$Cons = B.P_{NG} + A.P_{OG} \tag{17}$$

A = 0.246 *l/kWh* and B = 0.08145 *l/kWh* are the coefficient of the consumption curve, defined by the user [7]. The factor considered, in this work, to assess the emission of CO_2 was 3.15 *kgCO2/l* [8].

2.3.3. System optimization model

Minimizing both Levelized Cost of Energy (LCoE) and CO_2 emissions are the primary objectives. These conflicting goals necessitate a multi-objective optimization approach. Given the independent nature of the optimization parameters, a Multi-Objective Genetic Algorithm (MOGA) is employed.

This method, known for generating Pareto optimal solutions [11], is well-suited for addressing complex, non-linear engineering problems. By creating diverse population groups, the MOGA effectively explores the solution space, enhancing the likelihood of finding optimal or near-optimal solutions [12].

PV and wind energy outputs are determined using respective system models and component specifications. The battery bank, with a total nominal capacity of φ_r, has a discharge limit defined by the minimum state of charge. Initial system configurations must adhere to the inequality constraints outlined in Equation 13.

$$\begin{cases} SOC_{\min} \le SOC \le SOC_{\max} = SOC_r \\ I_{rg} \le I_{rrg} \\ P_{ond} \le P_{rond} \end{cases} \tag{18}$$

Where: I_{rrg} is the nominal current of the designed regulators *(A)*, P_{rond} is the nominal power of the inverter (W).

3. RESULTS AND DISCUSSIONS

3.1. Presentation of site and load profiles

3.1.1. Site profiles

The proposed methodology was applied using ten years of solar radiation, temperature, and wind speed data collected from the study site. The region exhibits favorable conditions for both solar and wind energy generation. Wind speeds are suitable for small wind turbines (0.2-10 *kW*), while the climate is exceptionally sunny, ideal for PV module deployment [3] [4]. Figure 3 illustrates typical hourly DHI and GHI values for the site.

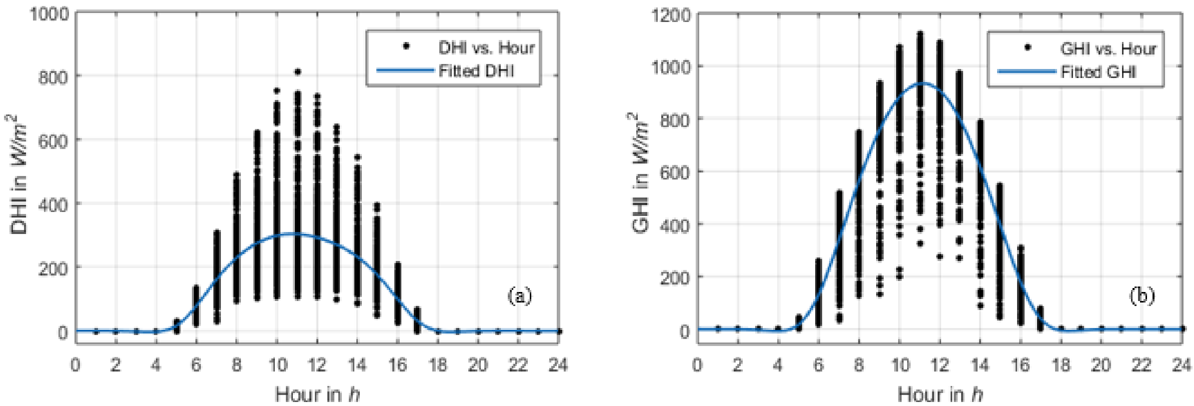

Fig. 2: (a) GHI, and (b) DHI respectively for sites in consideration

3.1.2. Presentation of loads

The loads profile reflect the typical energies consumption of commercial activities, domestic appliances of village and 50 % of commercial activities + 50 % of domestic appliances. Commercial activity constitutes the primary load [4]. The second load presents domestic appliances of a village.

As illustrated in Fig. 3, power demand exhibits slight variations between 5 *AM* and 5 *PM*, primarily attributed to water pumping, commercial refrigeration, and domestic appliances (refrigerators, televisions, radios) [13] [14].

Fig. 3: Presentation of the considered three types of load

Solar radiation levels are notably high during this period. While the primary energy consumption occurs between 5 *AM* and 5 *PM* due to water pumping and commercial activities. Nighttime demand arises from domestic appliances like lighting, refrigeration, and televisions, as well as continued operation of water pumping systems.

3.2. Result of sizing and technical-economic analysis of the hybrid system

The results presented in this section are sizing results of a hybrid system obtained using two scenarios. The first one consists of using the worst month method, the corresponding result of which is presented in table 1. The second scenario corresponds to the second method which is none other than the annual monthly average method, table 2.

According to this result presented in table 1, the most economical hybrid configuration is the one which corresponds to $f = 20$ % for the worst month method. For the annual monthly average method, table 2, $f = 60$ % is the most economical configuration. This configuration is composed of (16) photovoltaic panels and (01) wind turbine.

Table 1: Sizing according to the worst month method

N	S_{PV} (m^2)	Number of modules	S_{wind} (m^2)	Number of wind turbines	PV cost (€)	Wind cost (€)	Total cost (€)
0%	0	0	8.4682	2	0.00	6,846.23	6,846.23
20%	**4.8383**	**4**	**6.7745**	**1**	**729.07**	**3,423.12**	**4,152.19**
40%	9.6766	8	5.0809	1	1,458.14	3,423.12	4,881.26
60%	14.5149	12	3.3873	1	2,187.21	3,423.12	5,610.33
80%	19.3532	15	1.6936	1	2,734.02	3,423.12	6,157.13
100%	24.1915	19	0	0	3,463.09	0.00	3,463.09

Table 2: Sizing according to the annual monthly average method

N	S_{PV} (m^2)	Number of modules	S_{wind} (m^2)	Number of wind turbines	PV cost (€)	Wind cost (€)	Total cost (€)
0%	0	0	16.8055	3	0.00	10,269.35	10,269.35
20%	6.6354	6	13.4444	2	1,093.61	6,846.24	7,939.84
40%	13.2708	11	10.0833	2	2,004.95	6,846.24	8,851.18
60%	**19.9062**	**16**	**6.7222**	**1**	**2,916.29**	**3,423.12**	**6,339.41**
80%	26.5417	21	3.3611	1	3,827.63	3,423.12	7,250.75
100%	33.1771	26	0	0	4,738.97	0.00	4,738.97

For this scenario, the system can satisfy the load in the months of October, November and December, it is in deficit for the remaining months. Referring to the adopted sizing methods, the battery sizing result is shown in table 3.

Table 3: Battery sizing for scenario 1 and scenario 2

Method	E maximum daily deficits [*Wh*]	Capacity needed per day [*Ah*]	Number of batteries 12V/102Ah	Daily battery production [*Wh*]	Number of days of autonomy	PU battery (€)	Total Battery Cost (€)
Method 1	14290.32	3,423.52	20	19,584	1	277.76	5,555.26
Method 2	7200	1764.7	12	11,750	1	277.76	3,333.15

3.3. Optimal sizing results by Pareto front

A Multi-Objective Genetic Algorithm (MOGA) was employed to determine optimal configurations for the hybrid PV/wind/diesel/battery system. Results are presented as a Pareto front, representing a set of trade-off solutions between LCoE and CO_2 emissions. Each solution on the Pareto front corresponds to a specific hybrid system configuration and control strategy. For each configuration, both LCoE and CO_2 emissions were calculated.

Figs. 4 illustrate the optimal Pareto front, representing the trade-off between LCoE and CO_2 emissions. This Pareto front corresponds to a diesel generator configuration of three units. It is evident that a decrease in CO_2 emissions is associated with an increase in LCoE.

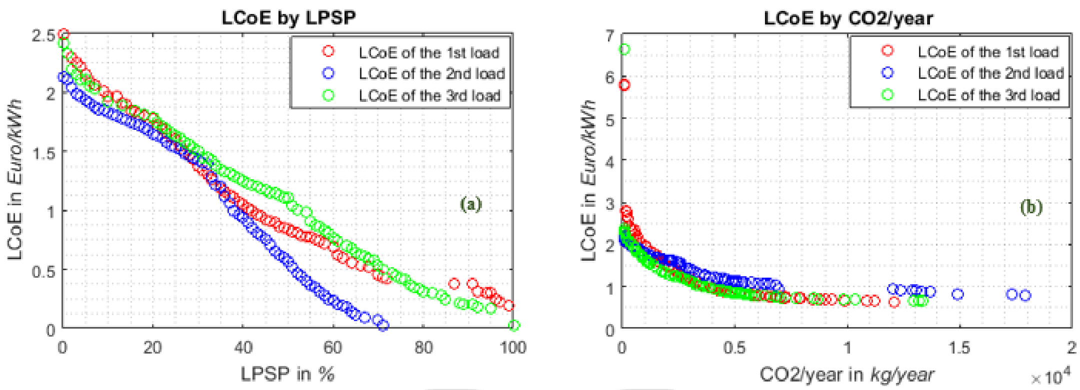

Fig. 4: Pareto optimal front of the Levelized Cost of Energy by (a) LPSP and (b) CO_2 per year

Tables 4 and 5 present the component sizes, energy output, and excess energy for the three selected loads (1, 2, and 3). A notable trend is the inverse relationship between LCoE and CO_2 emissions. For solutions 1, 2 and 3, 58 %, 31 % and 49 % of LPSP were chosen respectively. Compared to solution 3 with 1.112 €/kWh of LcoE, solution 1 LCoE reductions 0.726 €/kWh and solution 2 with 1.408 €/kWh, respectively.

Table 4: Solutions after an optimal Pareto front by LPSP

Solution	**1** (case of 1st load)	**2** (case of 2nd load)	**3** (case of 3rd load)
Number of PV modules	25	58	47
Number of Wind turbines	18	16	14
Number of Batteries	2	8	7
Number of Regulators	6	8	6
Number of Inverters	11	11	10
Number Diesel generators	1	1	1
LPSP (%)	58	31	49
Annualized cost system of energy (€/kWh)	0.726	1.408	1.112

It correspond to the use of the third type of load with 50 % of the first and 50 % of second types of load. All this choice is primarily attributed to a reduction in system components, particularly PV modules and wind turbines.

Table 5: Solutions of the optimal Pareto front with the use of the diesel generators

Solution	**A** (case of 1st load)	**B** (case of 2nd load)	**C** (case of 3rd load)
Number of PV modules	72	118	74
Number of Wind turbines	46	10	24
Number of Batteries	19	12	18
Number of Regulators	7	11	6
Number of Inverters	4	5	3
Number Diesel generators	13	13	12
Annualized cost system of energy (€/kWh)	1.779	1.701	1.492
Emission of CO_2 (kg/year)	1414.43	1446.02	1410.18

Conversely, diesel generator size and operating hours increase significantly in solutions B and C, leading to substantial CO2 emission increases of 5035.34 kgCO2/year and 1079.84 kgCO2/year, respectively. Solutions A, B and C are chosen around of 1400 kgCO2/year.

Solution A and B exhibit around 1.700 €/kWh of LCoE, compared to solution C with 1.4092 €/kWh of LCoE. All this solutions represent more different configuration size of components.

4. CONCLUSION

A methodology to size an optimal stand-alone PV/wind/diesel/battery bank, using a Multi-Objective Genetic Algorithm was developed in this paper. The developed methodology was applied on a remote site of Mahajanga, Madagascar to size hybrid systems using technical-economic analysis, minimizing the Levelized Cost of Energy (LCoE) and the CO_2 emission. The collected solar radiation, temperature and wind speed data was used in this study. The application of the methodology has allowed determining several solutions which are presented according to the worst month method, by the use of the annual monthly average method, and under form optimal Pareto forehead.

Results have allowed outlining the following points:

- By the worst month method,
- From the annual monthly average method,
- The increasing of the LCoE implies the decreasing of the CO_2 emission.

Battery bank was less solicited for the application on the sites when diesel generator is in action.

APPENDIX

Table -1: specifications of the components used to design and to optimize the hybrid system

	Specifications	**Values**
PV	Maximum power (P_{max})	180 *W*
	Maximum voltage (V_{mp})	36 *V*
	Maximum current (I_{mp})	5 *A*
	Open circuit voltage (V_{co})	44.6 *V*
	Short-circuit current (I_{cc})	5.4 *A*
	Temperature coefficient of I_{cc} (k_i)	(0.065±0.015) *%/ °C*
	Temperature coefficient of V_{co} (kv)	-(160±20) *mV/°C*
	Power temperature coefficient (kp)	-(0.5±0.05) *%/ °C*
	Yield	13.5 *%*
	Nominal voltage	24 *V*
	NOCT	48±2 *°C*
	Dimensions (L*W*T)/ Weight (kg)	1320*992*35 *mm* / 16 *kg*
	Guarantee	Power output: 10 *years* 100 *%*, 20 *years* 90 *%*
Wind	Nominal power	1000 *W*
	Speed wind rating	11.6 *m/s*
	Turbine start speed	3.1 *m/s*
	Speed stop	55 *m/s*
	Rotor mass	30 *kg*
	Rotor diameter	3 *m*
	Surface swept by the rotor	7,065 m^2
	Maximum rotation speed	360 *rpm*
	Number of blades	3
	Braking system	mechanical
Battery	Nominal voltage	12 *V*
	Ability nominal	102 *Ah*
	Minimum load	20%
	Charging efficiency	0.85
	the rate self-discharge	0.0014
Regulator	Nominal current	30 *A*
	Nominal voltage	48 *V*
	Cost	230 *€*
Inverter	Nominal Power	3500 *W*

	Nominal voltage	48 *V*
	Cost	2799 *€*
Diesel generator	Nominal output power	40000 *W*

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