

Article

Repowering Feasibility Study of a Current Hybrid Renewable System. Case Study, Galapagos Islands

Paul Arévalo , Marcos Tostado-Véliz *  and Francisco Jurado 

Department of Electrical Engineering, Superior Polytechnic School of Linares, University of Jaén, 23700 Linares, Spain; wpac0001@red.ujaen.es (P.A.); fjurado@ujaen.es (F.J.)

* Correspondence: mtostado@ujaen.es

Abstract: Renewable sources on islands seem to be the most attractive option to decarbonize and lower the price of electricity; currently, most islands do so by replacing their diesel generators with wind or solar sources, along with energy storage. The Galapagos Islands are no exception. This study presents a techno-economic analysis of hybrid renewable systems in the Galapagos Islands, considering the repowering of its renewable sources and reduction in the penetration of diesel generators. This study uses EnergyPlan software, where the best option is chosen based on technical, economic, and environmental indicators. Finally, several sensitivity analyses are done. The results show that by increasing the capacity of current wind and photovoltaic systems, the total annual cost reduces by 20% and 10.31%, respectively; this is a specific result of this study. Moreover, there is a reduction in CO₂ emissions produced by diesel generators, up to 38.96%.

Keywords: renewable energy; isolated systems; energy planning; solar energy; wind energy; EnergyPlan; decarbonization



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1. Introduction

1.1. Context and Motivation

Renewable systems are currently growing rapidly due to negative climate change produced by the burning of fossil fuels [1–3]. Although the supply of electricity in islands still depends mostly on diesel generators, transporting fuel to isolated communities adds extra costs, in addition to generating greenhouse gases that affect the environment [4]. The penetration of renewable sources in isolated systems could solve the aforementioned problems, reducing the operation of diesel generators [5]. For example, in the case of the Galapagos Islands, 85% of the electricity supply comes from a thermoelectric plant and only the remaining 15% from renewable sources [6]. In this context, planning and optimization of renewable sources for the Islands is clearly necessary.

1.2. Literature Review

Several authors have studied the feasibility of renewable sources on islands [7–12]. Normally, the authors analyse the penetration of wind turbines (WT), photovoltaic systems (PV), together with batteries (BAT) and diesel generators (DG). For example, in [13], the authors present a feasibility study of an autonomous (PV-WT-BAT) hybrid system for a remote island, showing that the optimal system has a level cost of energy of 0.595 \$/kWh with 100% renewable participation. Similarly, in [14], the authors designed and evaluated a hybrid renewable energy system (HRES) for the island of Masirah—the objective was to reduce the penetration of diesel generators. The results showed that around 75% could reduce the cost of energy by using a hybrid power system (PV-WT-DG); furthermore, the emission of greenhouse gases could be reduced by about 25%, compared to using diesel generators. The feasibility of renewable energy on islands is evident in several studies. In this paper, the most significant studies have been cited. In [15], the authors show the techno-economic and environmental suitability of an isolated microgrid system located

on a remote island in Bangladesh; the system is composed of (PV-WT-BAT-DG). With the proposed energy control measure, it is possible to reduce the net present cost of the project by up to 28% by increasing renewable penetration by 56%. Similarly, in [16], the authors propose a simulation framework for the economic optimization of a renewable system (PV-WT-BAT) based on the concurrent simulation of energy flows and economic estimates based on a single simulation core. Based on joint economic and energy constraints, the results show that the configurations are optimal and profitable using the standard open-source software SystemC-AMS. Another application of this software is presented in [17], where the authors propose a framework for the modelling and simulation of modern cyber-physical electrical energy systems (CPEES), formalizing the flow of information and energy in a generic CPEES, with multiple energy sources and loads. The experimental results, applied to a complex CPEES case study, seek to demonstrate the effectiveness of the proposed solution, in terms of accuracy, accelerate the current state of Matlab/Simulink, and support the design flow.

The optimization of HRES has been studied in the Galapagos Islands, as explained in [18]. J.-M. Clairand et al. considered the electricity demand of the Islands and the new electric vehicle stations, showing that investing in PV energy would reduce the net present cost up to 13.58%. Similarly, in [19], A.A. Eras-Almeida et al. performed optimization of the current HRES in the Galapagos Islands, pointing out that by increasing the penetration of renewable sources from 18% to 39%, the energy cost is reduced from 32.06 \$/kWh to 18.95 \$/kWh. It is important to mention that increasing the capacity of renewable sources does not always reduce energy costs. In [7], the authors carried out a techno-economic study of hydro-storage systems by wind pumping on Isla el Hierro. The results show that renewable systems are more expensive than the current conventional system on that island; however, by removing fuel subsidies, HRES are cheaper than the conventional system. The same concept is applied in this paper by not considering subsidies on fossil fuels. In the same context, A. Cano et al. [20] showed that it is possible to supply the Galapagos Islands, specifically the Baltra and Santa Cruz Islands, with 100% renewable energy until 2031. The studies cited above ([18,19]) used HOMER Pro software to perform the optimization of the proposed HRES. The HOMER (Hybrid Optimization of Multiple Energy Resources) software is one of the most widely used simulation tools for the analysis and optimization of HRES [21–25], mainly considering economic indices and certain algorithms pre-programmed by the software, causing difficulty in freely choosing HRES holistic and cross-sectoral planning and analysis [26]. To solve this problem, the EnergyPlan software is the most widely used for energy planning at different scales, since it allows the user to consider the energy system, studying the demands of electricity, heating, cooling, industry, transportation, and water. Furthermore, a software that uses a cross-sectoral approach such as EnergyPLAN, is designed for energy planning at an urban, regional, or national scale [26]. The use of the EnergyPlan software is not widely studied in the literature. In [27], the authors presented an evaluation of electricity storage with respect to thermal storage as part of two different energy planning approaches for the Samsø and Orkney Islands; the results show that the energy exchange between the two islands improves remarkably. The advantage of using EnergyPlan lies in how the proposed model can be improved in terms of intra-hourly variability, stability, and auxiliary services to achieve a better reflection of the energy requirements and power capacity [28]. The simulation based on alternative scenarios and different algorithms of energy dispatch supported by the EnergyPlan software could be useful to identify and obtain information on the main technical challenges involved to achieve this objective [29]. Therefore, the use of this software for an energy planning study and sensitivity study in the Galapagos Islands would help fill the gaps in the cited literature, propelling the benefits of EnergyPlan over the HOMER Pro software that has been used extensively in this context.

Based on the EnergyPlan software, in [30], the authors present a comparative study of two energy system analysis models. The system is modeled using the EnergyPlan and H2RES software for a solar, wind, and hydraulic system on the island of Mljet, Croatia.

The work compares methodologies and results in order to identify mutual benefits and improvements of both models. Similarly, in [31], an integration of renewable energy technologies and response to demand in interconnected energy systems is presented; with the EnergyPlan software, different integration scenarios of renewable sources and electric vehicles were modelled. The results showed that interconnections increased the share of energy from renewable energy sources in final energy consumption and decreased total critical excess electricity production. The penetration of 100% of renewable sources in the Islands can destabilize the electrical system; however, it is possible to find a configuration based on a series of simulations in the EnergyPan tool (e. g.) with WT and PV [26,32]. To have an energy reserve in the Islands and reduce the randomness of the RES, energy storage systems must be dimensioned; some authors have carried out simulations in EnergyPlan and HOMER [33]. A large part of the HRES studies in the Islands propose a 100% renewable system, despite the risk of loss of stability in the electrical system. The planning carried out by the authors is ideal to reduce CO₂ emissions and in some cases, the energy cost. However, no specific comparisons are made in reference to the capacity of each component or energy exchanges between the Islands with existing HRES in order to verify the viability of existing HRES repowering, which adds value to this study.

1.3. Contributions

The main contributions of this paper are explained below:

- First, a feasibility study was done to repower the current renewable system (PV–WT–BAT), as well as the battery storage system of the San Cristobal, Baltra, and Santa Cruz Islands in the Galapagos archipelago, with the aim of minimizing the penetration of diesel generators. The optimization problem is solved by EnergyPlan software.
- Dispatch simulations were carried out for each possible combined capacity of energy sources. It is observed that in the long term, renewable sources offer more feasibility.
- A virtual interconnection is made between the Baltra Islands—Santa Cruz and San Cristóbal, forming a single system; the energy exchange allows to improve the storage capacity and energy reserve.
- The analysis presented in this paper includes the study of various capabilities of WT, PV, BAT, and DG. The minimum cost is reached with specific values of each component.
- The evolution of the total cost is analyzed with respect to variation of the DG, PV, and WT capacity.
- The behavior of CO₂ emissions with respect to the variation of DG, PV, and WT capacity is studied. By 2050, the DG operation is mitigated.
- The surplus electricity with respect to the variation of the capacities of PV and WT is analyzed.
- A study of the total annual cost and imported energy is presented with respect to the variation in the capacity of the energy storage system. Lower costs are not always achieved by increasing BAT capacity.
- Finally, the energy flow between the three Islands proposed in this paper is studied.

In the remainder of this paper, Section 2 explains the methodology used in this work, Section 3 describes the mathematical models used in simulations, Section 4 presents the results and discussion. Finally, the paper is concluded in Section 5.

2. Methodology

For the feasibility study and energy planning of the Islands, the controller must receive as input variables the following parameters: wind speed, solar irradiation, electricity consumption of the Baltra, Santa Cruz, and San Cristóbal Islands for one year. The energy control strategy decides when to start a diesel generator if necessary. Subsequently, a mathematical modelling of each renewable source (RES), storage system (BAT), and DG is carried out, to finally perform an analysis of sensitivity, varying the capacity of each RES

until an optimal value is reached. In summary, the methodology presented in this paper is represented in Figure 1.

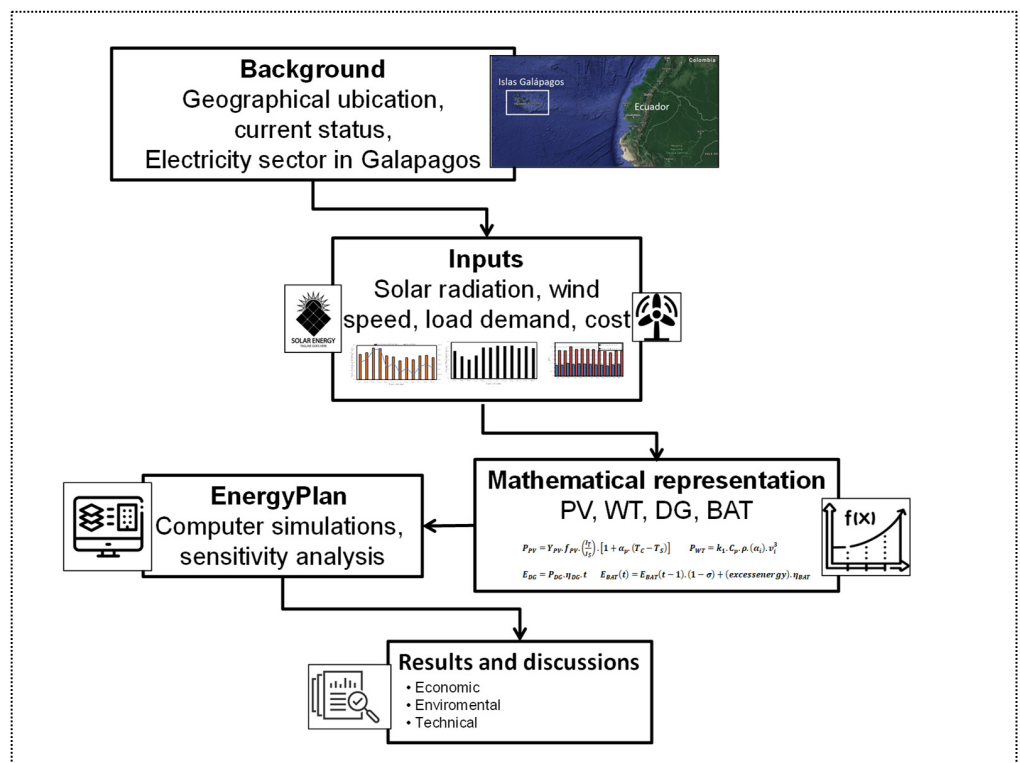


Figure 1. Graphical and chronological representation of the feasibility study and energy planning.

Background and Current Situation

Figure 2 shows the location of the Galapagos Islands, considered a natural heritage of humanity in 1978 by UNESCO. The administrative political division of the province of Galapagos, one of the twenty-four provinces of Ecuador, comprises three districts: Santa Cruz, San Cristóbal, and Isabela. The capital of Galapagos is Puerto Baquerizo Moreno, located on the Island of San Cristóbal [6].

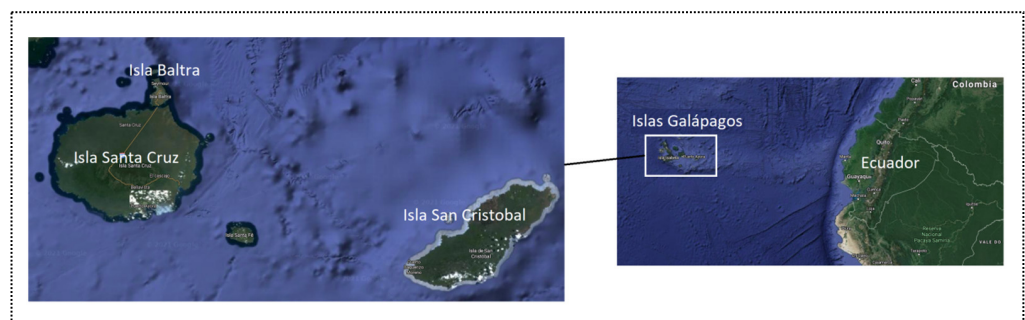


Figure 2. Geographical location of the Galapagos Islands (Baltra-Santa Cruz and San Cristobal).

Currently, the Galapagos Islands have an HRES as shown in Table 1. In this study, the Baltra, Santa Cruz, and San Cristóbal Islands were chosen, where the Baltra and Santa Cruz have an electrical connection but not San Cristóbal. Therefore, for the simulations in this paper, it is assumed that the three islands have electrical interconnection.

Table 1. Electricity sources in the islands under study, year 2020 [6,19].

Island	DG (kW)	WT (kW)	PV (kW)	BAT (kWh)
San Cristóbal	8990	2400	12	-
Santa Cruz–Baltra	13,900	2250	1575	4300

In 2018, the electricity consumption of the Baltra and Santa Cruz Islands was 37.42 GWh, and in the San Cristobal Island, it was 16.63 GWh, with a RES participation of less than 20%. The energy cost in the Islands is 38.84 \$/kWh. However, through government subsidy programs, the current rate is 9.8 \$/kWh for residential users and 10.30 \$/kWh for commercial users. In this paper, the unsubsidized cost is considered, so that RES has the opportunity to compete in conditions, similar to unconventional sources [34]. The monthly electrical energy consumed during 2018 in the Islands is shown in Figure 3.

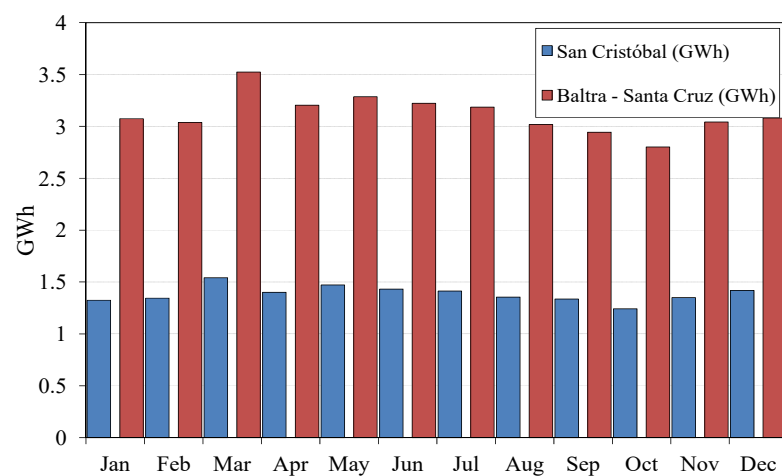


Figure 3. Average monthly energy consumption in the Islands in 2018.

On the other hand, the renewable resources present in the Islands (solar radiation and wind speed) have behaviour as shown in Figures 4 and 5, respectively. It is important to clarify the complementarity of the two renewable sources during the months of July to September—the solar resource decreases with respect to the other months; however, the wind resource increases in this time interval. The opposite occurs in the months of March and April, where the solar resource increases and the wind energy decreases. The average daily radiation is 5.70 kWh/m²/day and the average wind speed is 6.36 m/s [20].

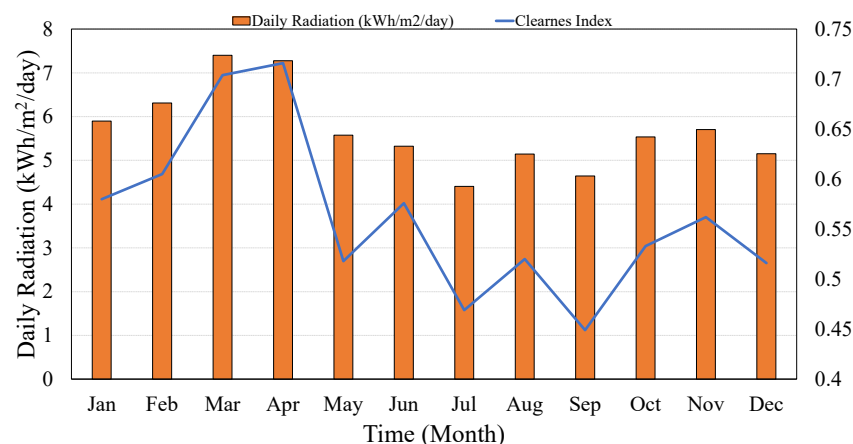


Figure 4. Daily solar radiation, monthly average values.

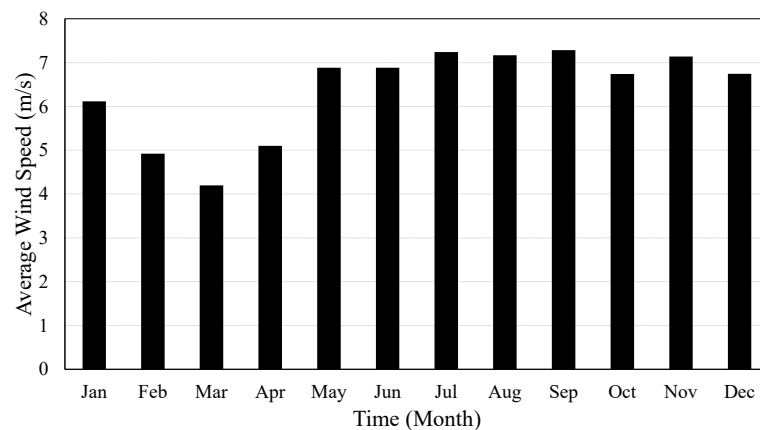


Figure 5. Average wind speed, monthly average values.

3. Mathematical Models

The following equations represent the physical and electrical behaviour of the components of the HRES.

3.1. PV System

The simulated photovoltaic panels are stationary, and the electrical power of a PV is calculated with Equation (1) [35–39]:

$$P_{PV} = Y_{PV} \cdot f_{PV} \cdot \left(\frac{I_T}{I_S} \right) \cdot [1 + \alpha_p \cdot (T_C - T_S)] \quad (1)$$

where, P_{PV} (kW) is the electrical power of PV system, Y_{PV} (kW) is the nominal capacity of the photovoltaic generator, f_{PV} (%) is the correction factor, I_T ($\frac{\text{kW}}{\text{m}^2}$) and I_S ($\frac{\text{kW}}{\text{m}^2}$) are the solar energy from the incident radiation of PV module and standard test conditions, respectively, α_p is the power coefficient, T_C ($^{\circ}\text{C}$) is the temperature of cell PV and T_S ($^{\circ}\text{C}$) is the temperature of cell PV under standard operating conditions [35].

3.2. Wind Turbine

The available power of each wind turbine is given by Equation (2) [40–44]:

$$P_{WT} = k_1 \cdot C_p \cdot \rho \cdot (\alpha_i) \cdot v_i^3 \quad (2)$$

where, P_{WT} (kW) is the electrical output power of WT, k_1 is a constant represents dimensions of a wind turbine (cross-sectional area in m^2), C_p is the power coefficient of the wind turbine, α_i is the soil roughness coefficient and ρ is the air density ($\frac{\text{kg}}{\text{m}^3}$).

Generally, WTs have a power curve that explains the range of their power according to the wind speed depending on each manufacturer.

3.3. Diesel Generator

The electrical energy E_{DG} (kWh) produced by a DG can be calculated with Equation (3) [45–48]:

$$E_{DG} = P_{DG} \cdot \eta_{DG} \cdot t \quad (3)$$

where, P_{DG} is the output DG electrical power (kW), η_{DG} is the efficiency of DG, and t (h) is the DG operating time in hours.

The detailed model of the DG depends on the fuel curve and is calculated in ref. [49], specifically in Section 3.3.

3.4. Batteries

Battery storage systems have become highly used components in isolated HRES, due to their easy installation, high energy density, and low maintenance cost [50]. The energy obtained from BAT $E_{BAT}(t)$ during its charging and discharging process, in time interval (t) , is calculated with Equations (4) and (5), respectively [46]. The equations imply that the batteries are recharged with surplus electricity from renewable sources, or in some cases from DG [51–53].

Battery charging process

$$E_{BAT}(t) = E_{BAT}(t - 1) \cdot (1 - \sigma) + (\text{excessenergy}) \cdot \eta_{BAT} \quad (4)$$

Battery discharging process

$$E_{BAT}(t) = E_{BAT}(t - 1) \cdot (1 - \sigma) - (\text{excessenergy}) \cdot \eta_{BAT} \quad (5)$$

where, σ is the battery self-discharge rate, and η_{BAT} is the efficiency of BAT.

In this paper, the same technical and economic characteristics of the system components currently installed in the Baltra-Santa Cruz Islands have been considered; the main economic parameters are shown in Table 2 and the technical parameters in Table 3 [19].

Table 2. Cost of the components currently installed in the Baltra Islands—Santa Cruz.

Component	Parameter	Unit	Cost
PV	Capital	\$/kWp	1210
	Replacement	\$/kWp	484
	O&M	\$/kWp/year	15
WT	Capital	\$/kW	1500
	Replacement	\$/kW	1200
	O&M	\$/kW/year	19
BAT	Capital	\$/kWh	300
	Replacement	\$/kWh	240
	O&M	\$/kWh/year	3.75
DG	Capital	\$/kW	0
	Replacement	\$/kW	340
	O&M	\$/kW/year	3

Table 3. Technical parameters of the components currently installed in the Baltra Islands—Santa Cruz [19].

Component	Type	Power of Each Unit	Technical Parameter for This Simulation
PV	Mitsubishi monocrystalline silicon modules	265 Wp	monocrystalline
WT	UNISON U57	750 kW	cut in wind speed 2.5 m/s; rated 11 m/s; cut off 25 m/s
BAT	Stationary lead-acid batteries	1500 Ah	Useful life 7 years
DG	Four Caterpillar DGs	650 kW	Generic
	One Caterpillar genset	1100 kW	
	Six Hyundai DGs	1700 kW	

3.5. Simulation Strategy

The simulation process is shown in Figure 6. First, several simulations of the current system are carried out obtaining a reference model. The current parameters shown in Tables 2 and 3 have been used—the interest rate is 3% and the cost of diesel is 0.8 \$/l [19]. The planning horizon proposed in this HRES is one year and the resolution time is hourly.

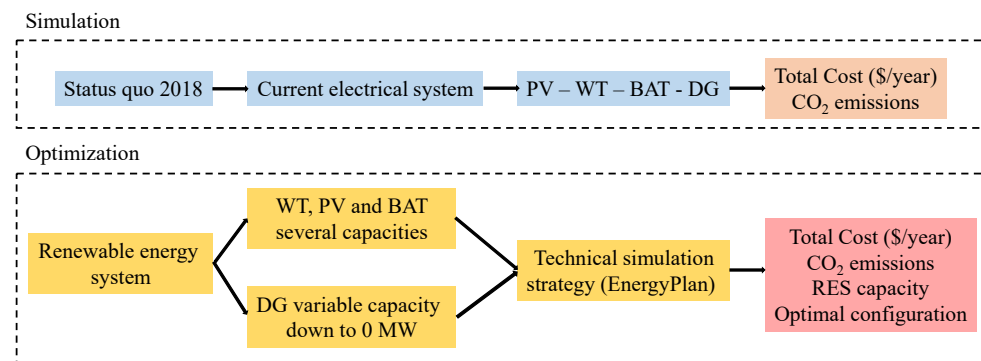


Figure 6. Pictorial representation of the simulation process in EnergyPlan.

For the optimization process of the system, the technical control strategy in EnergyPlan was chosen. In this way, the software allows to analyse a wider variety of renewable penetration, optimizing the total annual cost in the long term. Specifically, it is possible to cover the Islands with 100% renewable through this type of energy control.

The EnergyPlan software uses two simulation strategies. The first is known as the economic simulation strategy of the market and the second as a technical strategy. In this paper, the second was chosen as a proposal for the feasibility study of the proposed HRES. The first strategy is based on a short-term marginal price market model; this simulation strategy only uses variable costs and does not optimize the long-term cost basis of different power supply technologies. Furthermore, it only optimizes the supply side of the energy system, and not the demand. This strategy may not accurately represent how future energy systems are likely to depend on very high levels of non-triggered renewable energy. Therefore, the use of the technical simulation strategy is usually more accurate in the simulation of power systems with very large penetrations of intermittent renewable energy, which, in combination with the cost data of the technologies, makes it possible for the user to identify the lowest cost solutions over their entire useful life [54]. For this reason, the technical strategy was chosen. Furthermore, for simplicity's sake, this paper has not considered penalties for CO₂ emissions.

4. Results

Several parameters have been chosen where the main results of the simulation are presented; they are explained below:

4.1. Economic Results

The simulations have been done from the current installed capacity in the Baltra, Santa Cruz, and San Cristóbal Islands. Figure 7 shows the result of the simulations by varying the capacities of WT and DG. In the first case, the WT capacity increased from the current one (4.65 MW) to the value of 20 MW; the second case shows a decrease of DG until reaching a value of 5 MW. It is noteworthy that, by increasing the capacity of WT, the total cost is lower, reflecting the decrease in diesel consumption until DG reaches a capacity of 9 MW. When the DG drops to 5 MW, the total cost is higher because more WT must be installed to supply the unmet load. On the other hand, the reduction in total cost by increasing WT is balanced by one point (WT = 12.65 MW) for a DG capacity = 9 MW, with a total annual cost of 4.019 M\$/year. Thus, this configuration can be considered optimal.

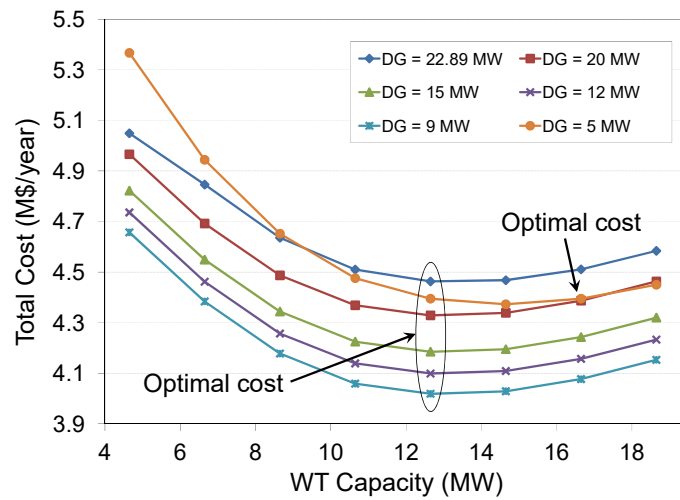


Figure 7. Total annual cost, variation in WT and DG capacity.

In the case of PV, the results are presented in Figure 8. The behaviour is similar to WT—when increasing the PV capacity, the total cost decreases significantly until reaching a point of equilibrium, in this case 7.58 MW with a DG capacity of 9 MW reaches a total cost of 4.53 M\$/year. If the DG is 5 MW, the cost is higher as well as the break-even point.

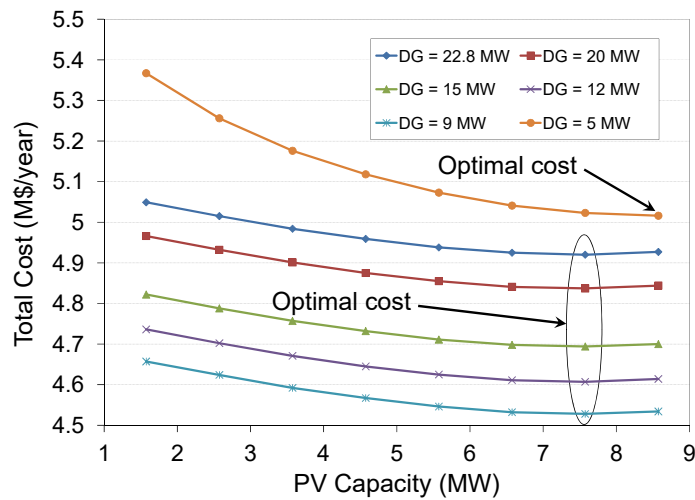


Figure 8. Total annual cost, variation in PV and DG capacity.

Similarly, if the DG capacity continues to decrease until reaching 0 MW, the total cost increases since it must be invested in higher RES capacities to cover the unmet load. Figure 9 shows a 100% renewable system; by varying the capacity of WT, the breakeven point is 24.65 MW and of PV is 15 MW, with a total annual cost of 6.71 M\$/year and 8.58 M\$/year respectively. Therefore, when the capacity of the DG = 0 MW, it is less expensive to increase WT than PV.

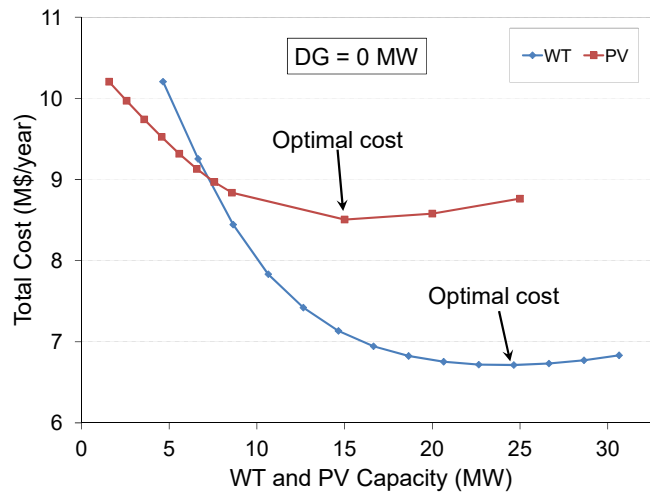


Figure 9. Total annual cost, variation in PV, WT, and DG = 0 MW.

4.2. Environmental Results

From an environmental point of view, it is obvious that the reduction in CO₂ emissions is less every month when increasing the WT capacity, as shown in Figure 10. The decreasing trend is similar for the different DG capacities; however, the maximum emission reduction is presented with DG = 5 MW. It is possible to mitigate approximately 30% of current CO₂ emissions with the optimal capacity of WT = 12.65 MW (see Figure 7).

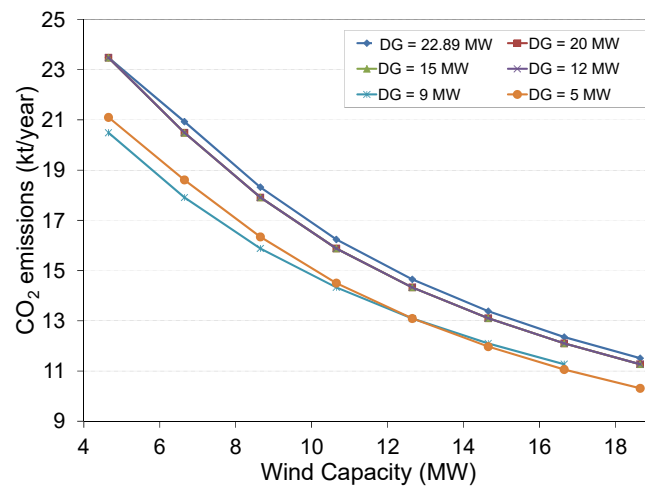


Figure 10. CO₂ emission reduction, WT and DG capacity variations.

When increasing the PV capacity, the results are different with respect to the variation of WT, as shown in Figure 11. The trend is the same, except when DG = 5 MW; in this case, it is possible to mitigate approximately 10% of CO₂ emissions with the optimal capacity of PV = 7.58 MW (see Figure 8).

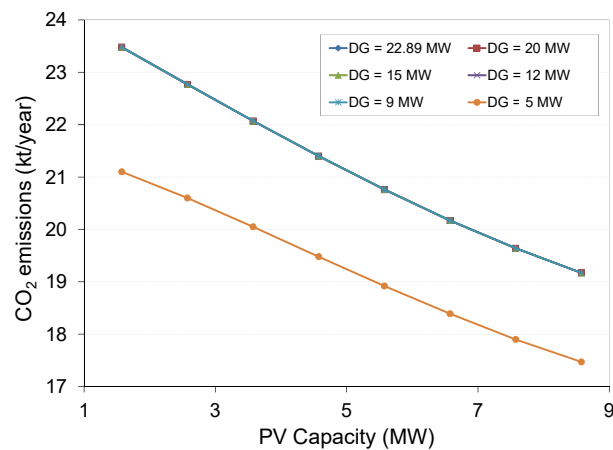


Figure 11. CO₂ emission reduction, PV and DG capacity variations.

Authors should discuss the results and identify how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

4.3. Energetic Results

An important aspect when sizing a renewable system is the surplus electricity that it can produce. In this case, the RES (WT+PV), by increasing its capacity increases the surplus electricity; this result is shown in Figure 12. The behaviour is the same when the DG has 5 MW and 0 MW of capacity. When the capacity of WT is greater than 10 MW, the electricity surplus increases more rapidly, reaching up to 60% if WT = 25 MW. The case of PV is a less steep slope, starting to steep equally at 10 MW capacity, reaching 30% with PV = 25 MW. It is important to note that the capacity of BAT has remained constant until now (4.3 MWh).

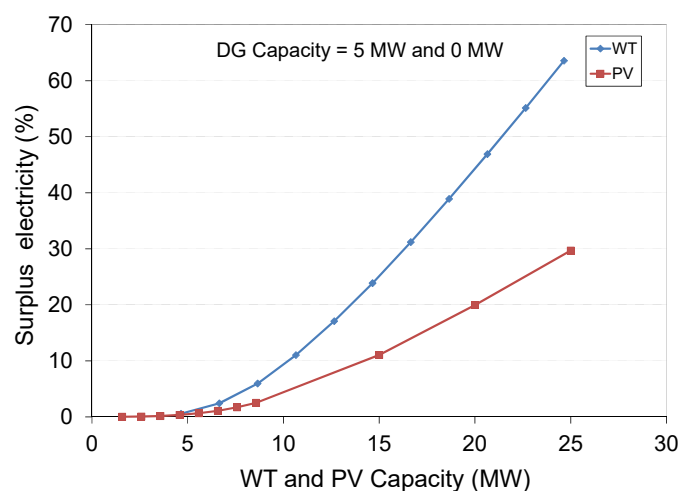


Figure 12. Surplus electricity produced by the HRES, when the capacity of DG = 5 MW and 0 MW.

As shown in Figure 13, if the capacity of the batteries is increased, the total cost is high, but the imported energy decreases. This last parameter describes the energy that could not be covered by renewable sources; it must be supplied already either by diesel generators or by any external system. The result shows that to reduce the import of 0.3 MW, approximately one million US dollars must be invested.

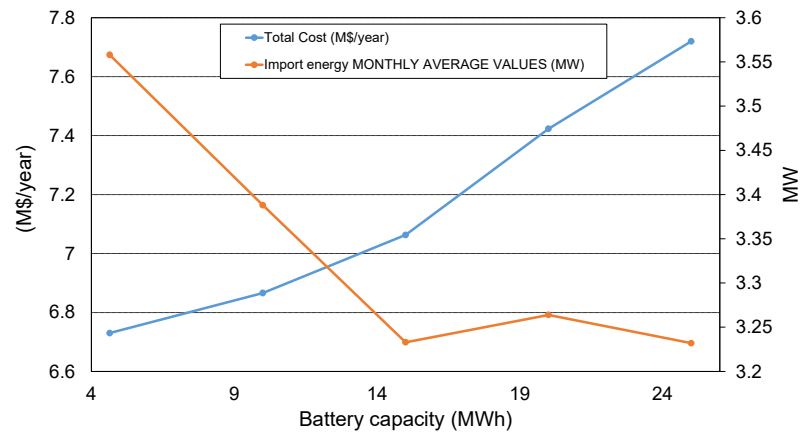


Figure 13. Total annual cost and imported energy, variation in the capacity of the energy storage system.

To determine the optimal capacity of the system, all the parameters analysed so far, total cost, CO₂ emissions, and surplus electricity must be considered. The system could be chosen as WT = 12.65 MW, PV = 1.58 MW, BAT = 4.64 MWh, and DG = 9 MW. The energy flow during a day in January 2018 is shown in Figure 14. It is evident that the RES generates more energy during the middle of the day due to the greater solar radiation; in the same way, the batteries remain charged during that period. However, during peak demand hours, renewable sources do not supply the demand and the battery quickly discharges, leaving the diesel generator to operate at dawn as a backup source. When the capacity of DG = 0, the optimal capacities of WT and PV are 24.65 MW and 15 MW, respectively; the result of the energy flows is shown in Figure 15. It should be noted that considering the useful life of the BAT, the replacement cost is every six years, which increases the cost of the system at higher BAT capacities. This is compared to what is explained in ref [55].

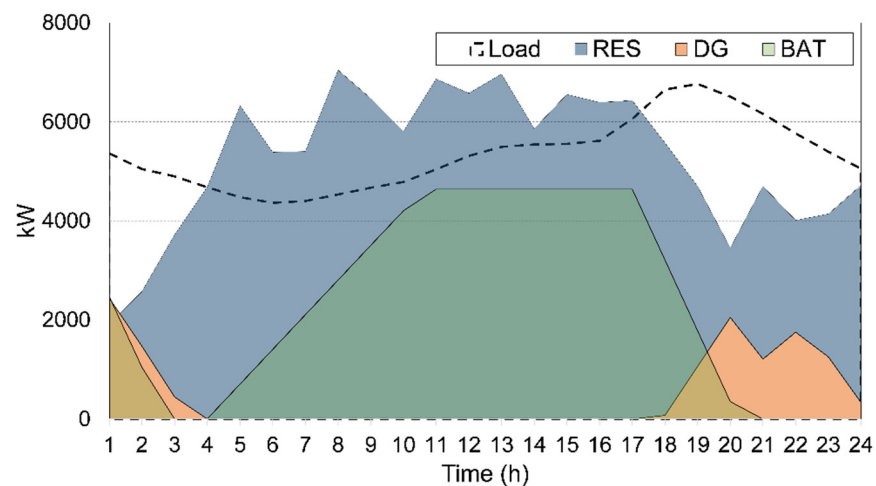


Figure 14. Power flow between source and demand.

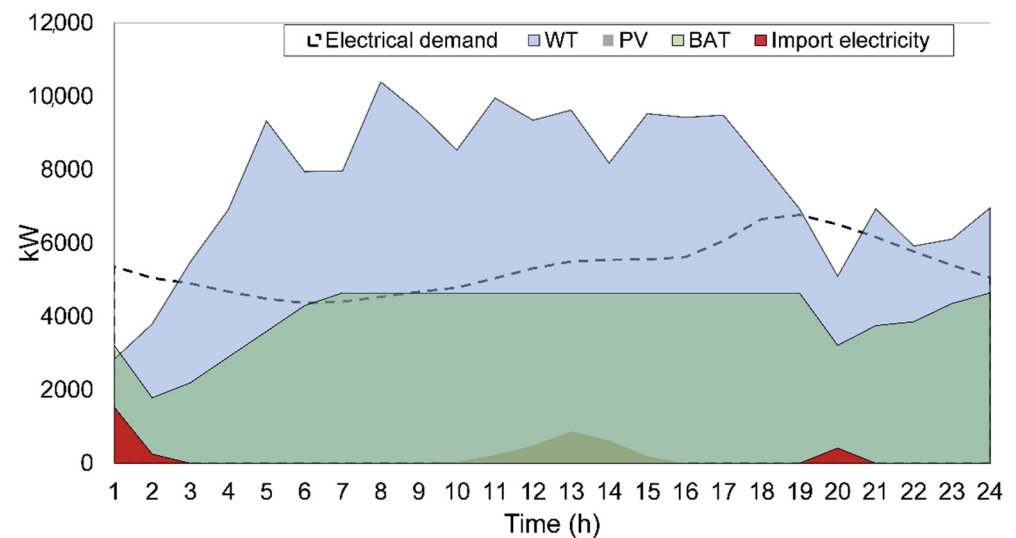


Figure 15. Power flow between source and demand, DG capacity = 0 MW.

5. Conclusions

In this study, a repowering feasibility study of a current hybrid renewable system was done for the Santa Cruz–Baltra and San Cristóbal Islands in Galapagos. To reach the objective, the EnergyPlan software was used, obtaining the following results.

It has been shown that it is possible to significantly improve the system currently installed in the Islands. By increasing the capacity of WT, the total annual cost decreases notably until it stabilizes at 4.02 M\$/year for a capacity of WT = 12.65 MW, and with a capacity of DG = 9 MW, reducing the total cost by 20%. The reduction in capacity of DG is supplied by WT, which reduces the O&M costs and diesel consumption of DG. By increasing the PV capacity, the total annual cost is lower, when the PV capacity reaches 7.58 MW and DG = 9 MW again; in this case, the cost reduction is 10.31% with respect to the current system.

On the other hand, the increase in HRES capacities and decreases in capacity of DG have caused a notable reduction in CO₂ emissions; in the case of WT, 38.96% less CO₂ has been emitted and with PV 16.35%. However, this increase in HRES produced a surplus electricity of 17.08% and 1.7% for WT and PV, respectively, which can be solved by increasing the capacity of the energy storage system.

Then, to supply the Islands with a 100% system, the WT capacity must be at least 24.65 MW and 15 MW of PV. Moreover, increasing the capacity of the batteries is extremely expensive; for example, it has been shown that if 0.3 MW of energy imports is reduced, 20 MWh must be increased, but the investment would be at least one million dollars. From this dimension, it is still necessary to import approximately 24% of the total electricity demand of the Islands.

Finally, if a 100% renewable system is considered, the stability of the power system could be compromised since it would depend on the randomness of its renewable sources (PV-WT). The only element that would maintain inertia and reserve would be the batteries—if its capacity is increased, the cost becomes unsustainable. A solution could be based on maintaining a certain capacity of the DG (e.g., 5 MW) to have a certain amount of rolling reserve and reduce the electricity surplus. In this paper, the economic results were similar when considering DG = 0 MW and DG = 5 MW.

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