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Analysis for the Implementation of Distributed Renewable Energy Generation Systems for Areas of High Vulnerability Due to Hillside Movements: Case Study of Marianza-Cuenca, Ecuador

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Abstract: This research presents a renewable energy system that takes advantage of the energy potential available in the territory. This study emerges as a relevant option to provide solutions to geological risk areas where there are buildings that, due to emergency situations at certain times of the year during deep winter, are a target of danger and where its inhabitants would find it difficult to abandon their properties. The record of mass movements covering the city of Cuenca-Ecuador and part of the province has shown that the main triggering factor of this type of movement comprises the geological characteristics of tertiary formations characterized by lithological components that become unstable in the presence of water and due to their slopes being pronounced. Hybrid systems are effective solutions in distributed electricity generation, especially when it comes to helping people and their buildings in times of great need and the required electricity generation is basic. A hybrid photovoltaic, wind and hydrokinetic system has been designed that supplies electrical energy to a specific area on the opposite geographical side that is completely safe. The renewable energy system is connected to the public electricity grid available on site; however, in the event of an emergency the grid is disconnected for safety and only the hybrid system will work with the support of a battery backup system. In this study, the Homer Pro simulation tool was used and its results indicate that renewable systems that include PV, HKT and WT elements are economically viable, with a COE of USD 0.89/kWh.

Keywords: hybrid system; vulnerability; renewable energy; buildings; energy

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1. Introduction

Renewable energies (REs) have been present since ancient times but have gained relevance in recent years as an option that is until now the only one in the face of global warming, an aspect widely discussed among experts, rulers and the general public [1]. Currently, the needs for comfort and the growing world population are demanding a significant increase in energy, while fossil fuels are running out and have the disapproval of the majority of the population due to the effects they cause on ecosystems as well as those that mainly affect human beings. There is a growing sense that additional pressure is being placed on traditional energy sources, causing them to fail to meet growing demands for energy needs in different applications such as transportation and residential use [2]. Since the 1970s of the last century, fossil fuels have been reduced, and world powers have been the main extractivists and consumers. Wars have been generated and many deaths have resulted from these policies of capturing subsoil resources such as oil, creating economic inequalities, and it is largely attributed that climate change is related to the combustion of these resources for energy supply purposes [3]. As a result, numerous countries have adopted renewable energy sources (RESs) to reduce their dependence on fossil fuels by seeking once and for all to leave behind the bad experiences lived in different parts of the world and to create solutions for humanity [4].

Regarding the impacts that global warming entails, among several, the effects of landslides due to hillside effects, prolonged droughts, the melting of the poles and changes in the habitat of species are attributed [5]. This article provides an approach to counteract the inevitable effects of landslides due to gravitational effects where there is a population and real estate that require contingency when an incident occurs [6]. The case of Marianza in Cuenca of Ecuador is analyzed, where there is the experience of earth movements impacting a range of buildings due to the drastic event of 27 March 2022 that affected the sector. From this situation, the need has arisen to design an energy system that allows the population to be rescued and property to be protected, specifically at critical moments in the night when landslides cause the destruction of infrastructure linked to the public electrical network [7]. As mentioned before and from now on, this will be addressed in great detail; renewable energies distributed on site are called upon to provide effective solutions from safe spaces where the equipment and service are available [8]. The connection of the renewable energy systems is made to the public electrical network to contribute at all times and to take advantage of the surplus energy to inject it into the network and in turn to take better advantage of the infrastructure, and the grid is disconnected and only the hybrid renewable energy system works when there is an emergency [9].

A series of events related to earth movements have occurred in Ecuador, especially in the southern area in which this research is immersed [10]. The most remembered event of great proportions is that of Josefina [11], as well as that of Alausí [12] and that of Marianza [13]. Earth movements occur in the Ecuadorian highlands because they are crossed by a long mountain range and, especially in winter, the land is susceptible to landslides, causing extremely serious consequences [14]. Focusing a little more on the movement of land masses provides insights into them and can take the form of drops, rises, slides or flows [15]. This may consist of free-falling material from cliffs, fragmented or intact masses that slide down hills and mountains, or fluid flows. Materials can move at speeds of up to 200 km per hour or more and slides can last a few seconds or minutes, or they can be slower, gradual movements over several hours or even days [16].

According to these negative experiences, this study is presented in which the most appropriate option possible is provided for the evacuation of people and safeguarding assets as much as possible in times of emergency with distributed energy systems. The appropriate thing in reality would be to clear the areas; however, from a social point of view it is very complicated for all people to abandon these territories and instead this energy generation system has been designed to provide facilities in times of emergency. It is emphasized that the hybrid renewable energy system is the most appropriate because it is diversified and the energy potential is available for its use and conversion into electrical energy.

Figure 1a shows the landslide at the Marianza site, while Figure 1b shows a view after the land pile on the main road has been resolved. As you can see, several homes upstream and downstream are preserved, but the dangers remain throughout the mountain range.

(a)

(b)

Figure 1. (**a**) General view of the landslide at the Marianza site. (**b**) General view after having resolved the accumulation of dirt on the main road.

1.1. Review of the Literature

The year 2023 saw global renewable energy capacity additions skyrocket by 107 gigawatts (GW), implying that greater confidence has been achieved in these systems. This is the largest increase ever recorded, with 440 GW in 2023 [17]. These values are equivalent to the entire installed power capacity of Spain and Germany combined. The growth that has impressed all energy managers is being driven thanks to changes in country legislation and the expansion of political support that has been encouraged at various summits such as COP 28 in Dubai [18]. However, it is still worrying that the world is still consuming fossil fuels in percentages similar to those in previous years, which implies that polluting energies are not being derailed and are quite strong [19]. The great confidence that renewable energy systems have achieved, which has just been articulated, had to go through a restructuring in the legal bodies of the countries, but it is yet to be internalized among citizens. The renewable energy industry has experienced a slow process that is just beginning to take shape in different regions [20]. Much more rigorous efforts still need to be made to demonstrate the substantial benefits that can be obtained, especially in rural areas [21]. The installation of these renewable energy systems is not difficult, which allows them to be deployed in the territory without major difficulties, mainly in sectors that never had access to electricity. This type of facility will allow for the development of new companies, the guarantee of services within infrastructure, the better use of rural land and the addition of value to products and services, while also creating new jobs [22]. Another important reason is that in locations far from urban centers, periodic transportation will no longer be necessary to transport fuel, which made the final product more expensive and the services received excessively expensive [23]. Finally, these purchased fuels required having adequate space to store them, which on many occasions has even generated accidents and human losses due to lack of security [24].

Different researchers and energy system designers addressed the importance of forming hybrid energy systems, taking advantage of the geographical conditions and the renewable energy potential of the areas [24–28]. Among the various forms of use are open water channels, as their energy capacity can be used by installing small turbines and together with other generation systems, such as wind and solar photovoltaic, it is possible to form hybrid systems [29]. Several authors recommend that before making investments it is advisable to ensure that the electrical demand can technically be satisfied 24 h a day [30–34]. In relation to what is indicated, the research focuses on the modeling of hybrid renewable energy systems to apply to the Marianza de Cuenca Sector in Ecuador, considering its available energy potential and the need to guarantee energy service to the population that is at risk of landslides and the fact that service must be guaranteed at all times [35].

Dibyendu Roy [36] presents the modeling and simulation of an energy system for supplying a remote area on an Indian island. Six different schemes were subjected to environmental, technical and economic analyses to determine the optimal design. In terms of economic evaluations, the lowest levelized cost of electricity was determined at USD 0.31/kWh and the highest return on investment at 26.4%; system six was much more competitive. The sensitivity analysis of the best optimized system was performed.

Access to conventional electrical distribution networks is not always available or is in turn disconnected due to risk situations as is the case of this study, where it has been seen that it is necessary to have a distributed electrical energy system [37]. Distributed generation is known as decentralized generation; it is located in much safer locations and has some important benefits, including low maintenance cost and lower complexity, and it is completely independent in transmission and distribution from generation to distribution. Although it is appropriate to connect to the public electrical network [38], commercial purposes and achieving better use of the surplus electrical power allow for supplying other areas of the region [39]. There are other reasons to use distributed generation, such as backup or emergency generation [40]. It is also recognized as an energy that can maintain important charge levels for the backup system, which is typically battery-based [41]. It is recognized in many international forums and COP 28 for being a source of green energy that uses renewable technology [42]. It is widely used for the electrification of remote places such as islands and areas far from populated centers completely disconnected from the public electricity grid, as highlighted by Daniel Okakwu et al. [43].

Renewable and non-conventional methods of energy generation such as solar, wind, hydraulic, geothermal, thermal storage, biomass and waste heat recovery have renewed the productive matrix of developed countries. Currently, these technologies are beginning to influence the energy systems of developing countries [44]. One recommended aspect is the implementation of hybrid systems [45]. That is to say, the more diversified generation sources are achieved, the more stable the obtained energy mix will be and, if applicable, an energy backup system would guarantee the continuity of the electrical service much more [46]. There are several experiences that confirm the above.

Vikas Khare et al. [47] planned to increase electricity production using hybrid renewable energy systems in exchange for traditional power plants to reduce air pollution. By increasing the number of renewable energy sources instead of a single energy source, hybrid renewable energy systems expand the variety of power generation systems. The numerous technologies available on the market make it possible to design renewable hybrid systems so that consumers have electricity for their various applications. The area that has developed immensely is the optimization of hybrid renewable energy systems, especially the new models that are observed, with some being more efficient than others and having various applications [48]. The analysis carried out by Peter Oviroh and Tien-Chien Jen in [49] regarding hybrid wind and photovoltaic systems is another of the interesting cases at the moment that includes a gasoline generator and analyzes the costs that must be paid for it in comparison with different renewable energy sources, with the trend increasing as more gasoline units are included.

Among the renewable energy systems that include more than two diversified sources, the mathematical model provided by Binayak Bhandari et al. [50] on the integration of small hydro–solar–wind sources stands out. He managed to determine that due to non-linear energy characteristics, wind and photovoltaic systems require special techniques to extract maximum power. The hybrid system has a complex control system due to the integration of two (or more) different energy sources.

Mohamed S. Soliman et al. [51] developed an energy management system monitoring an integrated hybrid battery/photovoltaic/tidal/wind source to supply power to a DC microgrid.

Rajib Lohan Dash et al. [52] conducted an energy, economic and environmental assessment of a hybrid tidal energy, biodiesel generator and wind energy system with energy storage for an Indian archipelago. Samuel Sami [53] also performed a mathematical model and simulation of the energy conversion equations that describe the total power generated by a hybrid solar photovoltaic and geothermal system. The model was intended to be used as an optimization and design tool model to predict results in fair comparison to the experimental data under various operating conditions. Mohamed Nasser et al. [54] performed an evaluation of the performance of the hybrid system of photovoltaic panels/wind turbines for the generation and storage of green hydrogen. The minimum and maximum value of LCOE was determined to be USD 0.137 to 0.219/kWh, LCOH to be USD 3.73 to 4.656/kg and LCOCH to be USD 5.922 to 7.35/kg.

Among the novel applications of hybrid systems are several, including Fernando Mejía Nova et al. [55] who presented a study of a hybrid wind/photovoltaic system to supply a set of buildings in the model of airplanes. The results showed that systems that include this diversity of generation sources have a higher cost but there is more guarantee of maintaining your charge levels in the batteries above 40%. In this same sense, reference [56] presents a hybrid solar photovoltaic and wind system for the reception and processing of satellite and microwave signals, thereby guaranteeing the telecommunications service at the level of the end customers. Jonathan Acosta et al. [57] carried out the modeling of a hybrid generation system for domestic use in isolated areas of Ecuador. Danny Ochoa and Sergio Martinez [58] performed innovative modeling of an isolated hybrid wind/diesel energy system to conduct frequency control studies for San Cristóbal Island in the Galapagos Archipelago.

Józef Paska et al. [59] went further with his research and presented an effective way to use primary energy sources. In experimental validation, he used Typhoon Hardware-in-the-loop HIL-402 devices in real-time operation.

1.2. Control Approach

Until some time ago, controlling energy systems in remote places or communities with limited electrical infrastructure was a real challenge, especially when single sources were available and it was difficult to configure hybrid systems because diversified energy potentials were not available in the areas [60]. Nowadays, these difficulties have been overcome and the control systems are much more sophisticated and their costs tend to be increasingly reduced [61]. Currently, great progress has been made in the area; energy control systems have been developed for smart homes. The researcher who has stood out the most in recent times is Marcos Tostado and he has two important investigations such as [62,63]. In their studies, certain authors have shown great stability in the operation of the control equipment as detailed in references [64,65]. In Ecuador, current legislation already allows for the installation of renewable energy systems with connection to the public electrical grid [66], that is, surplus energy can be injected into the electrical grid and in the case of an energy deficit it can be absorbed directly. However, in this study it is considered that human lives and the preservation of property are above all else; security in Ecuador is a right that the state must guarantee [67]. At an economic level, it is certain that economic items increase especially if energy backup systems are included, but when it comes to the security and human beings at risk, this last aspect prevails. To design the efficient management of resources and allow for the optimal functioning of each component and the general system, it was planned that from the load point of view it would be consumed as efficiently as possible [68]. That is, from the beginning, energy efficiency criteria are included; in the case of lighting systems, they must be changed to LED bulbs. The other systems remain as they are, because a radical change in the lives of the residents is not expected, which is an aspect to take care of. Ultimately, each application has particular requirements and, therefore, specific control objectives, as illustrated in [69].

1.3. Methodology

The scientific methodology used for the design of the hybrid renewable energy generation system for the Marianza Sector in Cuenca of Ecuador included the use of 100% renewable generation sources potentially available at the site that is at high risk of gravitational earth movements of a mountain range. In this study, the use of fossil fuels is not considered at all due to the nature of the sector, being highly vulnerable and experiencing possible landslides, which can cause explosions or material damage to the homes that need to be protected. To carry out this investigation effectively, we use the Homer Pro design tool that allows us to determine the effective interaction of this hybrid system that will regularly be connected to the public electrical grid and if an imminent risk is detected, the electricity sector will be disconnected. Furthermore, the public electrical grid will operate as an autonomous system specifically for this sector. The purpose is to guarantee electrical service in the sector or homes that are free of difficulties to provide help to the surrounding areas. Methodologically, the social and economic aspect is analyzed with the corresponding results in the study area.

In the methodological analysis of this study, the Homer Pro tool is used; considered by several researchers as a very versatile tool, it has an updated data structure of the existing equipment on the market and allows simulations to be carried out in different conditions. It is possible to establish a direct link with Matlab to present much more organized data and in an interactive graphical way; then, calibrations or optimization can be carried out according to the designer's interests in the operation of the hybrid system. This tool also allows you to perform an economic analysis and establish the years at which the system becomes profitable. The process for the design of the hybrid system is presented in Figure 2.

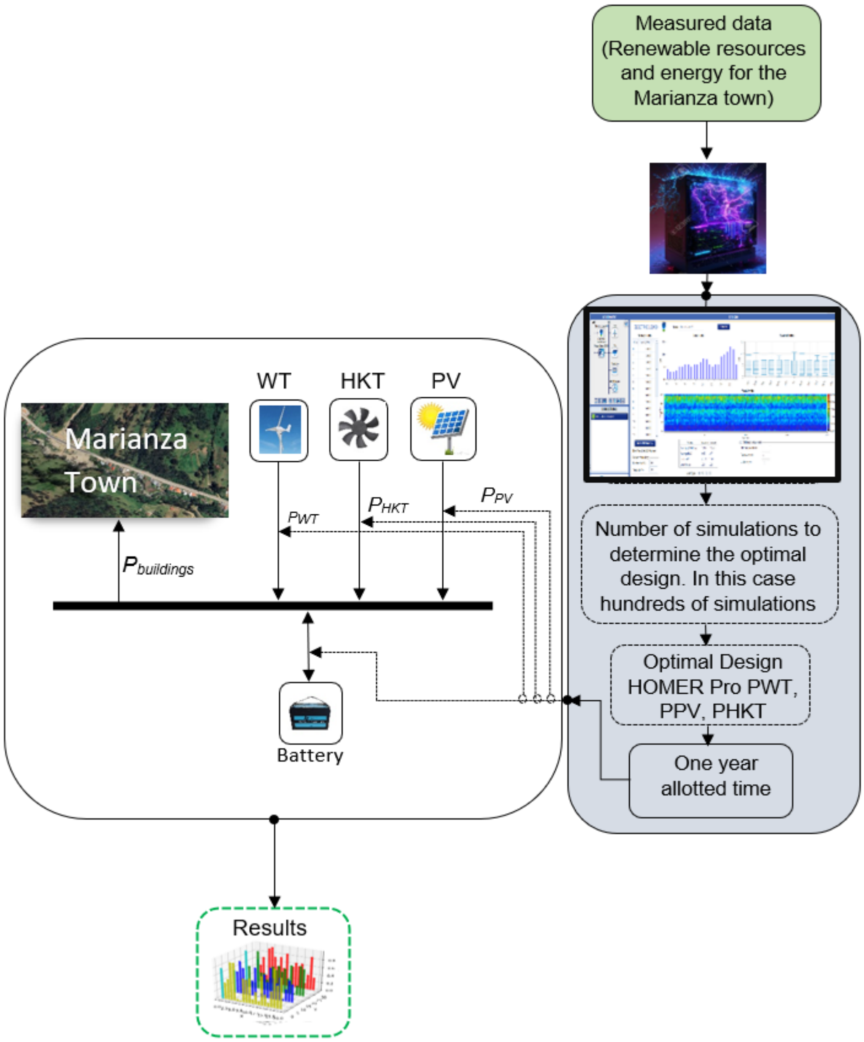
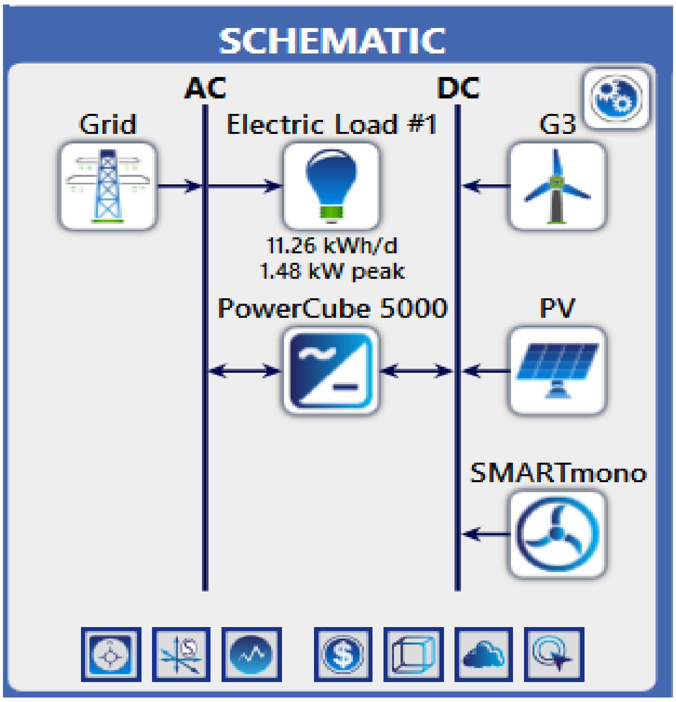


Figure 2. Methodological process of the hybrid renewable energy system for Marianza in Ecuador.

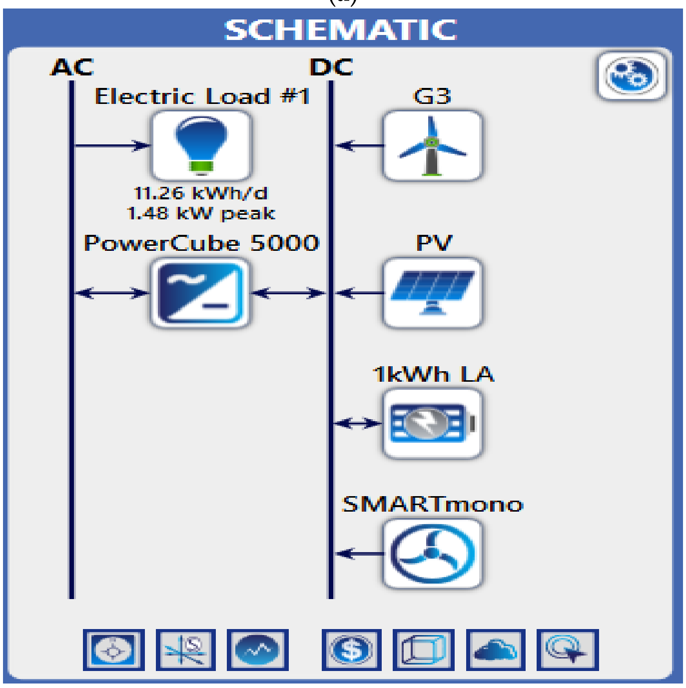
The study is organized as follows: In this first section, the introduction, review of the literature and methodology are specified, Section 2 presents the photovoltaic, wind and hydrokinetic hybrid system structure and Section 3 presents the modeling and simulation of the hybrid system designed for the town of Marianza. In Section 4 the social effect of implementing this type of facility is analyzed and in Section 5, the respective conclusions are finally issued.

2. Hybrid PV/Wind/Hydrokinetic System

Figure 2 shows a renewable energy system composed of wind, solar photovoltaic and hydrokinetic energy sources. In Figure 3a, the renewable energy sources are produced in direct current (24 V) and by means of a modern inverter, energy is supplied to the Marianza area in alternating current and its surpluses are fed to the public electrical grid or in turn when there is no power. When producing enough energy at some time of the day, it is absorbed from the network. Figure 3b shows that in the event of an emergency, the public electrical network is vulnerable because it is located along the road that, in the event of a gravitational movement of earth masses from the heights of the mountain ranges, is the first to be affected and to avoid greater impacts on homes, it is appropriate that the electrical grid be permanently disconnected. This is where the distributed renewable energy system and its backup system using batteries is essential in times of crisis; the electrical infrastructure that can be overturned is avoided and energy can be supplied to specific points from the other side of the area that is much more stable.



(**a**)



(**b**)

Figure 3. Schematic studied in Homer Pro to be implemented in Marianza. (**a**) Regular connection of the renewable energy system to the public electrical grid. (**b**) Renewable energy system with battery backup to respond to an electrical emergency in the Marianza Sector.

Our lithium battery charging control module is programed to start and end charging [70]. Below, Figure 3 shows the hybrid system that is implemented for this case study.

2.1. Daily Profile

In the place under study, a hybrid system is projected, taking advantage of the energy potential available in the territory, comprising wind, solar and hydrokinetic sources. For the purposes of guaranteeing service for the demand, the load was evaluated and the characteristic hourly data of the demand in the sector is used and entered into the Homer Pro tool as seen in Figure 4. The highest demand values are at around 20:00 and 22:00 of the day with peaks between 12 kW and 13 kW. The end-of-load power values should be fully covered by the renewable energy system according to the effective design of the hybrid generation system. If the demand for the electrical load is lower in the sector, generation maintains its generation profile and its surplus power can be used to be injected into the public electricity grid. In the event that for some exceptional reasons the demand increases or the hybrid system does not produce enough energy, energy flows are received from the public electrical grid. The maximum daytime load is 9.2 kW and at night it is 13 kW. It is also important to indicate that when there is an emergency due to the imminent risk of a landslide, the public electricity grid is disconnected and only the hybrid system operates. To prolong the electrical service in the area, a battery bank is included.

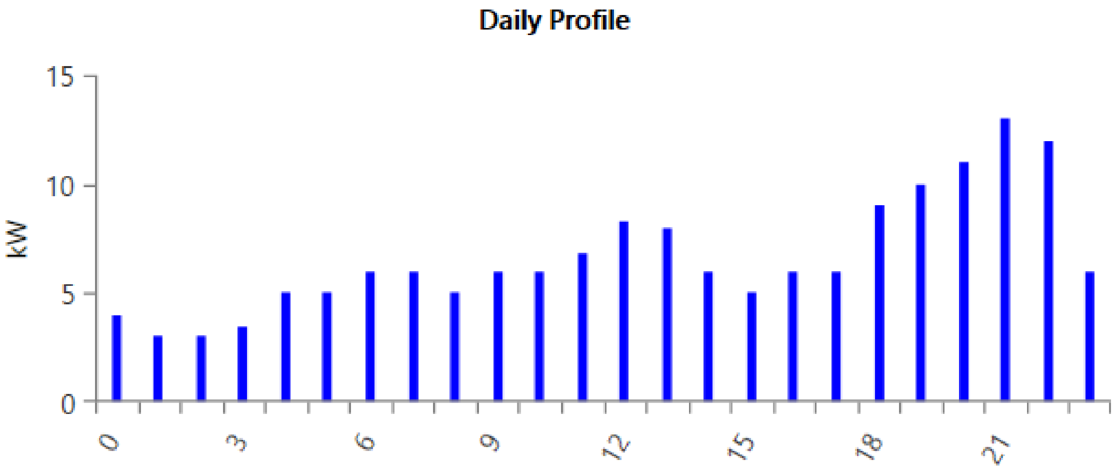
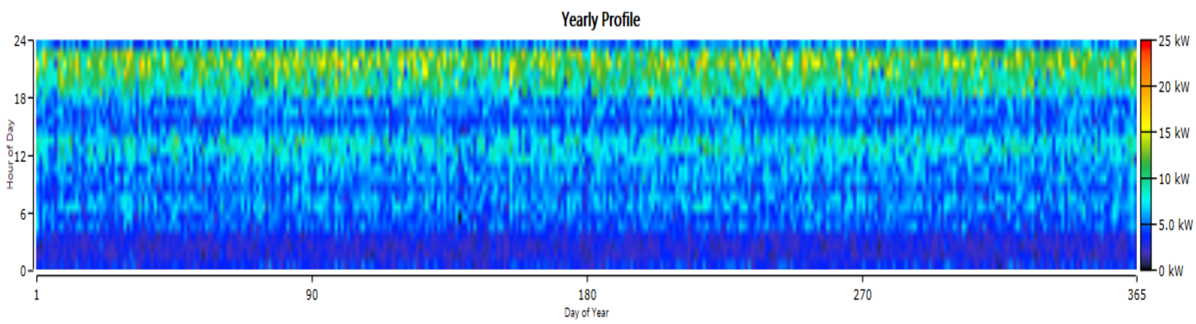


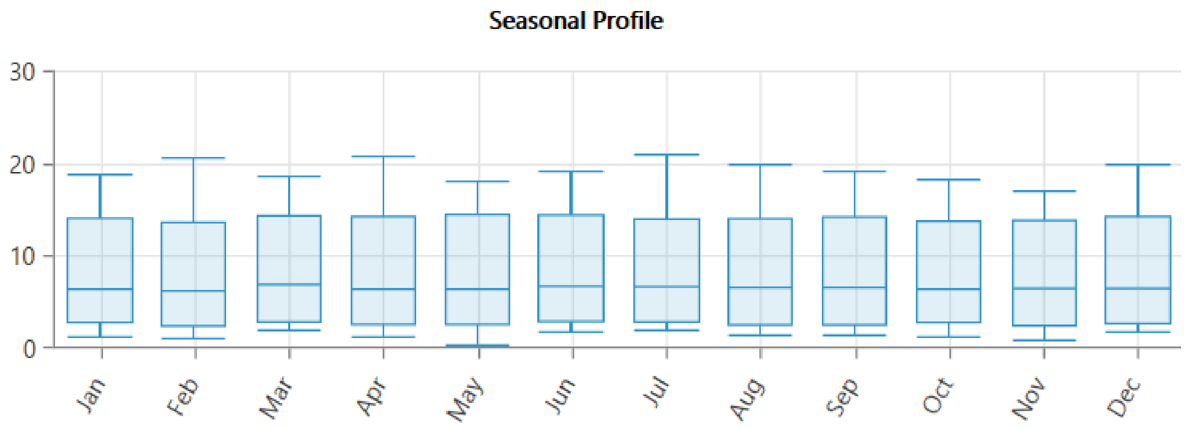
Figure 4. Electricity demand profile in Marianza, Ecuador.

Below, Figure 5a shows a spectrogram where the annual power demand is represented as a function of the hours of the day; meanwhile, in Figure 5b the seasonal profile is shown in monthly box diagrams and it does not exceed 21.2 kW of power.



(**a**)

Figure 5. *Cont.*



(**b**)

Figure 5. Yearly load profile. (**a**) Spectrogram of annual electricity demand. (**b**) Seasonal power profile represented in monthly box plots.

2.2. Renewable Hybrid System Model

The hybrid system designed in this study consists of three renewable sources, which are hydrokinetic (HKT), photovoltaic (PV) and wind (WT), with typical connection to the public electricity grid. However, due to the absence of the grid due to exceptional emergency cases, there will be a backup power system using batteries.

2.2.1. Hydrokinetic Turbine

In this research, a small open-channel hydrokinetic turbine is used to take advantage of the water currents coming from the sinkholes of the Cajas Sector. The selected turbine is 5 kW, operates from 0.5 bars of pressure and its pressure loss is negligible. The maximum hydraulic working pressure is 4 kg/cm^2. The volumetric flow rate 12 L/s. It is a fairly economical piece of equipment, available in the Ecuadorian market and is quick to pay for itself. With the implementation of this type of turbine, the energy supply will not be affected; it is environmentally friendly type of equipment and can be installed on the side of the canal, without affecting the flora and fauna of the sector at all. It also does not produce a visual impact; the installation is in line with the pipe. The size is very small and does not require exhaustive maintenance, and routine maintenance would be enough; moreover, it has a 2″ inlet and outlet and a very high performance with 1 kW/h. The working voltage is a 24-volt direct current.

The power generated by the hydrokinetic turbine P_{HKT} at an instant of time t is evaluated by Equation (1) where the area HKT A is given in m^2, ρ_W in kg/m^3, which is the function of the density of the water, v is the speed of the water flow in m/s, ($C_{p,h}$) is the combined efficiency of the HKT generator and η_{HKT} is the combined efficiency of the HKT generator.

$$P_{HKT} = \frac{1}{2} * \rho_W * A * v^3 * C_{p,h} * \eta_{HKT} * t \;\; [\text{Watts}] \tag{1}$$

For fluid velocity measurements, a flowmeter is used and the measurements were made in the open channel coming from the Cajas slope. The minimum speed was recorded at 2.1 m/s, the normal maximum speed reached 3.9 m/s; on average it is 3.1 m/s. These speeds are quite good; they are presented as a suitable option to generate energy in conditions such as those determined in this place. The turbine was selected based on availability in the market and is included in the databases of the Homer Pro tool, being a piece of equipment that best matches the speed characteristics determined on site; greater detail is presented in Table 1.

Table 1. HKT parameters.

Model	Smart Monofloat 5 kW
Country of origin	China
Manufacturer	Smart Hydro power GmbH
Dimensions	Length: 3130 mm Width: 1600 mm Height: 2010 mm
Weight (Kg)	380 kg
Number of rotor blades	3
Rotor φ	1000 mm
Capital cost (USD)	12,450
Replacement cost (USD)	12,450
O&M (USD/year)	450
Max. power output	2.82 m/s—5 kW

To calculate the total energy produced during the year, all the hours that the smart hydrokinetic turbine was active during are considered using Equation (2) presented below:

$$E = \sum_{t=1}^{t=8760h} P(t) * t \ \ [\text{Joules}] \tag{2}$$

2.2.2. Photovoltaic Solar Panels

The site to be electrified is in a phase of arduous investigation in different aspects. Solar power is considered as the main source of energy supply in this study due to the high solar radiation available at the site; preliminary results have determined this in reference [71]. For this study, photovoltaic solar energy in general terms is key to guarantee the production of energy on demand, and a better use of the environmental benefits is achieved with WT and HKT and when combined it is possible to obtain a much more guaranteed system with these new contributions without involving a high financial investment.

The PV module used in this study is a monocrystalline type; it has 166 mm cells with nine bushbars, at 24 V, of 230 Wp. It is suitable to be placed on roofs or clear sites; its installation is simple and it is easily attached to other equipment such as modern inverters and charge controllers. The technical details are presented in Table 2. Solar radiation is intense in this place, especially at midday, so solar PV energy has now become a technology of great interest for various applications both at urban and rural levels, and with it being an inexhaustible source, the production costs of this technology are increasingly trending downward. The output power of the solar PV system is given below in Equation (3):

$$P_{pv} = f_{pv} * Y_{pv} * \frac{I_T}{I_S} \ \ [\text{Watts}] \tag{3}$$

where f_{PV} is the progressive reduction factor, and it depends on situations such as loss of power due to the distance in the conductors, due to splices or terminal installations or due to a lack of cleaning on the surface of the PV. Temperature variations also influence the performance of the solar PV. I_S is considered as a base value of 1000 W/m^2 knowing that it is an optimal value of the desirable irradiation, I_T is known as the total incident radiation on the surface of the solar panels (kWh/m^2) and Y_{PV} is defined as the nominal capacity of the group of PV solar panels.

The temperature of the PV cells is transcendental and must be considered in the evaluation according to Equation (4):

$$T_C = T_{amb} + G_S \left(\frac{NOCT - 25}{1000}\right) \ \ [^\circ\text{C}] \tag{4}$$

where $NOCT$ is the normalized temperature of the cell that is considered with global radiation of 1000 W/m^2, with a reference ambient temperature at 21 °C. G_S represents the global solar irradiation and T_{amb} is the ambient temperature.

Table 2. Photovoltaic solar panel parameters.

PV Model	RS7E-230M
Maximum power	230 Wp
Manufactory	RESUN SOLAR
Control box	IP67
Open circuit	24.10 VDC
Short-circuit current	11.99 A
Dimensions (mm)	1560 mm × 700 mm × 35 mm
Number of cells (4 × 9.5 bushbars)	36 Cells
Capital cost	USD 250/200 Wp
Replacement cost	USD 250/200 Wp
O&M cost	USD 0
Derating factor	0.7
Slope	15 degrees
Lifetime	25 years

2.2.3. Wind Turbine

Generation depends mainly on the inlet wind speed (v_W). R is the turbine radius, the relation λ is defined as $\lambda = R\omega_m/v$ and ω_m is the velocity angle of the turbine shaft. Other parameters also intervene such as ρ_a being air density and C_p being the Betz coefficient that is in function angles β and λ. The power P_{WT} generated by the wind turbine can be evaluated using Equation (5).

$$P_{WT}(t) = \frac{1}{2}C_p(\lambda,\ \beta)\rho_a A{v_w}^3\ \ [\text{Watts}] \tag{5}$$

The power energy depends directly on the wind speed in two regions as follows:

(1) Wind speed below nominal. This is experienced when the load is below the nominal power P_{WT}^{ab}. By having wind speeds that exceed the nominal value, the turbine delivers constant power. If there is a very excessive speed that exceeds 20 m/s, the wind turbine stops for safety. As a reference, the minimum speed is v_i and the cutting speed is v_c.

(2) Turbine operation with a speed higher than the rated wind speed v_r.

The power output of the wind turbine is a function of wind speed as shown in Equation (6), detailed by reference [72]:

$$P_{WT}^{av}(t) = \begin{cases} 0\ if\ v_w < v_i \\ \frac{1}{2}C_p(\lambda,\beta)\rho_a A v^3(t)\ if\ V_i\ \leq v_w\ \leq\ v_r \\ P_w^r\ if\ v_r < v_w < v_c \\ 0\ if\ v_w >\ v_c \end{cases} \tag{6}$$

The parameters of the wind turbine are shown in Table 3.

Table 3. Wind turbine characteristics.

Model	G3 Wind Turbine
Manufacturer	Pika Energy
Cut-in wind speed	3 m/s
Capacity	3 kW
Blades	3
Rotor diameter	3 m
Capital (USD)	6000
O&M (USD/year)	500
Replacement cost (USD)	6000

2.2.4. Batteries

Using a battery bank, it is possible to store the excess energy produced by the hybrid system, especially if the connection to the grid is released and it works autonomously. The backup system increases the reliability of the electrical service by remaining 100% operational in the area. Since there are natural risks, as is in the case that we address in this study, it is appropriate that the service provided is maintained to operationalize actions in favor of the community that may be affected. Several of the events that occurred in Ecuador, such as the case of Rircay, Manabí and the town of Marianza itself, have left experiences whereby electrical energy has been the weakest point in limiting relief to the vulnerable population; many lives have been lost because the emergency entities could not act in time, for which, in this study, we propose promoting a continuous electrical service. As long as there is a connection between the electrical system and the public network, surplus energy will be injected.

The battery bank N_{bat} is calculated using Equation (7) whereby according to the projection of the hybrid system, which is generally 25 years, it is recommended to make the corresponding replacements.

$$N_{bat} = cell\left(\frac{Life_{HS} \, * \, Life_{bt}^{pu,year}}{T_{bat}^{life}}\right) \tag{7}$$

T_{bat}^{life}: period of time counted from installation until the battery bank is replaced.
$Life_{HS}$: parameter that determines the useful life of the entire hybrid system.
$Life_{bt}^{pu,year}$: specific battery life during the last year.

The state of charge (SOC) of the battery is considered according to the main parameters detailed in Table 4. In the storage system, two modes are established, which are charge and discharge, as evaluated by Equations (8) and (9) [73]. The energy storage system using batteries is directly related to the renewable energy generation system from the hybrid system, which in this case is from the three energy sources that supply the town under study.

Table 4. Battery characteristics.

Model	Kinetic Battery
Nominal capacity (kWh)	4
Nominal voltage (V)	12
Maximum capacity (Ah)	38
Capacity ratio	0.403
Roundtrip efficiency (%)	85
Rate constant (1/h)	2.77
Maximum charge current (A)	56
Maximum discharge current (A)	76
Replacement cost (USD)	700
Cost of capital (USD)	700
Operation and maintenance (USD/year)	15

η_{cbat} and η_{dbat} are the battery charge and discharge efficiencies, respectively. The SOC (t) is the state of charge of the battery at time t. E_{bat} is the battery capacity.

$$SOC(T) = SOC(t-1) + \frac{E_{bat}(t) * \, \eta_{cbat}}{P_{bat}} * 100 \tag{8}$$

$$SOC(T) = SOC(t-1) + \frac{E_{bat}(t) * \, \eta_{dbat}}{P_{bat}} * 100 \tag{9}$$

Energy generation and consumption are calculated as a function of time as follows:

- $P_{PV}^{T} + P_{HKT}^{T} + P_{WT}^{T} > P_{DEMAND}^{T}$: the total power generation of the hybrid system exceeds the load demand.
- $P_{PV}^{T} + P_{HKT}^{T} + P_{WT}^{T} = P_{DEMAND}^{T}$: the battery is totally stable and does not change.

In this case, the battery is 100% charged in time (T) and given by the following:

$$E_{bat}^{T} - E_{bat}^{T-1} \cdot (1 - \tau) + \left[\left(P_{PV}^{T} + P_{HKT}^{T} + P_{WT}^{T} \right) - \frac{P_{l}^{T}}{n_{inv}} \right] n_{bc} \tag{10}$$

where:

n_{inv}: efficiency of the inverter.
E_{bat}^{T} and E_{bat}^{T-1}: battery charge amounts at times $T-1$ and T.
n_{bc}: charge efficiency of the battery bank.
P_{l}^{T}: energy received by the demand in a specific hour.
τ: hourly self-release rate.
P_{PV}^{T}: power produced by the PV panel.
P_{WT}^{T}: power produced by the wind turbine.
P_{HKT}^{T}: power produced by the HKT source.
$P_{PV}^{T} + P_{HKT}^{T} + P_{WT}^{T} < P_{DEMAND}^{T}$: In this case, it is established that the load demand exceeds the total power generated by the hybrid system. At this time, the battery is in a position of liberation of its stored energy, as is expressed in Equation (11) [74].

$$E_{bat}^{T} - E_{bat}^{T-1} \cdot (1 - \tau) + \left[\frac{P_{l}^{T}}{n_{inv}} - \left(P_{PV}^{T} + P_{HKT}^{T} + P_{WT}^{T} \right) \right] n_{bf} \tag{11}$$

n_{bf}: battery discharge efficiency.

2.2.5. Inverter

The maximum dc to ac conversion capacity of the power inverter ($P_{inv}(t)$) depends on the inverter efficiency. It is expressed in Equation (12):

$$P_{o}(t) = P_{i}(t) \eta_{inv} \tag{12}$$

The input power to the $P_{i}(t)$ inverter will be given by the renewable energy system. In this study, the efficiency of the inverter is 96%.

2.2.6. Total Power

The total power obtained from the hybrid system configuration is defined in Equation (13):

$$P_{total}(t) = \sum_{pv=1}^{Sn} P_{PV}(t) + \sum_{WT=1}^{So} P_{WT}(t) \sum_{w=1}^{Sm} P_{HKT}(t) \tag{13}$$

where Sn, Sm, So are the total number of PV modules, wind turbines and hydrokinetic turbines, respectively.

2.3. Techno-Economic Analysis

The PV solar system is fundamental, and hydrokinetics and wind energy are incorporated into this source for its optimal configuration. It is important to establish the Net Present Cost (NPC) of the set of equipment that makes up the hybrid system presented in the previous sections to a minimum. On the other hand, to determine the Total Annual Cost (TAC), within the investigation, it is determined by Equation (14):

$$TAC = C_{acap} + \sum_{i=1}^{n} C_{0\&M,i} + C_f + \sum_{i=1}^{n} C_{R,i} \tag{14}$$

Contemplating a scheme of minimized costs $MinM_t(P_{pvD}(t), P_{pvA}(t), P_{wt}(t), P_{Bat}(t), P_{hkt}(t))$, each contribution seen from the point of view of its own restrictions is evaluated through Equation (15):

$$MinM_t\left(P_{pvD}(t), P_{pvA}(t), P_w(t), P_{Bat}(t), P_{hkt}(t)\right) = Min\left(M_{pvD}(t), M_{pvA}(t), M_{wt}(t), M_{Bat}(t), M_{hkt}(t)\right) \tag{15}$$

where M_t is the cost of the renewable energy system.

$M_{pvD}(t), M_{pvA}(t), M_w(t), M_{Bat}(t), M_{hkt}(t)$ are parameters that refer to the individual costs of each technology and its complements for the joint operation of the hybrid system.

To determine the total costs of the hybrid system, it is evaluated using the NPC parameter. It is calculated by Equations (16) and (17).

$$M_{NPC} = \frac{M_{ann,Tot}}{CRF\left(i, R_{proj}\right)} \tag{16}$$

where M_{NPC} is the net current cost, $CRF\left(i, R_{proj}\right)$ corresponds to the capital recovery factor with an interest rate of 1%, $M_{ann,Tot}$ is the total annual cost in USD/year and R^{th} is the lifetime of the project in years, as seen in Equation (17).

$$CRF(I, N) = \frac{I(1+I)^N}{(1+I)^N - 1} \tag{17}$$

N = Number of periods (years).

I = Interest rate.

The Cost of Energy (COE) is an essential parameter; the mathematical relationship is presented in Equation (18):

$$COE = \frac{M_{ann,Tot} - M_{storage}E_{thermal}}{E_{primAC} + E_{primeDC} + E_{def} + E_{gridsales}} \tag{18}$$

3. Modeling and Simulation

The objective of this study is to design a hybrid renewable energy system that guarantees electrical service to the population of Marianza, a town exposed to a risk of landslides and also prone to power outages from the public electrical network that is located on the edge of the road, which is the first infrastructure is to be affected; therefore, it is essential to boost the infrastructure, including through a renewable energy system that operates if there is an absence of the public electrical grid. Based on meteorological data related to PV, WT and HKT sources, the aim is to take advantage of energy resources and supply the total demand of the sector. The objective includes an analysis using the energy conversion structure using the Homer Pro tool as described in Figure 6.

3.1. Data Entry

In this case study, it is important to indicate that the equipment that installed to form the hybrid system is in safe spaces, free of terrain instability. That is, according to the topography of the land, there are facilities from the back side of the river in which a long strip of land is available and has sufficient parameters for the generation of renewable energy in the proportions necessary to supply the demand that was previously already detailed. It is appropriate to establish the most optimal locations on the site, especially in the position of the wind turbines, the avoidance of shadows from trees on the solar panels and the position for the water inlet of the hydrokinetic turbine, among others. The parameters detailed below are essential input data for the analysis of the design and simulation tool, such as solar radiation, wind speed and water kinetics.

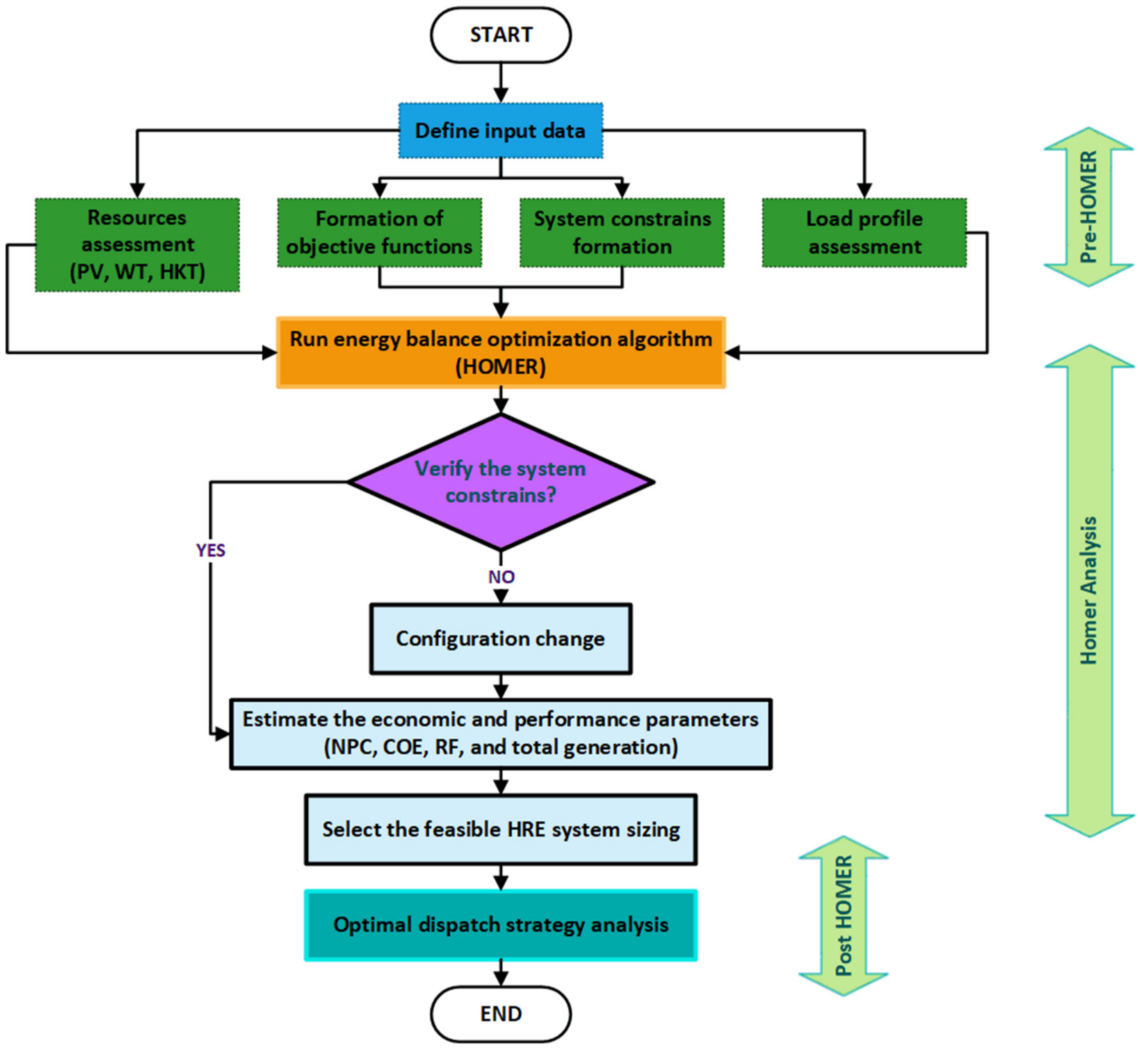
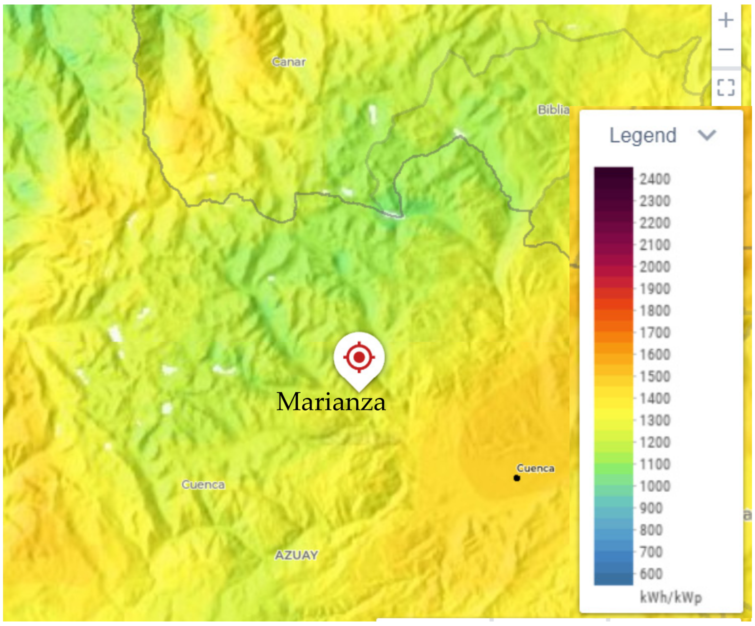


Figure 6. Flowchart for analysis using Homer Pro for hybrid system sizing.

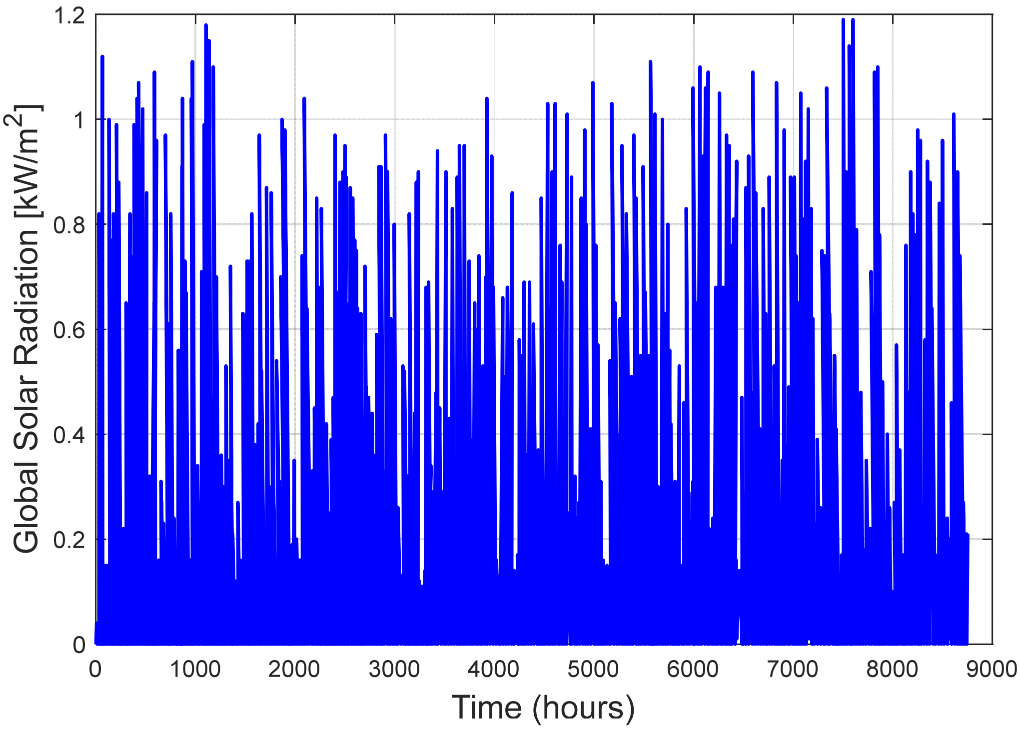
3.1.1. Solar Radiation

Various studies indicate that one hour of solar radiation available on the surface of our planet provides enough energy to keep the global economy supplied for a year [75]. This free and distributed energy is still not well used; the problem is in our ability to take advantage of this energy [76,77]. On the other hand, in relation to Ecuador, according to previous studies provided by [78,79], it is a privileged country in terms of solar resources, with the main advantage being located on the equinoctial line. The angle of incidence of sunlight is perpendicular to our surface. For comparison, the data is taken from a global solar incidence that illustrates this characteristic: in Spain there is 1400 kWh/m^2 year, while in Ecuador there is 4200 KWh/m^2 year [80,81]. In relation to an analysis site such as Marianza, 3700 KWh/m^2 year is available as identified in [82]. As such, important data provide evidence of the solar potential that the country has, which contributes to cover its energy demand in conjunction with other sources of renewable energy that are also variable but which together would be of great contribution to the site under study [83].

Figure 7a shows the solar radiation levels in the town of Marianza using the Global Solar Atlas tool [82], while Figure 7b presents the annual solar radiation profile.



(**a**)



(**b**)

Figure 7. Solar radiation in Marianza. (**a**) Solar radiation levels using the Global Solar Atlas tool. (**b**) Annual solar radiation profile.

3.1.2. Wind Speed

Wind energy is a clean source and, as a mature and economically competitive exploitation technology, is positioning itself as the fastest growing energy source in the world to the point that today there are already studies of bladeless wind generators as highlighted in [84].

In the global context, Europe already has the so-called Energy Sobriety Plan to accelerate the mobilization of the entire population towards the reduction in the consumption of fossil fuels [85] such as gas, gasoline, diesel and oil; renovate old homes with gas installations by switching to electric ones; harness wind and solar energy; and decarbonize transport and industry [86]. In this way, the population will be prepared for an imminent interruption of energy exports from Russia [87].

In Ecuador, wind energy has been used to a large extent, and it is already being used on San Cristóbal Island in the Galapagos Archipelago with a capacity of 2.4 MW [88]; in the Province of Loja, on the Villonaco hill, with an installed power capacity of 16.5 MW [89]; on Baltra Island, a capacity of 2.25 MW was achieved [90]; in Minas de Huascachaca on the border between Azuay and Loja, there is a capacity of 50 MW [91]. Using the Global Wind Atlas tool [92], it is possible to have data from various locations and explore wind potential for energy use, such as that of Marianza in Ecuador, with an average of 8.12 m/s as presented in Figure 8a.

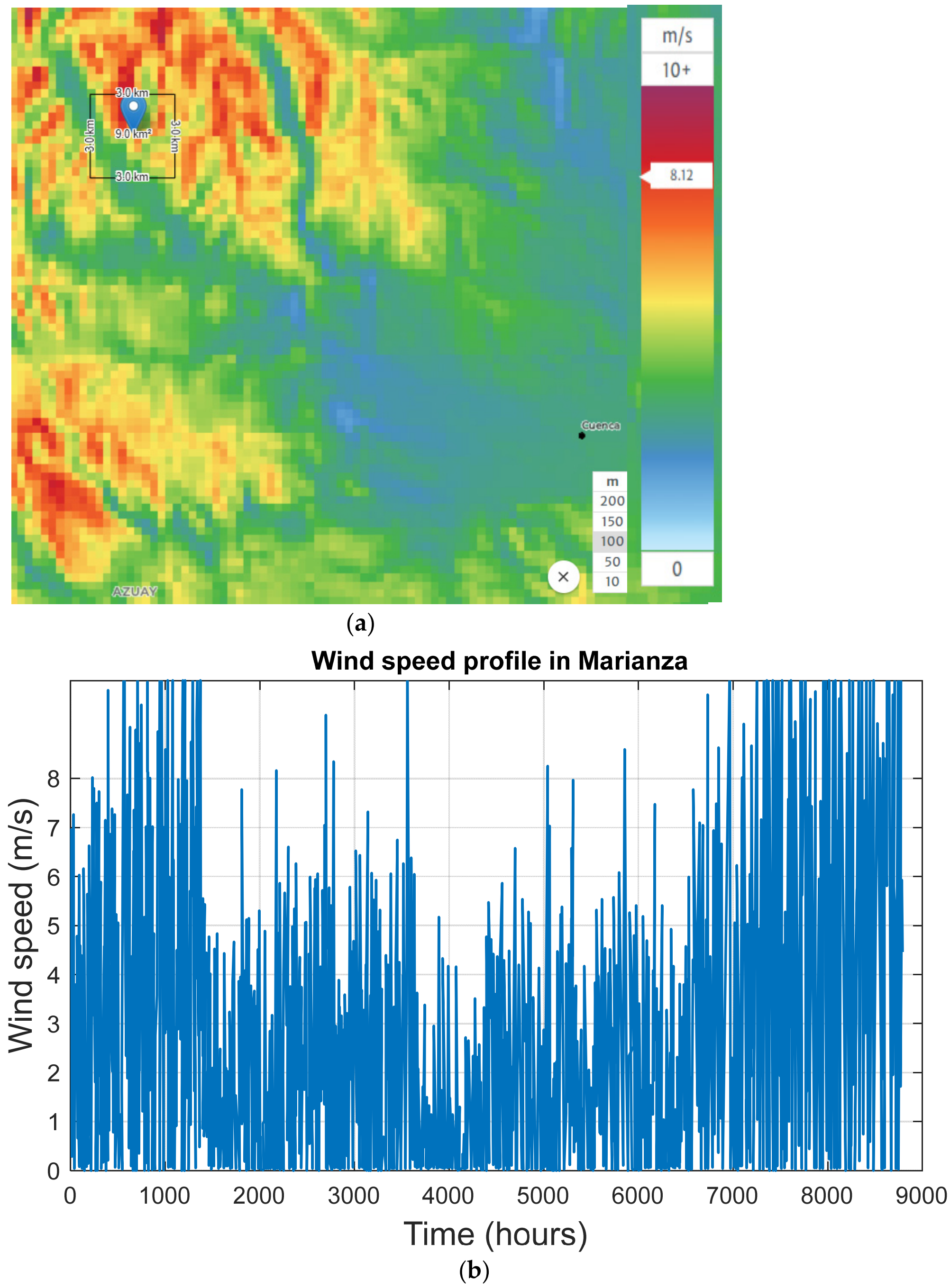
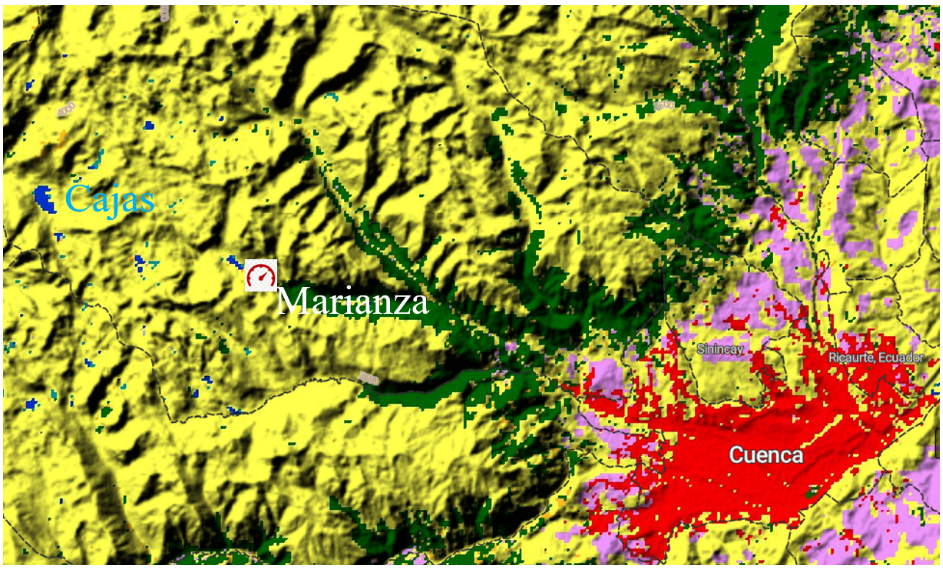


Figure 8. Wind speed in Marianza. (**a**) Wind speed using the Global Wind Atlas tool. (**b**) Annual wind speed profile.

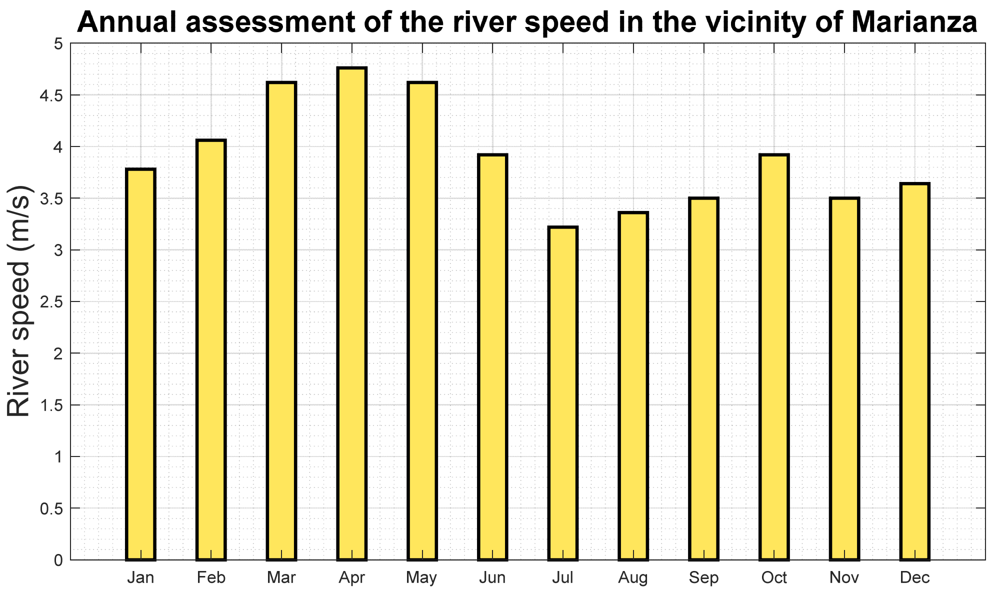
Figure 8b shows the annual wind speed profile in the town of Marianza.

3.1.3. River Speed

The Cuenca Canton, in most of its extension, has a large number of channels, streams and rivers within the interior of the province with different characteristics and with some being very conducive to generation due to their topographic characteristics such as large slopes, breaks and waterfalls. The Cajas area is an area rich in aquifer springs; its topography lends itself very well to low-scale energy generation but is very useful for surrounding areas, thereby being the interesting thing about this non-polluting technology. This study is in search of the virtuous and responsible use of renewable natural resources in order to determine technological feasibility for their sustainable use for energy development purposes (Figure 9b). The energy provided by rivers is used to obtain mechanical work and, from this, electrical energy.



(a)



(b)

Figure 9. Annual hydrokinetic data. (**a**) Place where an open channel free of geological risks is located. (**b**) Annual assessment of the river speed in the vicinity of Marianza.

An alternative or unconventional way to generate electricity is the use of kinetic energy from rivers. This type of generation is part of in-stream technologies, made up of microturbines and wheels or mills similar to waterwheels. These take advantage of the kinetic energy of a stream or river, converting it directly into mechanical shaft work. These designs allow for practical low-head, low-pressure technology eliminating the need to store large volumes of water. It is one of the valuable alternatives for energy generation; it can be used in places where there is opposition to mega electrification projects, as this system extracts energy for the production of electricity mainly from the available flow of the available water channel. The generation profile will depend to different degrees on local flow conditions. As a result, generation is dependent on precipitation and runoff, and it can have substantial daily, monthly or seasonal variations, especially when found in small rivers or streams that experience highly variable flows.

The presence of open water channels in the study area allows for the implementation of mills or microturbines connected to a low revolutions per minute (rpm) electrical generator to obtain electrical energy in a clean, constant and economical way. An advantage of this type of renewable energy, compared to others such as solar or wind (which are intermittent), is that the river flows 24 h a day, every day of the year, taking into account its seasonal variations with respect to flow. Next, Figure 9a presents the annual assessment of the river speed in the vicinity of the Marianza Sector.

3.2. Equipment Selection

When sizing the equipment, it is important to ensure that it is available on the market, its quality and recognition are considered and most of the equipment is included in the Homer Pro databases, and this is important when simulating the operation of the hybrid system and obtaining the operating results under the conditions specified in the area. The purpose is to be certain of satisfying the electrical demand of the population under study. Having specialized software, with high performance and recognition from several researchers and decision makers, is an important aspect to carry out a comprehensive evaluation from both a technical and economic point of view. The use of computer tools is the most appropriate in this aspect, with the equipment configurations and energy combinations being identified at different times of the day. It will also be possible to determine the effective performance on the battery bank in the event that there is no connection to the public electrical grid. The determination of the equipment, although it is developed from a technical-economic point of view, ends when the designer is certain that the results meet the conditions and expectations of the study, as well as the social approach that is intended to be provided, as proposed in this study. This is where the energy system becomes key; it is innovative and very applicable in the study area and can also be considered as a reference for other locations in Ecuador where it is common due to its geography to have these unfortunate events of landslides and falls of large volumes of land in sensitive parts.

The scheme that is totally appropriate to the object of study is summarized in Table 5. The primary electrical equipment and its main electrical operating parameters are detailed for its technical and economic evaluation that will consecutively evaluate the COE and the NPC.

Table 5. Total components of the hybrid system.

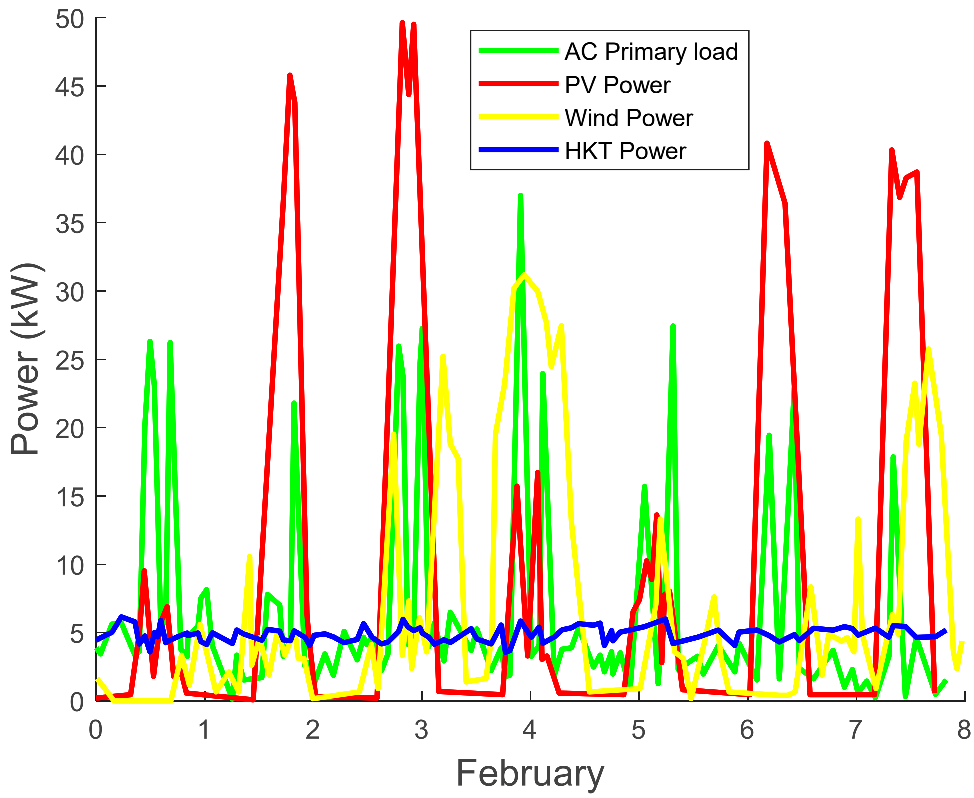
Equipment	Nominal Power (kW)	Price per Unit (Dollars)	Total Price
Solar panel	10	160	6000
Battery	20	400	8000
Regulator	1	2600	2600
HKT turbine	5	3700	3700
Inverter	65	1700	1700

Table 5. *Cont.*

Equipment	Nominal Power (kW)	Price per Unit (Dollars)	Total Price
Wind turbine	1.5	1250	1250
		Subtotal	23,250
		Volume discount	3000
		Total (dollars)	20,250

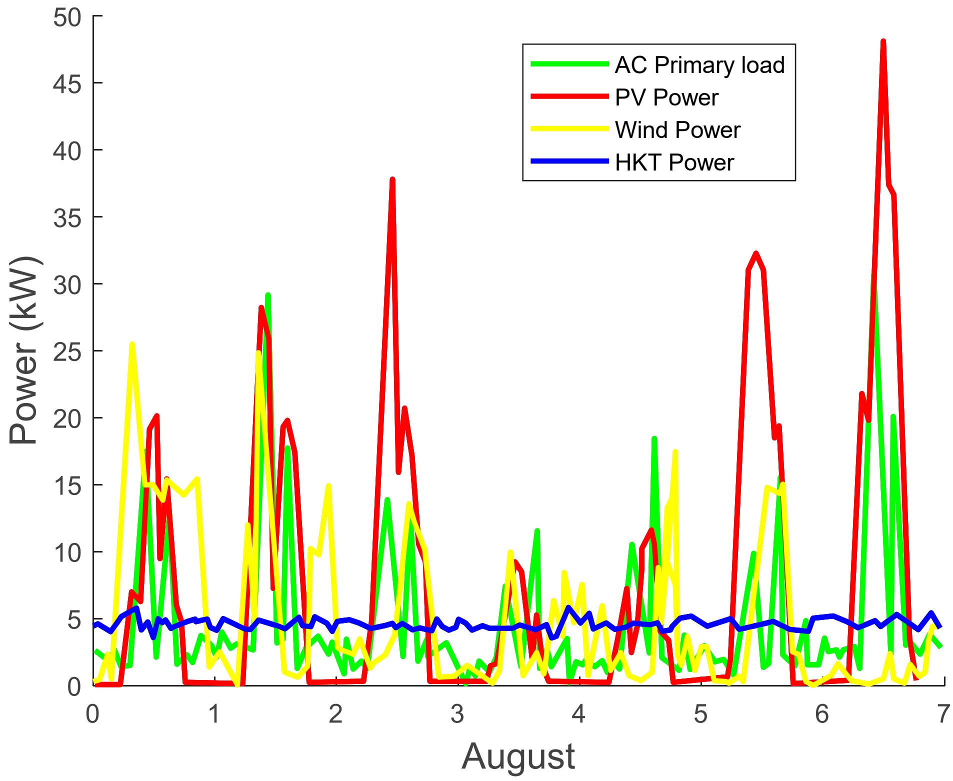
4. Results and Analysis

It is very important to carry out a joint analysis of the generation sources that interact to form the hybrid system. An energy balance is carried out in two months separated in the year, in this case in February and August of the year 2023. The analysis is seasonal by source (WT, PV and HKT) and is presented in Figure 10, being managed in reference to load demand. The analysis that is carried out consists of comparing hour by hour the production of electrical power based on the demand in those same hours with the purpose of guaranteeing the service at all times. This systematic evaluation can be considered as an interesting form of optimization of the energy resources and the necessary equipment that guarantees the integral functioning of the energy system. The partial powers generated by each type of technology and the load demand are identified in the balance. The months are defined in the analysis and the first full week of each month has been considered. The energy balance in each case is presented in Figure 10a,b. Meanwhile, the power production profile per calendar year is identified in Figure 10c. The power profile generated in the greatest proportion is solar; meanwhile, the other technologies, although not in large proportions, are less fluctuating and their production is during both day and night. Wind and hydrokinetics combine very well with solar photovoltaics.



(**a**)

Figure 10. *Cont.*



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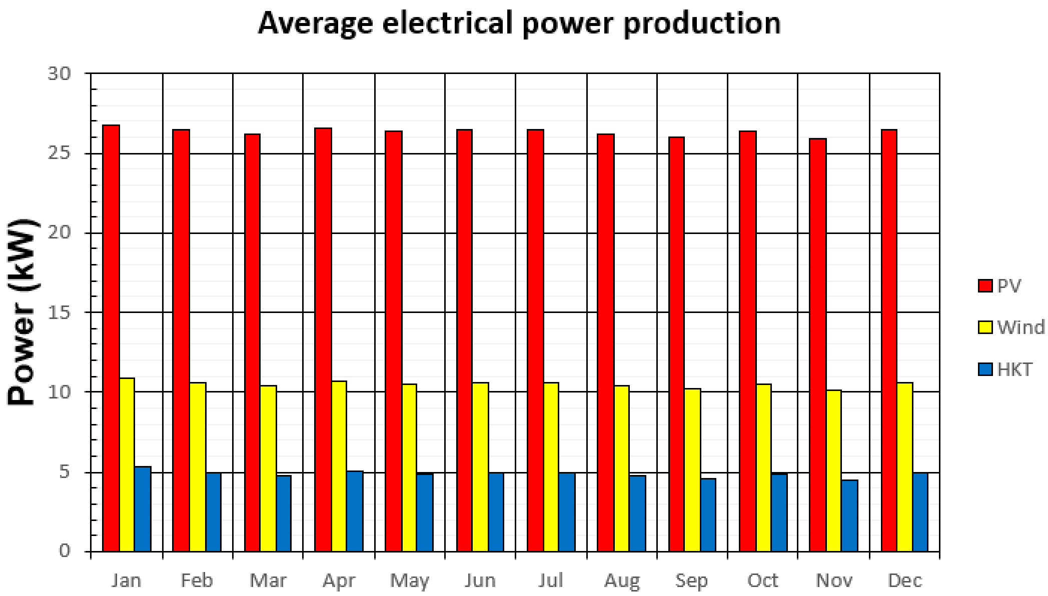

(**c**)

Figure 10. Hybrid system power balance. (**a**) Power balance from 6–12 February 2023. (**b**) Power balance from 7–13 August 2023. (**c**) Average electrical power production for the year 2023.

The production of photovoltaic solar energy is key in this study. Several authors recommend the use of photovoltaic solar systems that can be a substantial basis for being combined with other variable renewable energy systems. From an economic point of view, photovoltaic solar energy tends to increasingly reduce its production costs, which tends to be more viable for different electrification projects. The sector has many energy privileges without being exceptional as has already been stated previously, such as wind and hydrokinetic water, allowing for the design of a hybrid system with different technologies. The energy provided by HKT is characterized by being the least variable one possible because the channel current does not vary in large proportions throughout the day, having an important advantage of keeping the hybrid system active, in the same way the wind source also contributes to the mix, being energetic but with greater fluctuation throughout the day. However, according to the simulations carried out, the system as a whole maintains its generation levels depending on demand.

The Homer Pro has an evaluation module referring to the nominal cash flow that includes as main inputs the different equipment that is part of the hybrid system. The representation is made by vertical bars from point 0 downwards; they are economic flows or investment, while the ascending ones represent income. In Figure 11, the first downward bar represents the initial investment of the hybrid system located in the base year. There are also outflows of money for operation and maintenance or replacement. The project is planned for 25 years, involving economic outlays over time in excess of the initial investment. In year 25, a positive amount arises that can be interpreted as the first income from a technical point of view.

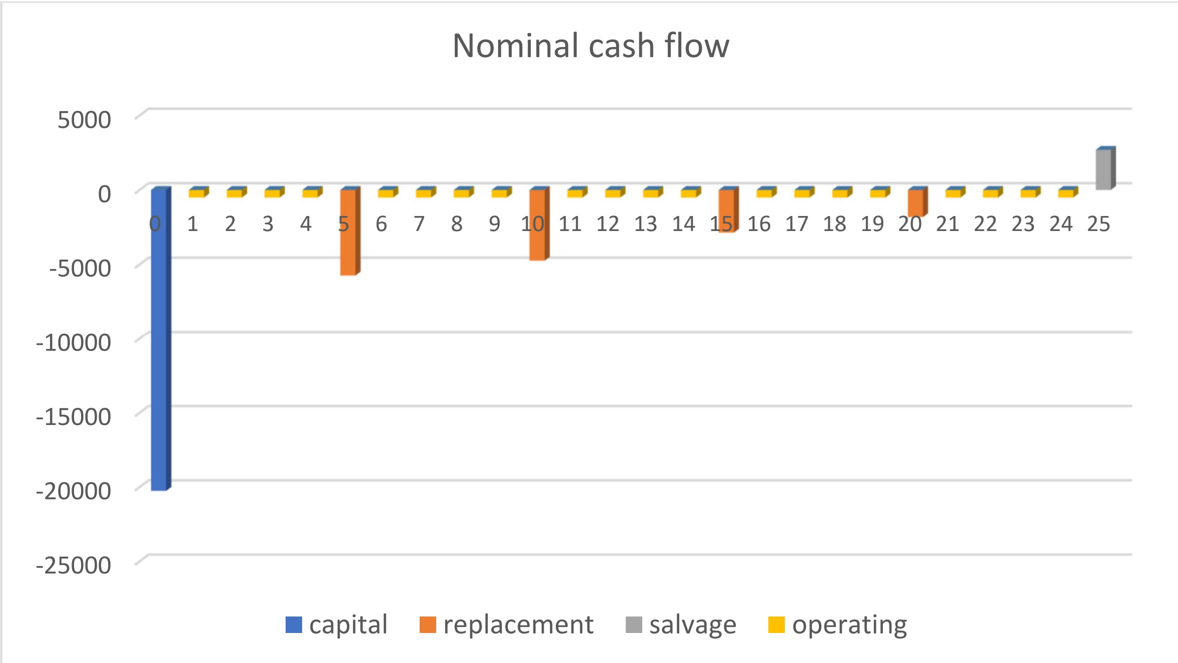

Figure 11. Cash flow of the hybrid system.

The initial investment in equipment amounts to USD 20,250. The amount invested will hardly allow you to recover the capital in the short term, which is why the feasible scenario is year 25.

The costs of renewable energy sources vary over the years. Figure 12 shows the variations in the capital cost of each equipment with respect to the NPC. The variation of 30% to 150% of the current prices in the components of the hybrid system was considered. The importance of maintaining an operational system is to maintain high production levels of photovoltaic solar energy. The greatest variation in price is presented by WT, HKT technology is the second renewable source that presents sensitivity and BAT presents low variation. The discount rate has shown a significant decreasing variation. Photovoltaic modules have a slight sensitivity with respect to the NPC.

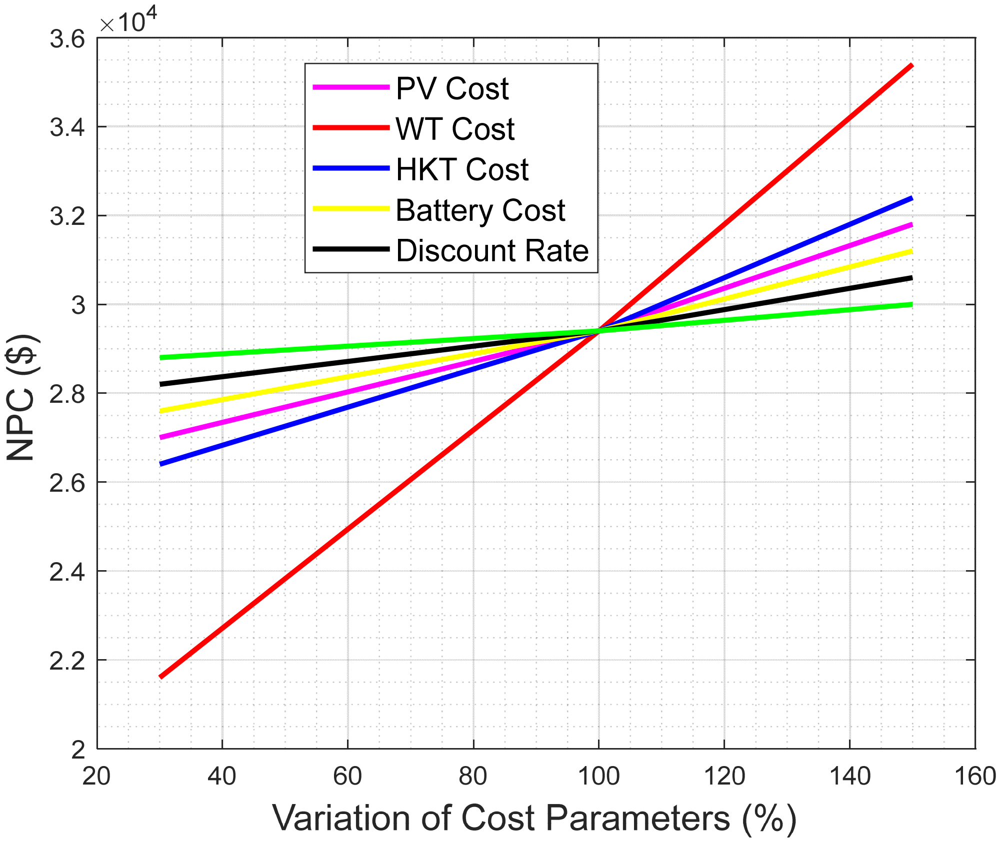

Figure 12. NPC of HRES systems.

The amount of power generated by each source was determined through the efficiency of each of the systems, excess power and the unsatisfied demand due to not being connected to the public electrical grid in the event of an emergency situation. The results are shown in Figures 13 and 14, respectively.

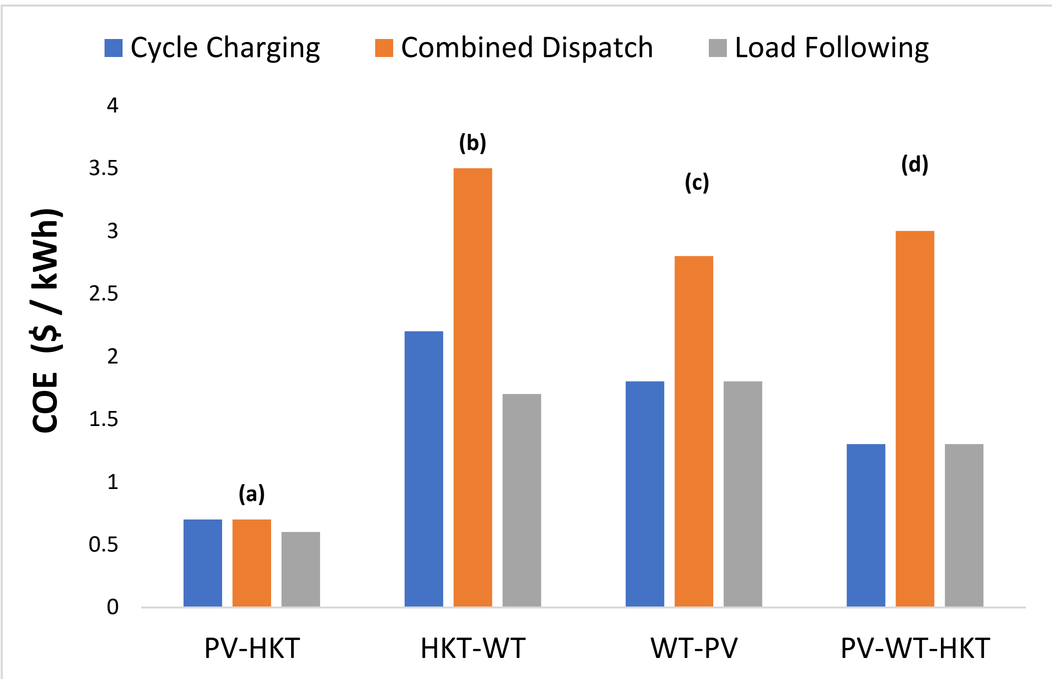

Figure 13. COE of HRES systems.

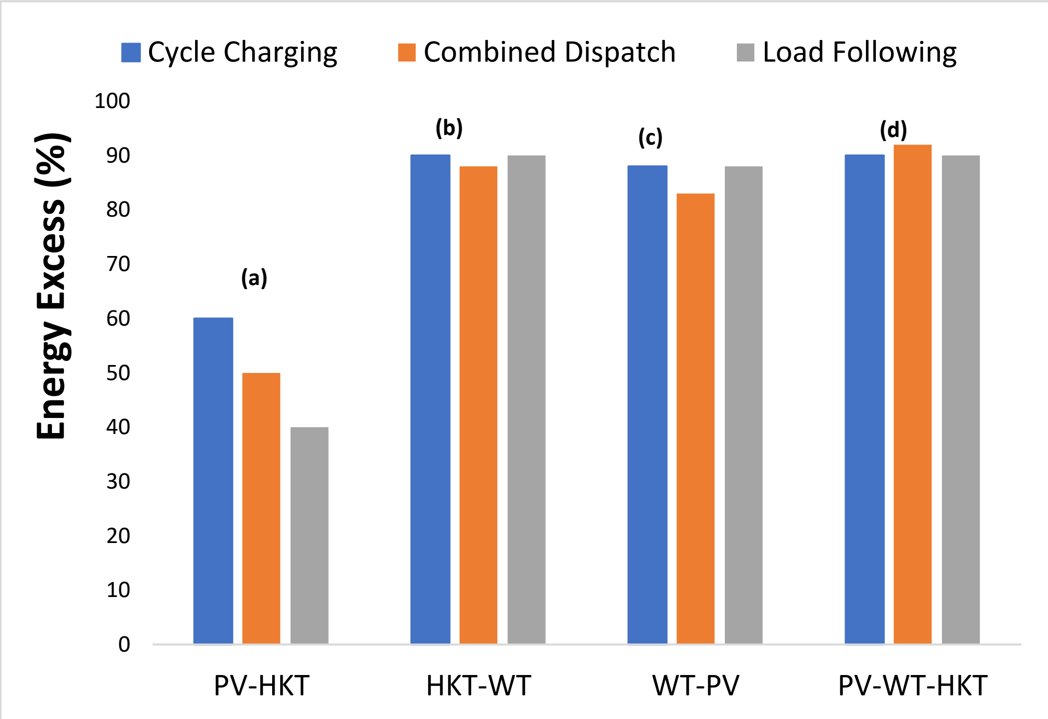

Figure 14. Excess energy produced by RES.

Considering the different combinations of sources referring to WT, PV and HKT, it can be seen in Figure 13 that Load Dispatch has a much higher COE with ($3.5/kWh) in scenario (b) with respect to cycle charging and load. following in the other two scenarios (a), (c) and (d).

In accordance with what was previously obtained, now when analyzing the excess energy it is guaranteed that there is a high availability of energy that can be injected into the network, it is coherent given that there is an important primary resource and with the technologies that are available its production will guarantee the supply of energy to the sector. Scenarios (b), (c) and (d) present quite similar energy excesses, only scenario (a) is smaller but not critical as can be seen in Figure 14.

5. Conclusions

In this study, a hybrid system was designed for the town of Marianza where diverse energy potentials such as wind, solar and hydrokinetic are available, with the purpose of providing electrical energy to the place and is established with connection to the electrical grid. The particularity expressed here is that the hybrid system can also operate without connection to the grid, or in turn the public grid goes out of operation unexpectedly due to geological situations that affect the entire area that is very susceptible to gravitational landslides. The fence line has no other alternative for designing a new network as it is located between mountains, so use is made of the side of the main road to distribute energy and street lighting. Given this peculiar situation, the hybrid system of renewable energy distributed in the portions of safe lands but that have high energy potential has been designed to supply the homes of the town. The PV–WT–HKT renewable sources were combined very well with each other; a battery bank is available for eventual operation outputs from the electrical grid and it is allowed to store electrical energy for mainly nighttime hours. In the study, real electricity demand data and energy data profiles measured on site were used, and the data is loaded into the Homer Pro tool. The optimization is carried out together using existing equipment on the market, including three energy controls, generating certainty of its operability in different conditions.

After analyzing the results, it is determined in this case study that the renewable hybrid photovoltaic, HKT and WT systems are economically feasible, and a COE of USD 0.89/kWh is determined. Then, using the CC and LF controls, the PV–WT–HKT system is more economical due to the important energy benefits of the place. It should be noted that in most systems, the LF control produces significant cost savings by not operating HKT, and it technically impacts the regular operation of the joint system, especially at night hours. The resulting most economical system of all combinations is PV–HKT, but it still leaves technical limitations, which is why it is confirmed that the best option is the PV–WT–HKT system.

Typically, the variation in the capital costs of clean energy sources affects the COE and the NPC, with wind turbines being the most affected and the most sensitive to the increase in their costs.

It is desirable that the minimum nominal state of charge of the batteries is not 0 V for any reason. For this particular case, it has been designed with 30%, a limit that is still bearable at the operating level. By reducing this value, the cost of the system as a whole tends to be lower, but it is forced to increase the penetration of renewable energies in a diversified way. Hybrid systems that include PV and WT sources are more susceptible to variations in this analysis, especially when HKT is at full load.

The simulations were carried out in the Homer Pro tool with time intervals of 5 min, which have proven to be more accurate. To achieve the viability of the hybrid system in a given location, it is important to evaluate the impact of economic and technical factors, trying to achieve a balance between these two. In this research, it has been shown that a system formed by the three proposed renewable sources with respect to any of its combinations of sources is more economical and pollution-free.

Author Contributions: Data curation, D.I., F.C.-G. and E.G.M.; formal analysis, F.C.-G. and D.I.; writing—original draft, F.C.-G. and D.I.; writing—review and editing, M.F.J. and E.G.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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