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Analysis of Renewable Source Self-Consumption Systems: Energy, Economic and Social Impact

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Abstract
This work analyzes renewable source self-consumption systems as an alternative to conventional fossil fuel sources for the residential, commercial, and industrial sectors. The proposed configuration is a hybrid array of individual or combined renewable energy sources like photovoltaic panels, wind turbines, hydroelectric micro-turbines, low enthalpy geothermal or biomass units, etc. The paper studies the energy balance for a prototype installation based on standard energy consumption and power supply from renewable sources, aiming to optimize the system performance by saving energy, increasing efficiency, and minimizing energy waste. The paper also analyzes the feasibility of the proposed configuration, its capacity for variable operating conditions adaptability, and the implementation factor in modern society. This work also evaluates the environmental impact of self-consumption systems powered by renewable sources in urban areas, which are deeply sensible to pollutant gasses emissions. The simulation analysis shows that this solution reduces greenhouse gas emissions and helps mitigate climate change by reverting the carbon dioxide balance in the atmosphere.

Keywords: Self-Consumption System, Sustainable Development, Renewable Energy Sources, Economic and Social Impact, GHG Emissions Reduction

1. Introduction

Climate change forces politicians to adopt solutions to mitigate the environmental impact caused by the continuous growth of the atmosphere pollution level due to the massive consumption of fossil fuels, petrol, gas, or coal [1,2]. The alternative to conventional power sources is renewable ones, which avoid GHG emissions and contribute to mitigating the effects of excessive carbon dioxide concentration in the atmosphere [3-5]. Developed countries in modern society are eager energy eaters because of the increasing welfare and the associated power demand; this situation becomes critical if we consider developing countries searching for the same welfare level and their populations like China, India, Brazil, or Indonesia, which represent half of the World inhabitants [6-9].

It is a fact that renewable energies cannot entirely replace conventional power sources, especially in the industry sector, due to their low energy density and intermittency [10-13]. Nevertheless, some sectors, like the residential one, are good candidates for renewable energy implementation since their power demand is low and energy consumption is covered using single or hybrid renewable power sources [14-17]. Power independence from foreign energy resources contributes to promoting and implementing local natural resources in many world areas [18-21]. Power supply easy access and low prices also help to adopt renewable energies as a principal power source for households and small facilities [22-24]. The CO_2 emissions estimated reduction if the residential sector moves from conventional to renewable energy sources largely overpasses the expected atmospheric carbon dioxide concentration lowering [25-27].

Many works prove the benefits for individuals and collectivity of implementing renewable energies in the residential sector, especially in detached or semi-detached houses where available space for power sources to energy demand ratio is higher. The many developed studies cover energy, economic, social, environmental, and health topics, quantifying the benefits or analyzing the impact on society [28-32]. Despite the intensive analysis of the topics related to self-consumption installations and how they influence energy saving, environmental impact, economic benefits, and social behavior, there are still aspects that people should know to improve their life quality and manage the installation at the best operating conditions. One of the paper's goals is to explore the unknown aspects that relate household power consumption and renewable energies, like evaluating accurate balance, appropriate renewable energy source selection, optimizing energy use from renewable sources, etc.

2. Self-Consumption Scenarios

Self-consumption can be defined as the share of the total system production directly consumed by the system owner. Self-consumption systems include two installation types: the ones that produce all the energy they consume and the others where there is a deficit in the energy balance, which an external source compensates for. In both configurations, the principal power source is the self-energy generation system, currently renewable energy sources like solar thermal or photovoltaic, wind, biomass, geothermal, micro-hydro, and others. Since the most current energy consumed type is thermal and electric, we primarily focused on these two power modes. Nevertheless, thermal energy is hard to manage in the long term. Therefore, we focus our attention on electric energy consumption. On the other hand, technological advances permit household heating with electric energy at a relatively low cost and high energy efficiency using heat pumps [33-35] or aerothermal units [36-38]. Direct electricity generation from renewable energy derives from solar photovoltaics and wind energy [39-41], while solar thermal [42,43], geothermal [44], and biomass [45-47] are more suitable for thermal energy production. Other renewable energy sources like micro-hydro, wave, or tidal are of reduced application in household installations because of the water supply dependence.

As we mentioned before, self-consumption does not imply a full energy demand coverage by an on-site renewable energy system; in some cases, it is more effective and economically profitable to reduce the coverage factor to a limit where reliability, feasibility, and economic profit are optimum [48-50]. Indeed, some countries regulate the energy demand coverage factor by renewable energies to avoid energy waste in case of power surplus with no storage option or transfer to a secondary system. Power management optimization requires an energy balance in-deep analysis, considering short-term power generation and demand. Since the power generation depends on the type and size of the renewable system, single or hybrid, and the energy demand changes with human habits, it is necessary to develop a specific protocol applicable to any self-consumption system.

3. Self-Consumption Design

Due to the variability and intermittency of renewable energy sources, especially solar and wind, the power generation profile does not match energy demand. A storage unit or a grid connection is mandatory to compensate for the energy gap. The first option has the advantage of independence on external sources and energy cost invariability; the second provides unlimited energy supply unless a blackout occurs, subject to electric company restrictions. The option selection depends on several factors: user investment capacity, availability of grid connection nearby, appropriate space for storage unit location, or design complexity, among others of less importance [51-53]. A third option is a hybrid system with a storage unit and grid connection, having the advantage of a redundant system with a higher power supply warranty but at a higher investment cost and more complex design. From the three options, we select a self-consumption system with a grid connection and no storage unit. This configuration reduces the design complexity, the initial investment, and the maintenance costs. The power system comprises a PV array and a domestic wind turbine (Figure 1).

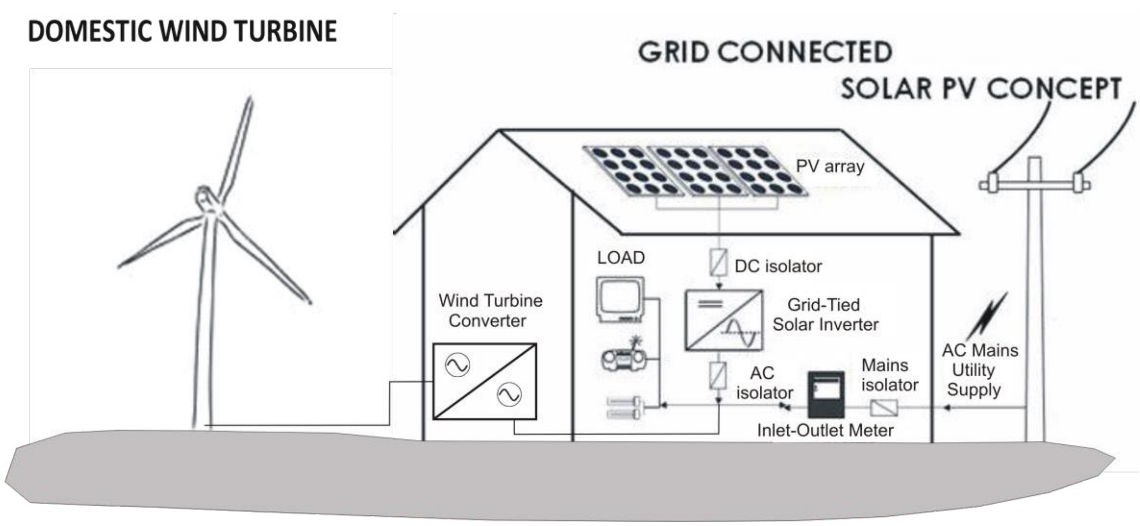

Figure 1: Hybrid Wind Turbine – PV Array

The power source configuration depends on the energy demand coverage factor; since wind and solar systems operate independently based on the energy resource, we divide the power supply into four periods depending on the operational power source, wind turbine, PV array, hybrid system, or none. Wind and solar energy complement each other throughout the day quite effectively, according to the records available from both sources [54-57]. Figure 2 shows the monthly daily average solar and wind evolution.

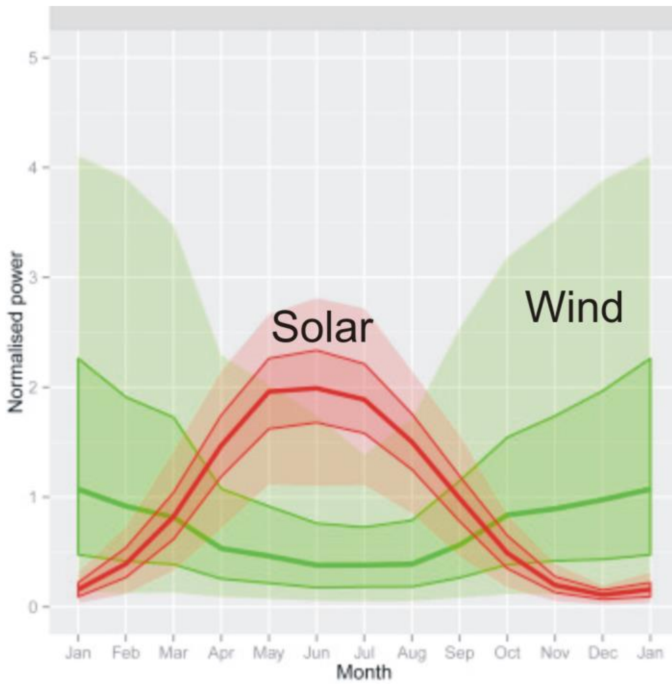

Figure 2: Monthly Daily Average Solar and Wind Resource [58]

We observe that solar energy increases while wind power decreases, complementing each other throughout the day. The selected area is a windy zone where wind speed never stops throughout the day. Disaggregating the daily average in hourly values, we obtain (Figure 3):

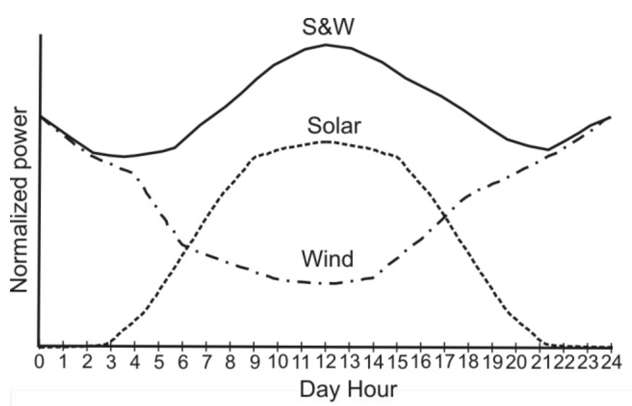

Figure 3: Hourly Distribution of Solar, Wind and Combined Power Generation

The label S&W in Figure 3 accounts for the combined solar and wind power. We realize the global output power evolution (solid line) shows a maximum at midday, matching the solar energy peak value; at this point, the wind energy is minimal. The normalized power shown in Figure 3 is consistent with solar and wind energy behavior in many geographical areas; therefore, we may consider the hourly distribution representative of a standard place with solar and wind energy power resources.

4. PV Array

The PV array sizing depends on the energy demand and provided coverage factor by solar photovoltaics. Considering the hourly energy consumption as C_i, where sub-index i accounts for the day hour, we may establish:

$$P_G^{PV} = n_1 P_o^{PV} = f_i^{PV} C_i \quad (1)$$

Superscript PV represents the photovoltaic section of the system, while subscripts G and o account for the PV global array and single panel. f is the energy demand coverage factor, and n is the number of PV panels in the array.

PV output power corresponds to the maximum value since the PV array includes an MPPT (Maximum Power Point Tracking) device to operate the PV panel at the peak power point. Computing the daily energy consumption, we determine the number of panels from the following equation:

$$n_2 = ceil\left(\frac{C}{\xi_{PV}}\right) = ceil\left(\frac{\sum_{i=1}^{24} f_i^{PV} C_i}{P_o^{PV} t_{psh}}\right) \quad (2)$$

t_{psh} represents the peak sun hours' time, and *ceil* is a rounding function, returning the next upper value to the integer part of the fraction. The peak sun hours' time is characteristic of the geographical area, given by:

$$t_{psh} = \frac{\int_{sr}^{ss} I(t)dt}{I_{\max}} \quad (3)$$

I represents the instantaneous solar radiation throughout the day, with the sub-index max accounting for the average standard peak value, accepted as 1000 W/m^2. The limits of the integral, *sr* and *ss*, correspond to sunrise and sunset hours, given by [59]:

$$\begin{aligned} ss &= 12 + \frac{\arccos\left(-\tan\delta \tan\phi\right)}{15} \\ sr &= 12 - \frac{\arccos\left(\tan\delta \tan\phi\right)}{15} \end{aligned} \quad (4)$$

ϕ is the latitude of the location, and δ is the declination, which depends on the day of the year as [60,61]:

$$\begin{aligned} &\delta = \left(180/\pi\right)\left(a_o - a_1 \cos B + a_2 \sin B - a_3 \cos 2B + a_4 \sin 2B - a_5 \cos 3B - a_6 \sin 3B\right) \\ &B = (J-1)\frac{360}{365}\,;\, a_o = 0.006918\,;\, a_1 = 0.399912\,;\, a_2 = 0.070257 \\ &a_3 = 0.006758\,;\, a_4 = 0.000907\,;\, a_5 = 0.002697\,;\, a_6 = 0.00148 \end{aligned} \quad (5)$$

The maximum between n_1 and n_2 is the selected number of PV panels to guarantee that the PV array covers the maximum demanding power and energy from the self-consumption installation.

In case we need to install more than one row of PV panels, the minimum distance between rows is [62]:

$$d = L\left(\cos\beta + \frac{\sin\beta}{\tan\alpha_s}\right) \quad (6)$$

L and β are the PV panel length and tilt, and α_s is the solar height, given by [59]:

$$\alpha_s = \frac{\pi}{2} - \arccos\left(\cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta\right) \quad (7)$$

ω is the hour angle, determined by [59]:

$$\omega = 15(12 - ST) \tag{8}$$

ST is the solar time.

The area covered by the PV array, S_{PV}, depends on the number of rows and columns according to:

$$S_{PV} = n_r n_c Wd + n_s LW \cos\beta \tag{9}$$

W is the PV panel width, and n_r and n_c are the number of rows, columns. n_s is the number of panels left over from the matrix [n_r, n_c]. If the PV array stands on the same plane:

$$S_{PV} = LW(n_r n_c + n_s) \tag{10}$$

Considering the previous development, the supplied energy by the PV array is:

$$\xi_{PV} = \sigma_{PV} S_{PV} t_{sph} = \eta_{PV} I_{\max} S_{PV} t_{sph} \tag{11}$$

σ and η are the PV panel surface power density, in W/m2 and efficiency.

5. Wind Array

Domestic wind turbines have lower power generation and smaller sizes with a typical hub height of around 10 meters; therefore, we should measure the wind resource at that height to evaluate the wind turbine energy supply. We determine the wind speed distribution at the hub height using the Global Wind Atlas (GWA) tool [63], which considers the orography and meteorological data. In this work, the calculation extends the wind resource analysis and evaluation to a 9 km^2 surface.

The wind turbine calculation follows the same procedure as for the PV array; therefore, applying Equations 1 and 2 to the wind array, we have:

$$P_G^w = n_3 P_o^w = f_i^w C_i \tag{12}$$

$$n_4 = ceil\left(\frac{C}{\xi_w}\right) = ceil\left(\frac{\sum_{i=1}^{24} f_i^w C_i}{P_o^w t_{op}}\right) \tag{13}$$

The wind turbine working time corresponds to the daily period where wind speed operates between limits (Figure 4).

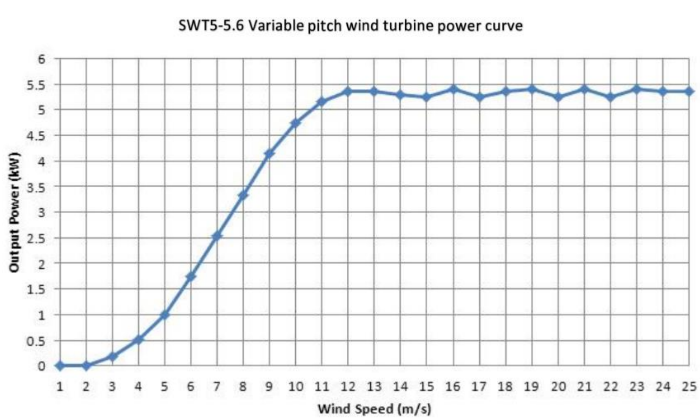

Figure 4: Wind Turbine Power Curve [64]

Figure 4 shows the typical wind turbine power curve for specific wind speed limits; since region 2 corresponds to the transient state until reaching the full load operation mode (region 3), we consider the working time corresponding to this latter region. The calculation of the working time requires the Weibull curve for the selected wind turbine since it provides the wind speed probabilistic distribution (Figure 5).

Because the wind speed is variable and unpredictable, we need to use the probability function of wind speed occurrence to determine the wind turbine output power; therefore, Equation 13 converts into:

$$n_4 = ceil\left(\frac{C}{\xi_w}\right) = ceil\left(\frac{\sum_{i=1}^{24} f_i^w C_i}{\sum_{u=u_o}^{u=u_f} p(u)P(u)t_{op}(u)}\right) \quad (14)$$

$P(u)$ represents the wind turbine power corresponding to the specific wind speed (u), $p(u)$ is the probability of the u-wind speed occurrence, and $t_{op}(u)$ is the wind turbine working time for that speed.

As in the PV array case, the maximum between n_3 and n_4 determines the number of domestic wind turbines.

6. Hybrid Array

The hybridization of PV arrays and wind turbines for household applications requires a control unit since they operate at different voltages and types of current. PV array supplies continuous current at low voltage while wind turbine operates with alternate or continuous current but at higher voltage. The control unit may adopt two different configurations:

• Type 1: Double DC/DC converter and a single DC/AC converter. One of the DC/DC converters connects to the PV array and converts incoming voltage to DC household operational voltage. The second DC/DC converter connects to the wind turbine system and converts its output voltage to the working household and battery DC voltage. Finally, the DC/AC converter transforms the DC voltage from the two DC/DC converters in AC at the appropriate voltage for household appliances operating in alternate current and for grid connection

• Type 2: A single DC/DC converter for the PV array, converting the PV output voltage to the household and battery working DC voltage. A single DC/AC converter to transform the PV voltage supply into AC at the appropriate voltage for household appliances operating in an alternate current and for grid connection. A single AC/DC converter to convert AC power supply from a wind turbine into working DC voltage for household appliances. Finally, a single AC/AC converter to adapt AC voltage from wind turbine to household appliances AC voltage and grid connection

The control unit type selection depends on the wind turbine output power type, alternate or direct current. Figures 5 to 9 show the different configurations for the control unit.

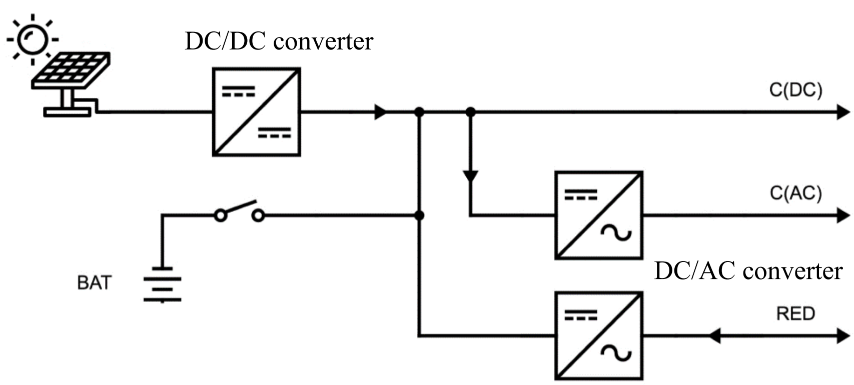

Figure 5: Layout of Single Dc/Dc and Single Dc/Ac Converter for PV Array

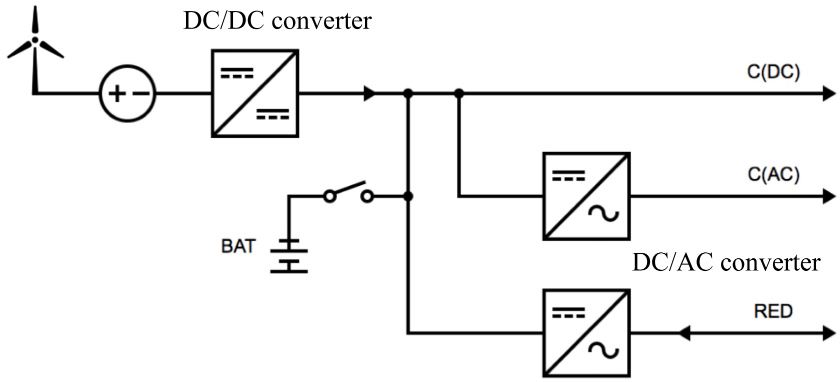

Figure 6: Layout of single DC/DC and single DC/AC converter for wind turbine

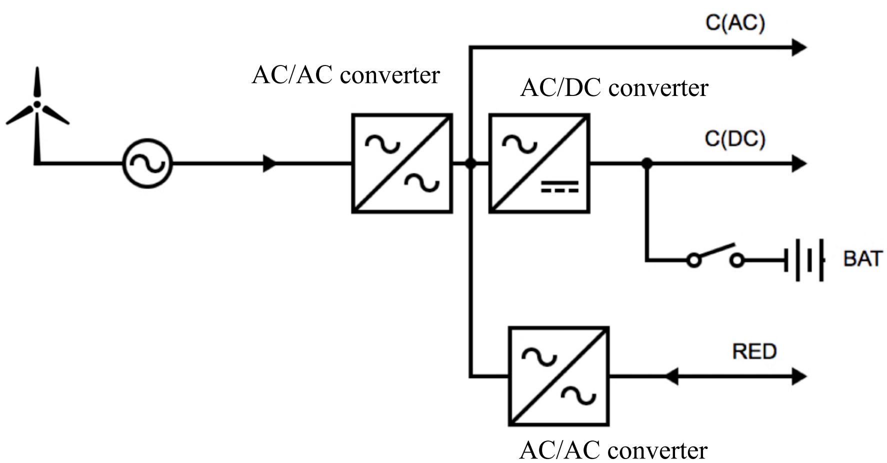

Figure 7: Layout of Double Ac/Ac and Single Ac/Dc Converter for Wind Turbine

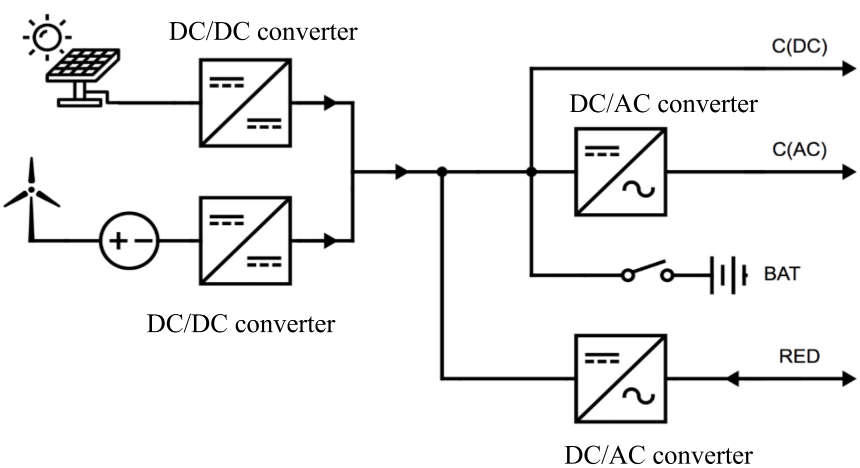

Figure 8: Layout of Double Dc/Ac and Double Dc/Ac Converter For Hybrid System With Dc Wind Turbine

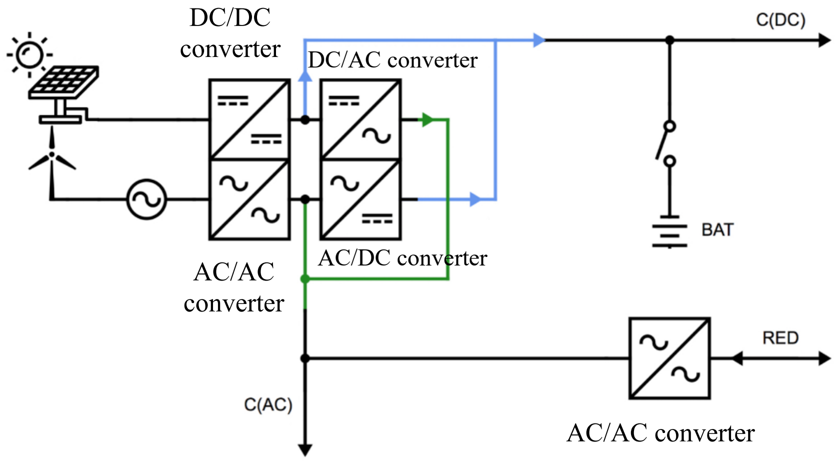

Figure 9: Layout of Multiple Dc/Dc, Ac/Ac, Dc/Ac, And Ac/Dc Converter for Hybrid System with Ac Wind Turbine

7. Household Array

The selected household array corresponds to five detached houses in Fuerteventura (Canary Islands), a windy place with high yearly insolation levels and poor electric power supply. The grid connection is accessible but scarce since there is only one thermal power plant on the island, located in the capital city, far away from many inhabited places. We select this location as representative of many places around the World with difficult, scarce, or no access to the electric grid and easy access to renewable energies. A low population density characterizes the inhabited places where renewable energy sources can supply the energy demand most of the time. Figure 10 shows the Fuerteventura island map with the thermal power plant location. White dots in the map represent small cities and towns.

Figure 10: Map of the Selected Geographical Area [65]

The typical construction structure is a one-story building with a flat rooftop, providing good available space for PV array installation. Households are separated from each other, giving enough space for domestic wind turbines. Figure 11 shows a schematic view of the prototype installation.

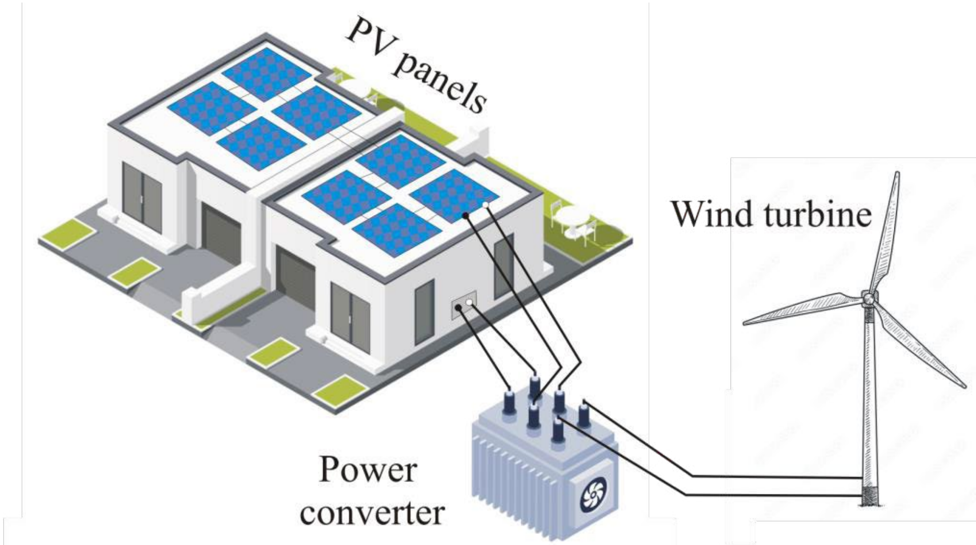

Figure 11: Schematic view of the Prototype Installation

According to the electricity distribution company, the average energy consumption in a middle-class house is 18 kWh/day [66]. Therefore, the global energy consumption for the household set is 90 kWh/day.

Solar resource is obtained from the meteorological service database for the selected location (Figure 12) [67].

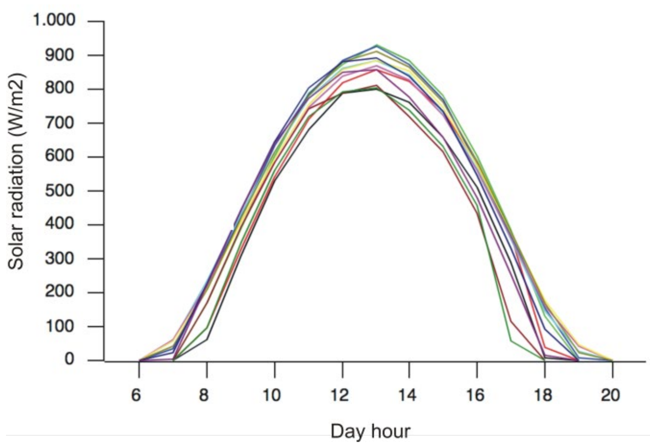

Figure 12: Average Hourly Daily Evolution of Solar Radiation for The Location of Fuerteventura (Canary Islands)

Lines in Figure 12 correspond to the months of the year. We calculate the peak sun hours for every month using a professional calculator application based on Equation 3. Table 1 shows the results of the calculation [68].

Month	1	2	3	4	5	6	7	8	9	10	11	12
t_{psh} (h)	4.39	5.24	6.12	6.16	6.40	6.42	7.17	6.95	6.93	5.82	5.02	4.36

Table 1: Monthly Peak Sun Sours for The Location of Fuerteventura (Canary Islands)

Using data from Table 1 and applying Equations 1 and 2 for a PV panel of 480 Wp, we obtain n_{PV} =32 as the number of panels in the PV array, corresponding to a global output power of 90.9 kWh/day for the average peak sun hours value of 5.915, enough to cover the household set energy demand in a sunny day.

Since the solar radiation distribution is not uniform throughout the year, we determine the monthly average solar photovoltaic output power, yielding (Table 2):

Month	1	2	3	4	5	6	7	8	9	10	11	12
t_{psh} (h)	67.4	80.5	94.0	94.6	98.3	98.6	110.1	106.8	106.4	89.4	77.1	67.0

Table 2: Monthly Average Solar Photovoltaic Output Power (kWh/day)

We realize that in some months, November through February, the energy balance is negative, while in others, April through September, the balance is positive, with a null balance in March and October. Therefore, we need a storage unit, a battery, or an additional power source like a wind turbine.

If we decide to include a battery in the power system configuration, we have to store the global energy balance for the months where energy demand exceeds solar photovoltaic generation; mathematically:

$$\xi_{bat} = \sum_{i=1}^{12} \left(C_i - P_i^{PV} \right)^+ \tag{15}$$

Applying data from Table 2, we have ξ_{bat} = 78.9 kWh, corresponding to a lead-acid battery of 6575 Ah operating at 12 VDC. Since the battery operates at an average efficiency of 95% for the charge/discharge cycle, the battery capacity should be 6921 Ah.

We select a typical model for household applications of 6 kW output power at maximum wind speed if we use a domestic wind turbine as an additional power source. The daily wind speed profile comes from the meteorological service for the selected location [69] (Figure 13).

On the other hand, the wind direction for the selected location is relatively constant, which reduces the output power fluctuations and improves the wind turbine performance (Figure 14).

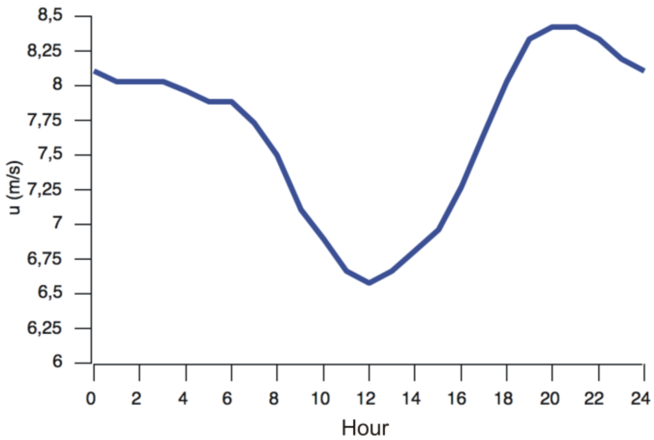

Figure 13: Average Daily Wind Speed Profile

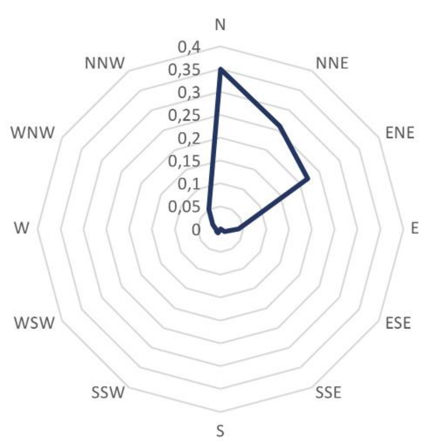

Figure 14: Compass Rose for the Selected Location

Using data from Figure 13 and applying the following expression, we can determine the wind energy generation, ξ^w, as:

$$\xi^w = \sum_{i=1}^{24} p(u_i) P_i^w \tag{16}$$

P^w is the associated power to the u-wind speed, given by:

$$P^w = \frac{1}{2} C_p \rho A u^3 \tag{17}$$

C_p is the wind turbine power coefficient, characteristic of the wind turbine model, ρ is the air density, and A is the wind turbine rotor-blade area.

The wind energy calculation result yields 31.06kWh/day.

Averaging the wind speed from Figure 13, we obtain u_{av} = 7.65 m/s. Now, considering a domestic wind turbine of 2.4 m diameter with a power coefficient of 0.35 and applying the Equation 17, we have:

$$P^w = \frac{1}{2}(0.35)(1.225)\frac{\pi}{4}(2.4)^2(7.65)^3 = 434\,W \tag{18}$$

Since the wind turbine operates 24 hours a day, applying Equations 12 and 13 yields $n^w = 3$. The wind turbine array requires a minimum separation distance between elements estimated in eight times the wind turbine diameter to avoid turbulences [70]. Therefore:

$$d = 8D = (8)(2.4) = 19.2\,m \tag{19}$$

Arranging the wind turbine array to minimize the busy area, we place the three turbines at the vertices of an equilateral triangle for a global area of 80 m^2. Figure 15 shows the wind turbine array layout.

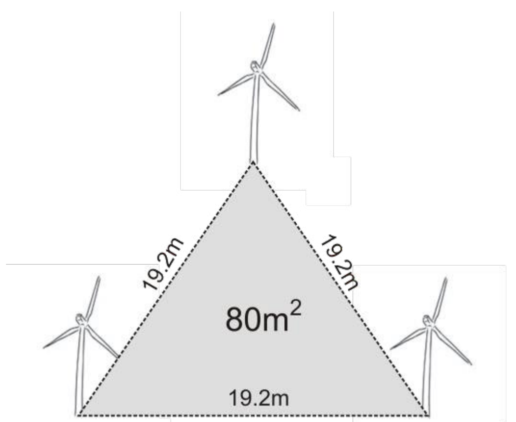

Figure 15: Wind Turbine Array Layout

8. Hybrid Array

The combination of photovoltaic panels and wind turbines in a hybrid array should reduce the number of PV panels and wind turbines; nevertheless, since at night, the PV array does not produce energy, if we intend to cover all energy demand by renewable sources, we cannot reduce the number of wind turbines. In such a case, we reduce the PV panel number to match the energy demand at any daytime.

Using Figure 3 and considering the normalized power as the reference for the required energy demand, we determine that a 40% reduction in the PV power generates enough energy to cover the unbalance between the household array set energy demand and wind power production; therefore, the number of PV panels should be $n^{PV} = 20$, after rounding.

9. Energy Balance

We determine the daily and annual energy balance for the photovoltaic, wind turbine, and hybrid array. We disaggregate the average daily energy demand in hourly values to evaluate the energy balance more accurately. Because the hourly energy consumption does not follow a set pattern, we estimate a sinusoidal function as the closest evolution to current energy demand. Using this pattern, we obtain the following energy balance for the three configurations (Figures 16 to 18).

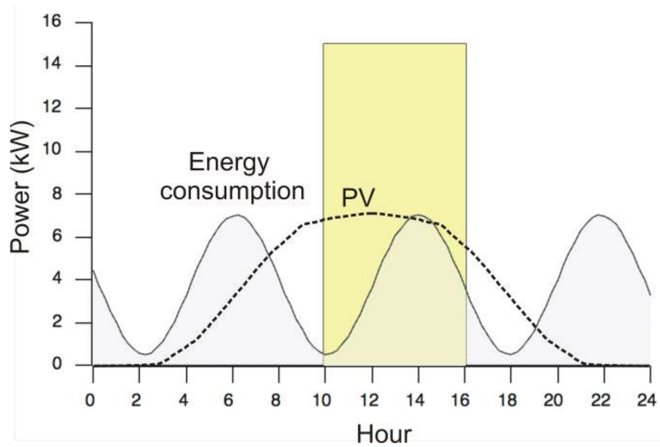

Figure 16: Daily Hourly Energy Balance with PV As Power Source

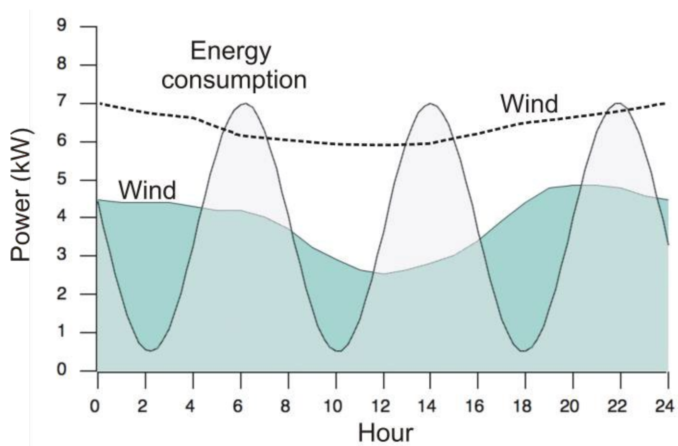

Figure 17: Daily Hourly Energy Balance with Wind Turbine as Power Source

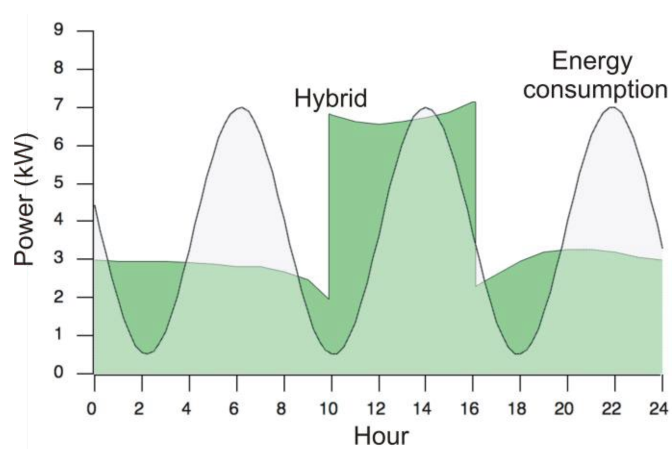

Figure 18: Daily Hourly Energy Balance with Hybrid System as Power Source

The rectangle in Figure 16 represents the energy supplied by the PV array considering a peak sun hour square function for the working time. Analyzing the PV array case, we observe the energy balance is positive between 7.30 am and 7 pm and is negative the rest of the day. This situation requires a battery to store the excess generated energy during the period of positive energy balance to use when the balance is negative. Formerly, we calculated the battery size corresponding to the required stored energy.

For the wind turbine case, we realize that using the initial setup number of three wind turbines, see dashed line in Figure 17, the wind array covers the energy demand most of the daily time, except during the peak energy consumption. If we reduce the number of wind turbines to save space and money, the array does not cover energy demand in many hours, from 4 am to 8 am, from 11.30 am to 4 pm, and from 8 pm to 11.30 pm. This configuration forces us to use a battery of the same capacity as in the PV array case.

Finally, if we use a hybrid system, the energy balance is positive in some intervals and negative in others. The positive intervals correspond to the day hours from 0.30 am to 4 am and from 8.30 am to 8 pm, representing a long working time, and compensate for the negative periods from 4 am to 8.30 am and from 8 pm to 0.30 am. The use of a battery is mandatory. This configuration operates with fewer PV panels, 20 instead of 32, and wind turbines, two instead of three, saving space and money.

Repeating for the annual balance, we have (Figures 19 to 21):

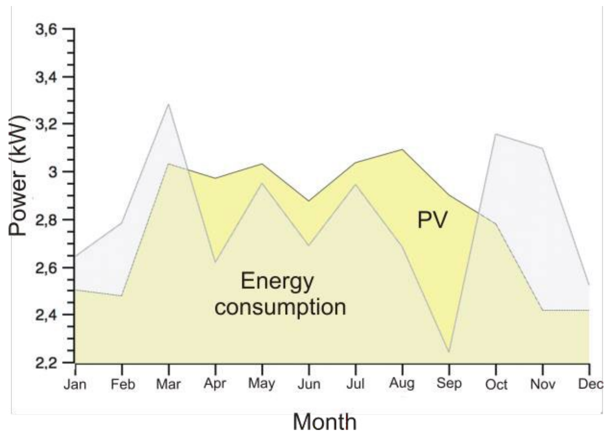

Figure 19: Yearly Monthly Energy Balance with PV As Power Source

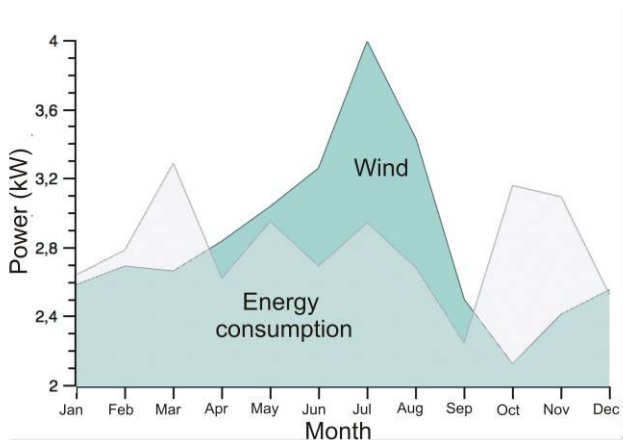

Figure 20: Yearly Monthly Energy Balance with Wind Turbine as Power Source

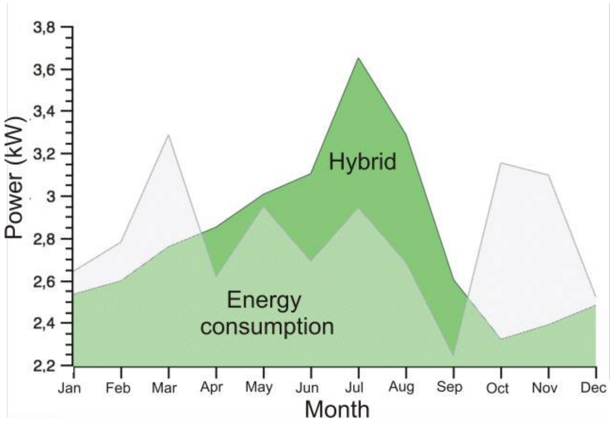

Figure 21: Yearly Monthly Energy Balance with Hybrid System as Power Source

The analysis of the annual energy balance shows that in autumn and winter, the PV array, wind turbine, and hybrid system do not cover energy demand, requiring the assistance of the storage unit; however, during spring and summer, any of the three configurations supply more energy than needed, allowing to recharge the battery. Analyzing the contribution of the PV array and wind turbine to the hybrid system power supply (Figure 22), we observe that the wind turbine is responsible for 2/3 of the energy generation, matching the selected power distribution according to the PV array size and the wind turbine's number.

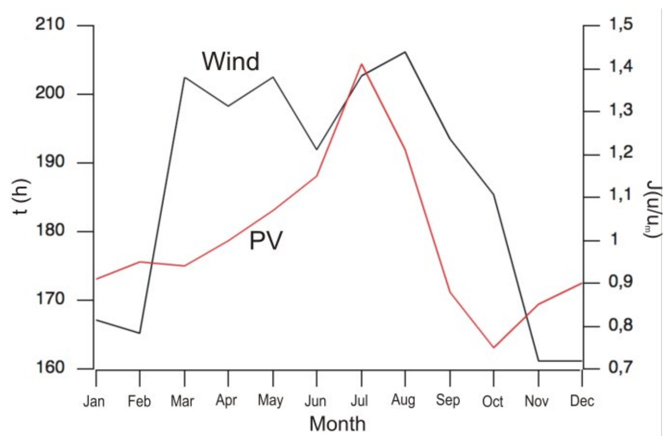

Figure 22: Contribution of PV Array and Wind Turbine to the Global Power Supply in the Hybrid Mode

The parameters t(h) and J(u/um) (Y-axis) correspond to the monthly cumulative peak sun hour and index for the wind energy output power. u_m represents the wind speed average value.

We may quantify the energy balance, κ, from the expression:

$$\kappa = \int_{t_o}^{t_f} G(t)dt - \int_{t_o}^{t_f} C(t)dt \tag{20}$$

G(*t*) and *C*(*t*) are the generation and energy consumption functions.

Retrieving data from previous development in this work (Table 3):

κ	PV	Wind	Hybrid
Daily	1.71	3.18	1.86
Annual	-0.08	0.45	-0.03

Table 3: Daily and Annual Energy Balance (kWh)

We observe the positive daily energy balance in good agreement with expected results since we slightly oversized the PV array and the wind turbines set. For the annual energy balance, we realize that PV and hybrid provide null balance while wind turbine supplies more power than needed, a consequence of the oversizing.

10. Economic Analysis

Considering the elements to operate the PV array and the wind turbine set, depending on the operating mode, we should include for every system the following components:

a) Solar photovoltaic power source mode
• PV array: 32 panels of 480 Wp and the supporting structure
• Converters: Two DC/AC and one DC/DC
• Control unit: includes voltage regulator, power analyzer and MPPT unit
• Battery: 20 elements of 350 Ah at 12 VDC, lithium-ion technology
• Supporting structure

b) DC Wind turbine power source mode
• Wind turbine: 2 of 6 kW DC mode
• Converters: Two DC/AC and one DC/DC
• Control unit: includes voltage regulator, power analyzer and MPPT unit
• Battery: 20 elements of 350 Ah at 12 VDC, lead-acid technology
• Tower: 2 units

c) AC Wind turbine power source mode
• Wind turbine: 2 of 6 kW AC mode
• Converters: Two AC/AC and one AC/DC
• Control unit: includes voltage regulator, power analyzer and MPPT unit
• Battery: 20 elements of 350 Ah at 12 VDC, lead-acid technology
• Tower: 2 units

d) Hybrid system with DC wind turbine
• PV array: 20 panels of 480 Wp and the supporting structure
• Wind turbine: Two elements of 6 kW each (DC mode)
• Converters: Two DC/DC and two DC/AC
• Control unit: includes voltage regulator, power analyzer and MPPT unit
• Battery: 8 elements of 350 Ah at 12 VDC, lead-acid technology
• Supporting structure for the PV array and two towers for the wind turbines

e) Hybrid system with AC wind turbine
• PV array: 20 panels of 480 Wp and the supporting structure
• Wind turbine: Two elements of 6 kW each (AC mode)
• Converters: Two AC/AC, one DC/DC, one DC/AC, and one AC/DC
• Control unit: includes voltage regulator, power analyzer and MPPT unit
• Battery: 8 elements of 350 Ah at 12 VDC, lead-acid technology
• Supporting structure for the PV array and two towers for the wind turbines

We estimate a 20% of the investment for installation costs, and 5% maintenance cost per year. The lifespan of every installation is 25 years.

According to the above information, the economic analysis yields (Table 4):

Mode	Investment	Installation	Initial cost	Maintenance	Overall cost
PV	16878/18397	3376/3679	20253/22076	21097/22996	41350/45072
Wind (DC)	17077/18614	3415/3723	20492/22337	21346/23267	41839/45604
Wind (AC)	40858/44535	3415/3723	44273/48258	51073/55669	95346/103927
PV+Wind (DC)	17150/18694	3430/3739	20580/22432	21438/23367	42018/45799
PV+Wind (AC)	32866/35824	3430/3739	36296/39563	41083/44780	77379/84343

Table 4: Economic Analysis of the Selected Installation (€/$)

The analysis of Table 4 shows that the wind turbine AC model increases the initial cost to more than double that of the DC model; therefore, it is not a suitable option for autonomous off-grid installations. The only reason we may adopt this configuration is for an on-grid installation since the cost of the grid connection significantly reduces the initial investment and makes it comparable to the price we should pay for an on-grid wind turbine system operating in DC mode.

Comparing the other configurations, we realize the investment, initial cost, maintenance, and overall installation cost are similar, with a price difference of less than 1.5%. These results show that there are no economic criteria to select one of the three options, PV array, wind turbine, or hybrid system, only technical or willing. PV array or wind turbine sets have a less complex design but require larger battery sizes, resulting in a more expensive additional cost when replacing the battery. Since the lead-acid battery lifespan depends on operating mode and daily depth of discharge, it is difficult to predict how long a battery lasts. Nevertheless, based on previous studies [71-72]. we estimate a 7-10 years lifespan for current operation with renewable energy sources; therefore, for a 25 years operation, we should replace the battery three times on average, representing an additional cost of 15600 € (17000 $), which favors the selection to the hybrid mode.

11. Environmental and Social Impact

The principal power plants in modern society use fossil fuels like coal, petrol, and gas, generating massive GHG emissions that contribute to climatic change and global warming. Using renewable energies is the alternative to avoid continuing to pollute the atmosphere and creating an irreversible environmental impact. Retrieving energy consumption data for the selected installation and considering a standard ratio of 0.825 tCO_2/MWh [73].

The reduction in carbon dioxide emissions is:

$$m_{CO_2} = \chi C = (0.825)(32.4) = 26.73\, tCO_2 \quad (21)$$

Averaging this data over the total population yields:

$$m_{CO_2} = \frac{26.73}{20} = 1.34\, tCO_2 / person \quad (22)$$

Extrapolating to the island population of 120000 people, we have:

$$m_{CO_2} = (1.34)(120000) = 160380\, tCO_2 / year \quad (23)$$

This enormous reduction in CO_2 emissions requires the interconnection between communities and villages, using a local network that compensates for eventual unbalances between energy consumption and power generation related to expected values.

Another factor that influences the viability of the proposed system is the availability of free space to install the photovoltaic panels and wind turbine arrays. If the buildings are of the selected type with flat roofs and a single height, the implementation of photovoltaic panels is guaranteed; otherwise, it is necessary to use available land in the nearby building, which may not be possible in all cases. Available free land near the buildings is necessary for wind turbine installation since placing them far away increases energy losses and reduces power supply, economic profitability, and system reliability.

Large installations in large areas also promote the job creation since the maintenance requires specialized people to deal with; the job creation favors the social impact in the community and benefits people, commercials, and industry.
Additional benefits come from the silent operation of PV arrays and noise reduction of wind energy compared to electric generators to power households in autonomous off-grid communities.

12. Conclusions

PV array or wind turbine set represents a feasible alternative to conventional power sources in self-consumption buildings with low population density and available solar and wind resources.

The PV array or the wind turbine set complements each other to increase reliability, reducing dependence on external sources and contributing to minimizing fossil fuel consumption.

Energy analysis proves that a PV array or wind turbine set supplies enough power to cover household energy demand: daily, monthly, or yearly, using an electric storage unit as an energy reservoir. The hybrid system is economically competitive with a single source, PV, or wind turbine, lowering the battery replacement cost due to the lower battery size. Any of the three power source options, PV array, wind turbine, or hybrid system, shows a similar initial investment, with only technical or willing criteria for selection.

Using renewable energy for household self-consumption installations significantly reduces carbon dioxide emissions, improves air quality, and benefits the environment. It also favors social impact by creating a market niche for people specializing in renewable energy system maintenance.

Implementing renewable energy sources for off-grid houses operating under self-consumption mode is feasible, reliable, and profitable, provided we have space for a PV array or wind turbine location [74].

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