



# Decarbonizing the Galapagos Islands: Techno-Economic Perspectives for the Hybrid Renewable Mini-Grid Baltra–Santa Cruz

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Received: 15 February 2020; Accepted: 12 March 2020; Published: 14 March 2020



Abstract: The fragile ecosystem of the Galapagos Islands is being affected by population growth, intensive tourism, the exploitation of local resources and the high consumption of imported fossil fuels. This unsustainable development model makes the provision of services such as electricity a challenge. This research investigates the hybrid renewable mini-grid Baltra-Santa Cruz, which represents 62% of the electricity generation mix of the archipelago. This study aims to support the Galapagos Zero Fossil Fuel Initiative and the Sustainable Development Goal 7 through the reduction in diesel consumption and electricity generation costs. To do so, HOMER Pro, a specialized hybrid renewable mini-grid planning tool, is used to perform several techno-economic assessments, focusing on different electricity demand scenarios. Therefore, multiple pathways are compared to identify the most reliable alternatives towards the progressive decarbonization of this hybrid system. The results indicate that installing 18.25 MWp of photovoltaic and 20.68 MWh of battery capacity could reduce the Levelized Cost of Electricity (LCOE) from 32.06 to 18.95 USc/kWh, increasing the renewable energy (RE) share from 18% to 39%. Additionally, the successful application of energy efficiency measures would even reduce the LCOE to 17.10 USc/kWh. What is more, distributed energy is considered the most attractive way to involve islanders in the energy transition process. Finally, this paper offers a comprehensive business model proposal to achieve a resilient energy supply, based on a combination of auctions and energy community models, which demands high political will, reliable and innovative regulations and social awareness about energy use.

**Keywords:** Galapagos Islands; decarbonization; hybrid renewable mini-grid; renewable energy; techno-economic analysis; HOMER Pro; business models; auctions; energy community model

# 1. Introduction

Achieving Sustainable Development Goal number 7 (SDG7), namely to ensure access to affordable, reliable, sustainable and modern energy, is a global challenge which should be encouraged in order to decarbonize the electricity supply, particularly in countries with high levels of electricity demand [1]. For islands, this is more worrying, since their size and remoteness increase electricity prices because of the high cost of imported fuels, which limits their economic development [2,3]. Furthermore, most islands worldwide have non-interconnected power systems based on diesel power plants [3,4], which affects the reliability and stability of the power supply, especially under extreme weather conditions [3].



In those contexts, the interconnection with the mainland is commonly unprofitable due to high initial investment of submarine cable connections [2,3]. Indeed, investments in submarine connections are higher than renewable energy (RE) implementation [5]. Despite these factors, non-interconnected islands have a promising potential to become low-carbon economies because of their abundant RE resources. In small islands in the Pacific, which have the highest electricity generation cost at the regional level because of their remote location from the mainland, hybridizing diesel gensets (DGs) is possible thanks to 3 MWp of solar photovoltaic (PV) and 5 MW of wind potential. This capacity, combined with battery storage systems, could reduce the Levelized Cost of Electricity (LCOE) from 45.1 to 35.9 USc/kWh [6].

Two decades ago, islands started the transition from only diesel power plants to hybrid renewable mini-grids to meet ambitious RE targets [7]. Regarding the current prices of RE technologies, hybrid systems are the most cost-effective solution for these territories [8]. Nevertheless, only a few islands have achieved self-sufficiency through hybrid power systems, e.g., El Hierro and Graciosa islands, where 100% of electricity is generated by RE resources. In these developed islands, this positive outcome is the result of suitable policies, investment capacity, mechanisms and business models to implement RE projects, local human resources and collective awareness about the use of energy, keeping low growth rates of electricity demand [8]. For instance, in the Canary archipelago and in the Graciosa island, the annual growth rate of electricity demand is 1.35% [9] and 3.9% [10], respectively. There are others such as the Tokelau Islands with 70% of RE penetration because of their very low electricity consumption (480 kWh/capita/year) [8]. Here, social, institutional and financial barriers remain a concern for the implementation of RE projects [11]. On the other hand, in Martinique and Reunion islands, RE introduction is limited to 30% due to stability issues [12,13]. In Reunion Island, more than 60% of electricity generation comes from coal-fired and oil power plants and the electricity consumption increases by 2.5% per year [14]. Here, technical conditions have a considerable influence on political choices. For the least-developed islands, such as the Pacific Islands, political willingness, the lack of funding and local capacities are major barriers for RE introduction [8]. For islands, it has been possible to achieve high RE shares; however, more research and more specific case studies based on techno-economic perspectives remain needed.

The present research focuses on the hybrid renewable mini-grid of Baltra–Santa Cruz (two interconnected islands), located in the Galapagos archipelago, 1000 km from the Ecuadorian coast in the Pacific Ocean. Here, 82% of electricity (29 GWh) is generated by a diesel power plant, which represents 7.9 million liters of diesel consumption [15]. The RE share is only 18% and the annual growth rate of electricity demand is, on average, 7% (2007–2018) [16]. This value is higher than the growth rates of the aforementioned islands, which have achieved high RE shares. In Galapagos, the power sector is a monopoly and energy costs are highly subsidized, which affects the competitiveness of RE technologies. For instance, the subsidized electricity generation cost is 24.31 USc/kWh, which has not been audited to clarify the real cost [17]. Furthermore, Ecuador ranks third in terms of fossil fuel subsidies in Latin America [18]. This represents 5.4% of the Ecuadorian Gross Domestic Product (GDP) and 14% of the government revenues [19]. The lack of refining capacity forces Ecuador to import diesel to generate electricity [20]. Contrary to that, flexible support mechanisms at different levels of the energy supply chain can replace subsidies to ensure gaps in funding and the implementation of hybrid power systems [21]. This highlights that the Galapagos Islands should diversify their energy mix, including the exploitation of more RE resources [22] and adequate mechanisms for business [8]. Therefore, supporting the 2030 Agenda for Sustainable Development and, specifically, the achievement of the SDG7, requires great effort and the implementation of reliable strategies. This means that realistic techno-economic proposals and the definition of powerful partnerships are needed. Thus, the following research questions arise in this study:

- What is the techno-economic RE potential to support the Agenda for Sustainable Development?
- To what extent can energy efficiency support the Agenda for Sustainable Development?

 Which business models are needed to support the implementation of new RE capacities and energy efficiency?

To address these issues, this research applies several techno-economic assessments to optimize the hybridization of the Baltra–Santa Cruz power system. Likewise, the applicability of distributed generation is evaluated in sectors with high electricity consumption. HOMER Pro, the specialized mini-grid planning tool, is used to identify the optimal designs. HOMER is the widest simulation and optimization tool for realistic applications [23–25], especially in far-flung areas [25]. This research considers technical, socio-economic, environmental and political conditions of Baltra and Santa Cruz Islands as drivers or inhibitors for RE implementation. This study contributes with a proposal to decarbonize the hybrid system of Baltra–Santa Cruz and the identification of distributed generation potential, increasing the RE capacity to guarantee the electricity requirements of islanders and considering the natural and ecological conditions of the context. Furthermore, a business model is presented to facilitate the implementation of RE power and energy efficiency means. This paper is structured as follows: Section 2 gives an overview of the case study; Section 3 describes the data and methodology applied. Results and discussion are presented in Section 4. Section 5 shows the business model proposal. Finally, Section 6 presents the conclusions and policy implications.

## 2. Galapagos Islands Framework

The Galapagos archipelago, formed by 19 volcanic islands and 200 islets, was recognized as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1978 [26,27]. Here, 93% of the total area is protected, while the remaining is inhabited [26,28]. In 2018, the Galapagos registered 32,000 inhabitants [29] and 276,000 tourists [30]. The average annual population growth rate is 7% [29] and it is expected that there will be a tourism growth rate of 8% to 2030 [31]. Tourism is the most important economic activity in these islands [32], which is generating a conflict between resource conservation and economic development [33]. This activity threatens the islands' resilience through its effects on the economy, population growth, resource consumption, invasive species arrival and lifestyle of residents [34]. While the Ecuadorian government, via the Government Council for the Galapagos Special Regime (CGREG), has tried to control the demographic growth [35], the future population growth will be linked to the tourism sector [33,35]. The main economic activities related to tourism—accommodation, food services and commerce [26]—account for 25% of the Galapagos' GDP (\$242.7 million US) [36]. The current economic growth model based on tourism has become unsustainable [34], which makes the provision of services, such as electricity, more challenging when combating climate change. Only in Santa Cruz Island, the electricity consumption is approximately 1633 kWh/capita/year [16,37]. In fact, the Galapagos province presents the second-highest electricity consumption per capita in Ecuador [38].

#### 2.1. Energy Policies Status in the Galapagos Islands

To preserve the fragile ecosystem of the Galapagos archipelago and to promote its sustainable development, the Ecuadorian government launched the Zero Fossil Fuel Initiative in 2008. In the electric power sector, this policy focuses on the replacement of fossil fuels by RE resources [39]. Thus, the Ministry of Energy and Non-Renewable Natural Resources (MERNNR), in cooperation with donor governments, has developed RE projects to reduce fossil fuel consumption and CO<sub>2</sub> emissions and to avoid fuel spill risk by maritime transportation [40]. However, this initiative lacks a clear guide for RE implementation and environmental conservation.

In the Galapagos Islands, the vertically integrated power sector has limited private participation by the Electrical Sector Regime Law (1996, modified in 2010) [41] and the Organic Law of Public Electricity Service (LOSPEE) (2015) [42]. The LOSPEE only allowed RE projects to be funded by the General National Budget. Nevertheless, in 2019, the General Regulation of the LOSPEE [43] was published to enable new ways of partnership for the RE sector. Thanks to this, mixed and private companies, foreign public entities and solidarity and popular economy enterprises can receive concessions to manage

and implement RE projects. In addition, the Ecuadorian Electricity Master Plan (PME) 2016–2025 [44] contains the list of priority projects to increase renewable electricity generation. Moreover, those possible new partners can propose additional RE initiatives thanks to the General Regulation of the LOSPEE. This regulation [43] is based on the targets of the National Plan of Development 2017–2021 [45] which prioritize RE resources exploitation to reduce the dependency of fossil fuels. What is more, new companies interested in developing RE projects can receive an income-tax-exemption for five years [46].

As regards distributed generation, the photovoltaic microgeneration to electricity self-sufficiency for final consumers of electricity regulation [47] and its amendment [48] promote the installation of PV systems up to 300 kWp per user in the residential sector and below 1000 kWp per user in the commercial and industrial sectors. This regulation is not limited to rooftop PV systems. A net-metering scheme is applied to compensate electricity costs. Thanks to this mechanism, consumers are billed for their "net" electricity use and the associated costs become credits for the following months if the electricity balance is positive for users. [47]. The National Rate Schedule for Electricity Companies establishes the tariff applied in the different sectors [49]. For instance, to sell electricity or purchase it from the grid, the average tariffs applied are 9.8 and 10.30 USc/kWh in the residential and commercial sectors, respectively [49]. The PV generator's capacity corresponds to the annual electricity needs of users [47].

Additionally, diverse energy efficiency measures have been adopted to reduce electricity consumption, such as the replacement of street-lights, light-bulbs and refrigerators in the residential sector [50]. Currently, the National Plan for Energy Efficiency [51] leads the following actions: The adoption of the Ecuadorian Building Standard (NEC) in the residential, commercial and public sectors; the replacement of energy-inefficient electrical appliances based on labeling schemes; and the implementation of Energy Management Systems based on the standard ISO 50001 in public institutions and commercial sector. These measures should help to reduce the consumption of 0.78 million barrels of oil equivalent (MBOE) in 2035. Moreover, the Organic Law of Energy Efficiency fosters the creation of financing incentives to channel external funds from cooperation agencies [52].

Despite these efforts, according to the First Intended Nationally Determined Contribution (INDC) of the Ecuadorian government to the Paris Agreement under the United Nations Framework on Climate Change, the Galapagos Islands are becoming much more vulnerable due to negative effects of climate change. In fact, the average temperature has increased by 1.4 °C and it could be higher than 2 °C, which is the expected temperature in the mainland [53]. The Ecuadorian Ministry of Environment (MAE) has stated the islands as a priority area to implement adaptation and mitigation plans. Here, environmental sustainability, biodiversity conservation and appropriate management of natural resources are key factors [54]. As in other Pacific islands [55,56], the Galapagos should redirect their plans to develop more RE projects and attain energy identity, reflecting their own needs and reducing fossil fuel dependency and electricity demand. Hence, energy transition must be accelerated to reduce environmental risks on these islands.

#### 2.2. The Electricity Generation Matrix of the Galapagos Islands

In the Galapagos Islands, the Electricity Corporation of Ecuador (CELEC EP) manages diesel generation and electricity transmission and the Electricity Company Galapagos ELECGALAPAGOS manages the renewable generation and electricity distribution. Both public companies combine electricity generation tasks through an official agreement, which allows ELECGALAPAGOS to reduce its economic deficit, setting its operation and maintenance (O&M) costs of generation in the National Interconnected System (SNI) [57]. In the mainland, the average cost of electricity generation is 4 USc/kWh [58]. This very low price is explained by the hydroelectricity contribution to the national electricity mix. The hydro penetration was 90% in November 2019 [59].

In the inhabited islands of the Galapagos, there are four isolated power systems: San Cristobal, Baltra and Santa Cruz (two interconnected islands), Isabela and Floreana [40]. In 2018, the total electricity supply was 57 GWh, of which 16% was produced by renewable power plants. The electricity demand was 51 GWh and the diesel consumption was 13 million liters [15]. The difference between

supply and demand corresponds to 10% of energy losses in the distribution system and 1% of the electricity consumption of auxiliary equipment [15]. Table 1 [60] shows the power capacity installed by technology on each island.

Island	Diesel (MW)	Wind (MW)	PV (MWp)	Diesel (MW)	Biodiesel (MW)	Batteries (MWh)	Total (MW)
San Cristobal	8.99	2.4					11.39
Santa Cruz-Baltra	13.9	2.25	1.57			4.3	17.72
Isabela	2.63		0.95			0.33	3.58
Floreana			0.21	0.15	0.15	0.38	0.51

Table 1. Hybrid power system configuration of the Galapagos Islands.

The most vulnerable Pacific islands have been depending mainly on donor countries [61]. In fact, in the Galapagos Islands, RE investment has been covered by the national government with the support of donor countries and international cooperation agencies. Private participation has been extremely limited because of protectionist policies. The San Cristobal Wind Farm (2007) was supported by the Global Sustainable Electricity Partnership (GSEP), the United Nations Foundation (UNF) and the United Nation Development Program (UNDP). In Floreana, RE initiatives (2011) were funded by the UNDP; the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU); the Germany International Cooperation Agency (GIZ); and the Inter-American Institute for Cooperation on Agriculture (IICA). In Santa Cruz, the Korea International Cooperation Agency (KOICA) co-financed the PV system of 1.5 MWp (2015). In Baltra, 67 kWp (2016) were covered by the Japan International Cooperation Agency (JICA) and the wind farm (2014) was co-funded by the Global Environment Facility (GEF), UNF, UNDP and GIZ. In Isabela, the hybrid renewable mini-grid is being co-funded by the German government through the KfW Development Bank [8]. In this island, the project aims to hybridize the thermal power generation (diesel and biodiesel). However, the biodiesel availability, which is mainly produced in Ecuador to satisfy the fuel needs of the hybrid system Floreana, is a big limitation because of the low production of jatropha [15].

#### 2.3. Hybrid Renewable Mini-Grid Baltra-Santa Cruz

In Santa Cruz, which is the island that experiences the most tourism, 61% of the population in the archipelago resides there [30,37]. Here, implementing sustainable strategies would lead to a positive impact on the electricity mix of the Galapagos Islands. The present research focuses on the Baltra–Santa Cruz hybrid power system. Baltra and Santa Cruz Islands are interconnected by a transmission line of 34.5 kV and 51.4 km of cable. This interconnection consists of different segments: 20 km of overhead cable, 21.5 km of underground cable, 900 m of submarine cable (crossing the Itabaca channel) and 9 km of aluminum cable set up over metal poles [39]. The interconnection line connects 14 MW from Baltra to Santa Cruz, while Baltra substation has 10 MW of capacity [62]. This infrastructure has cost \$14.2 million US (\$1014 US/kW installed) [39].

Figure 1 shows the configuration of the Baltra–Santa Cruz power system. Santa Cruz has a PV system of 1.5 MWp and a diesel power plant of 13.9 MW composed of 11 DGs. Baltra has a PV system of 67 kWp, a wind farm of 2.5 MW (three wind turbines, each one of 750 kW) and a battery storage system of 4.3 MWh [40]. The battery bank is hybrid, the lead-acid batteries (4.03 MWh) store the energy surplus generated by RE systems and the lithium-ion batteries (0.268 MWh) regulate the energy fluctuations of the wind farm [39]. This is an experimental and innovative configuration to strike a balance between performance, size, lifetime and storage device costs [63,64]. In 2018, electricity consumption was 32 GWh [15] and the peak demand was 7.26 MW [65]. In those islands, according to the PME 2016–2025 [44], 9.75 MW of wind and 5.34 MWp of PV are planned to be installed by 2023, but the projects lack financing.



Figure 1. Configuration of the Baltra-Santa Cruz Island system (own elaboration).

In 2018, this system generated 35 GWh and the RE share was only 18% [15]. The RE generation represents a saving of approximately 2.6 million liters/year and a reduction of 5150 tons of CO<sub>2</sub> emissions [51]. In the Galapagos, according to the Ecuadorian Agency for Regulation and Control of Electricity (ARCONEL), the electricity service cost is 38.84 USc/kWh, which includes the cost of electricity generation (24.31 USc/kWh) and the cost of electricity distribution (14.53 USc/kWh) [17]. However, in this year alone, the operational deficit of generation, which is covered by the National Interconnected System, reached \$7.2 million US [58]. Furthermore, the electricity tariff is, on average, 9.8 USc/kWh for residential users and 10.30 USc/kWh for commercial users [49]. The Baltra–Santa Cruz power system is highly subsidized in every stage of the electricity service chain.

#### 3. Materials and Methods

The techno-economic analysis of the Baltra–Santa Cruz hybrid renewable mini-grid was done using HOMER (Hybrid Optimization of Multiple Electric Renewables) Pro 3.13.1. This specialized mini-grid program was developed by the National Renewable Energy Laboratory (NREL) and transferred to a private company. The software allows one to design the main components from an energy system and to simulate the dispatch for one reference year (hourly increments) based on detailed input data such as load profiles, technology generation options, O&M schedules, component costs and RE resources [66]. Simulation, optimization and sensitivity analysis are the tasks of this software [67]. The simulation analyzes the current operation of a hybrid system, the optimization leads to the least-costly system configuration and the sensitivity analysis allows one to analyze the impact of sensitivity variables on the energy system [66].

Researchers widely use HOMER to analyze and optimize hybrid power systems that incorporate high introduction of RE technologies in islands. For instance, Demiroren and Yilmaz [68] estimated the reduction in the LCOE using RE in Gökceada Island, Turkey. As a result, introducing grid-connected wind turbines is the cost-optimized solution for this location. Padrón et al. [67] assessed hybrid power systems for supplying electricity to Autonomous Desalination Systems (ADS) in Lanzarote and Fuerteventura Islands in the Canary Archipelago. The authors observed that a PV/wind/DG combination is the most techno-economically viable application. Kalinci [69] concluded that the grid/wind (grid-connected) and the PV/wind/fuel cell (isolated system) are the optimum options to provide electricity to Bozcaada Island, Turkey. Ali, Shafiullah and Urmee [70] determined that a PV/diesel/battery hybrid system is the most economical and environmentally friendly solution for the Hulhumalé Island. What is more, regarding specific evaluations of the Galapagos Islands, in reference [71], the optimization of the Baltra–Santa Cruz power system was investigated, including induction stoves and electrical vehicles as new loads. The findings show that PV is the most feasible alternative to satisfy an additional demand and reduce the LCOE. In reference [50], implementing

a hybrid solar/biogas system was shown to be the recommendable configuration to reduce fossil fuel consumption in the inhabited islands. However, most of these studies used limited data and, above all, none of these studies considered local conditions to limit the techno-economic assessments. Rosso-Cerón et al. [72] noted that energy planning is a classic problem of optimization with constraints of investment capacity, demand or resources. Moreover, reference [8] identified that technical, socio-economic, environmental and political limitations must be considered as constraints in energy planning. For instance, in the Galapagos Islands, there is a conflict between protected areas and the use of land for RE implementation. This research is distinguished from the aforementioned studies because of the consideration of the real electric power system constraints and environmental conditions in the planning process. The use of the local and reliable information provided by ELECGALAPAGOS guarantees the quality of this study. Figure 2 shows the workflow of the methodology applied based on the HOMER tool. This section describes the input parameters, the energy system model, the scenarios applied and the main outcomes of this research.



Figure 2. The conceptual flow of the HOMER tool.

#### 3.1. Techno-Economic Information

## 3.1.1. Renewable Energy Resources

In the Galapagos Islands, solar and wind resources are complementary and negatively correlated. This helps to overcome the most common drawbacks of hybrid energy systems: Weather, climate change and their unpredictable nature [73]. A recent study showed these islands as one of the most suitable areas to install PV projects in Ecuador [74]. Here, the maximum daily Global Horizontal solar Irradiation (GHI) is 7.40 kWh/m<sup>2</sup>, which usually takes place in March during the dry season, while the minimum daily GHI is 4.40 kWh/m<sup>2</sup> and occurs in July [75]. On the other hand, the maximum and minimum wind speed registered are 7.28 m/s (cold season) and 4.20 m/s (dry season), respectively, at a height of 50 m on Baltra Island. Table 2 shows detailed data on RE resources in the territory [76]. Solar and wind data were measured by ELECGALAPAGOS from 2015 to 2016 in Santa Cruz and from 2009 to 2018 in Baltra, respectively. Figures 3 and 4 show the average meteorological data introduced in HOMER.

Table 2. Renewable energy resource.

Resource	Average	Min	Max
Daily irradiation (kWh/m²/day)	5.70	4.40	7.40
Wind speed (m/s)	6.36	4.20	7.28



Figure 3. Average monthly data: Global Horizontal solar Irradiation (kWh/m<sup>2</sup>/day).



Figure 4. Average monthly data: Wind speed (m/s).

# 3.1.2. Load Data

In 2018, the electricity consumption was 32 GWh in Baltra and Santa Cruz (61% of the total electricity demand of the archipelago) [15]. In the same year, the registered peak demand was 7.26 MW [65]. There are 7500 users: Residential (5905), commercial (1093, including tourist sector), industrial, street lighting and others (other services include water pumping, water pumping for rural communities, special clients, electric vehicles, social services, public services, rural communities and housing religious

groups). The residential and commercial users represent 41% and 42% of the electricity consumption, respectively. The industrial sector consumes 1% of the total electricity and the remaining portion (16%) corresponds to street lighting and other services [77]. Figure 5 (monthly load profile) shows that the period of higher electricity consumption is from December to May during the tourist season [65]. This corresponds to the dry season, which is characterized by higher temperatures and sporadic heavy rains [54]. The opposite is observed between June and November. In the daily load profile (see Figure 6), the higher demand takes place between 19:00 and 22:00 [65]. For simulation scenarios, the hourly load profile from 2018 was introduced in HOMER. These data present a random variability of 9.68% day-to-day and 6.76% timestep.



Figure 5. Monthly load profile of Baltra–Santa Cruz (kW) for 2018.



Figure 6. Daily load profile of Baltra-Santa Cruz (kW) for 2018.

Additionally, to determine the annual growth rate of the electricity demand, the monthly statistical data on electricity demand from 2007 to 2018 were analyzed. Then, the result is an annual growth rate of 7% [16].

For the purpose of this paper, the demand was also analyzed as follows:

First, as the growth rates of population and tourism are expected to increase by 2030 (see Section 2), it was assumed that the growth rate of electricity demand would keep increasing by 7% over 10 years. Therefore, the hourly load profile from 2018 [65] was applied as a baseline profile to simulate the demand to 2030, regarding the current annual growth rate of electricity demand (7%). As a result, the electricity consumption and the peak demand would be 73.7 GWh and 16.35 MW, respectively, in 2030.

Second, considering that the application of the National Plan for Energy Efficiency [51] would provide successful results, a significant reduction in the annual growth rate of electricity demand would be obtained. The estimated hypothetical value of this reduction is 3.5% (half of the current value), which is close to growth rates from other islands, such as El Hierro and Graciosa, where tourism plays also a crucial role in development [8]. Therefore, an hourly load profile was simulated to 2030, using a growth rate of 3.5%. Then, 49.45 GWh and 10.97 MW of electricity and peak demand, respectively, would be supplied in 2030.

Third, as the residential and commercial sectors are major consumers in Santa and Baltra Islands [77], the feasibility of distributed generation was analyzed, using as baseline their load profiles from 2018. In this year, the annual electricity consumption of one residential user was, on average, 2320 kWh [78] and the commercial user consumed, on average, 12,575 kWh [79]. Both profiles present the same characteristics as the total load profile previously described [65].

#### 3.1.3. Existing System

#### Photovoltaic and Battery Systems

In Baltra, the PV system of 67 kWp, whose tilt angle is 11°, is composed of 252 Mitsubishi monocrystalline silicon modules (14 series × 18 parallel), each one having 265 Wp [40]. There is a Three-phase inverter of 100 kW. The Fuji Electric battery bank works at 448 V. There are 1344 (224 × 6) stationary lead-acid batteries and their cell capacity is 1500 Ah at 2 V each. Likewise, there are 161 (23 × 7) lithium batteries and their cell capacity is 75 Ah at 22.2 V each. ELECGALAPAGOS controls the state of charge (SOC) of the lead-acid batteries (4.03 MWh) between 40% and 100% to store the energy surplus, whereas the SOC of the lithium batteries (268 kWh) is controlled between 40% and 60% to regulated energy fluctuations [80]. The batteries have a downtime of 144 hours per year according to the maintenance plan of ELECGALAPAGOS [81]. This PV system generates approximately 136 MWh/year, avoiding the emission of 3600 tons of CO<sub>2</sub> [51].

In Santa Cruz, the Puerto Ayora PV system (1.5 MWp) consists of 6006 BJ-power monocrystalline silicon panels of 250 Wp each. The generator's tilt angle is  $6.5^{\circ}$  and the performance ratio (PR) is 0.793. There are 91 SMA Sunny Tripower Three-phase inverters (17 kW each) and each string has 22 PV modules connected [40]. This PV system produces 2.4 GWh/year that means 1500 tons of CO<sub>2</sub>/year are not emitted to the environment [51].

#### Wind Turbine System

The Baltra wind farm (2.25 MW) consists of three UNISON U57 turbines of 750 kW each and its Hub height is 50 m [39]. Thanks to the ELECGALAPAGOS data, the wind power curve [82] has also been characterized in HOMER. This project generates 5.8 GWh/year, avoiding the consumption of 1.8 million liters of diesel [51].

#### Gensets and Fuel Consumption

In off-grid systems, gensets are expected to operate as a backup, but in the Baltra–Santa Cruz hybrid renewable mini-grid, these components constitute the main generation system. There are four Caterpillar DGs of 650 kW each that have a remaining life of 43,800 hours. One Caterpillar genset of 1.1 MW has a remaining life of 90,000 hours. The remaining life of six Hyundai DGs (each one of 1.7 MW) is 90,000 hours [60]. The installation cost of a DG is approximately \$340 US/kW [83]. ELECGALAPAGOS sets the minimal loading of DGs at 25% [84,85], the value recommended by the manufactures. Following the Maintenance Plan of ELECGALAPAGOS in 2018, one Caterpillar and every Hyundai DG are in maintenance between 120 and 240 hours. The O&M costs of DGs are \$2.5 US/hour, \$4.23 US/hour, \$6.55 US/hour for 650 kW, 1.1 MW and 1.7 MW, respectively [81].

In 2018, the Baltra–Santa Cruz hybrid system consumed 7.9 million liters of diesel, equating to \$1.8 million US. In the mainland, the subsidized diesel price is 24 USc/liter (including taxes) [86]. Shipping

this fuel to Baltra Island costs 12 USc/liter. Thus, the final cost of diesel is 36 USc/liter [83]. This is a low price compared to the international market, where the fuel price is 56 USc/liter (2018) [87]. Then, the real fuel price would be 80 USc/liter, adding taxes and shipping costs [83,88].

#### Biodiesel

Biodiesel (jatropha oil) was included in this study to analyze another option to optimize the Baltra–Santa Cruz generation system. Jatropha is cultivated in Manabí, in the coastal region of Ecuador [89]. The Ecuadorian government has tried to promote the local production of biodiesel to reduce the dependency on diesel imports and support the homeland economy. However, the low levels and high costs of biofuel production make it difficult to achieve this target. The amount of jatropha available depends on the harvest and this, in turn, depends on climatic, logistical and social factors [90]. For Floreana Island, the smallest of the inhabited islands, 648 liters of biodiesel were supplied in 2018, which represent only 1% of the total fuel consumption [15]. The biodiesel cost is \$2.31 US/liter [91]. In January 2019, a minimum production of 21,900 liters of biodiesel was expected to cover less than 20% of the fuel required by the hybrid system located on Floreana island [15,92]. Despite this low production, the national government has planned to use biodiesel to run DGs in another hybrid system located on Isabela Island. To cover the deficit of the Ecuadorian biodiesel market, the Ministry of Energy and ELECGALAPAGOS have started to analyze the option of importing biodiesel from China, whose cost is \$1.22 US/liter (including taxes and transport costs) [88] to replace diesel consumption.

In this research, both diesel and biodiesel (from Ecuador and China) are considered to perform optimization assessments (see Section 3.3). The purpose is to analyze their techno-economic feasibility to fuel gensets.

#### **Operating Reserve**

Regarding stability issues, based on the Ecuadorian Dispatch and Operation Regulation 006/00 (2000) [93], there is an operating reserve of 15% to regulate frequency and to cover system failures: 5% of the reserve is intended to regulate the primary and secondary frequency, guaranteeing the reliability and stability of the power system, while the remaining 10% is designed to cover large deviations in the system, e.g., systems failures, the power output of a genset and load or renewable resource fluctuations. In reference [2], the authors asserted that small islands should operate with a rule n-1 diesel unit to increase the reliability of the power system. This configuration allows the system to meet the peak load without the largest unit in operation. This statement matches with the Ecuadorian regulation [93] and practices in terms of generation systems stability [94].

It should be emphasized that the old 006/00 stability regulation is only based on DGs. In Ecuador, there is no specific regulation for hybrid systems that include batteries and DGs. In HOMER, 15% of the operating reserve includes both DGs and battery storage systems [66]. Generally, the size of a diesel power plant needs to be capable to serve the peak demand during a year [95]. However, several studies [96–99] have demonstrated that battery energy storage systems can support black starts, voltage and frequency regulation and supply the peak load demand. In fact, batteries can ensure that dispatchable power is available during periods of peak demand and low RE generation [96]. What is more, there are real-life applications on Graciosa, Lanai and Japan's Oki islands, where battery storage systems are used to ensure stability and integration of variable renewables [100]. This is a very important factor for the applied scenarios, since the Ecuadorian Zero Fossil Fuel Initiative inhibits increasing diesel-power capacity.

### 3.1.4. Costs

Table 3 shows the investment, replacement and O&M costs of components. In the simulation analyses, investment prices and O&M costs of DGs and RE technologies correspond to registered costs by ELECGALAPAGOS [81,83,101]. First, the capital costs of previous installations were included in the simulation analysis and these were set at \$0 US in the optimization process. New RE investment

includes every cost associated with the installation such as equipment and control systems, wiring, mounting hardware, power connection and civil work. For optimizing the island system of Baltra–Santa Cruz, RE investment costs have been well-researched. In the international market, RE costs are much lower than registered investment costs by ELECGALAPAGOS [81,83,101]. Indeed, there is a cost reduction tendency for the coming years. The current PV and wind investment costs were taken from reference [102] and batteries costs from reference [103]. Second, a recent study [104] presents the future evolution of RE and batteries costs in Latin America. According to this study, the investment costs of PV, wind and battery systems would be reduced by 20% in the medium term. Third, according to

the ELECGALAPAGOS expenditures, the O&M costs of RE technologies represent 1.25%/year of the initial investment [81,83]. Thus, for the simulation and optimization processes, the replacement and O&M costs represent 80% and 1.25%/year of the initial investment [102,103], respectively. Based on the information provided by ELECGALAPAGOS, PV replacement cost is 40% of the capital cost alone, discounting civil work (37%) and metal structures (3%) [105] and DG replacement cost is the same as the capital cost [105].

Component	Parameter	Unit	Simulation	Optimization
	Capital	USD/kW	340	0
Diesel	Replacement	USD/kW	340	340
	O&M	USD/kW/hour	2.5-6.55	2.5-6.55
	Capital	USD/kWp	10,600 <sup>1</sup>	1210
PV	Replacement	USD/kWp	484	484
	O&M	USD/kWp/year	15	15
	Capital	USD/kW	4485	1500
Wind	Replacement	USD/kW	1200	1200
	O&M	USD/kW/year	19	19
	Capital	USD/kWh	856	300
Battery	Replacement	USD/kWh	240	240
	O&M	USD/kWh/year	3.75	3.75
Fuel	Diesel	USD/liter	0.8	0.8
	Ecuador-biodiesel	USD/liter	-	2.31
	China-biodiesel	USD/liter	-	1.22
Othere	Interconnection			1014
Others	Baltra–Santa Cruz	U3D/KVV	-	1014
Distributed	Capital	USD/kW	-	1432
generation	Replacement	USD/kW	-	215
generation	O&M	USD/kW/year	-	18

**Table 3.** Economic values for simulation and optimization analyses.

<sup>1</sup> This investment cost has been registered and reported by ELECGALAPAGOS [101].

Table 3 also shows interconnection costs [39] and distributed energy costs [102,106] which are applied in the scenarios described in Section 3.3.

Finally, in the simulation and optimization analyses, diesel cost was set 80 USc/liter. In the biodiesel optimization scenarios, the cost was \$2.31 US/liter or \$1.22 US/liter. The project's horizon was set as 20 years. The discount rate was 12% [107] and the inflation rate was 0.27% [108]. The lifetime of PV generators, wind turbines and storage systems was set as 25, 20 and 15 years, respectively. The technologies described in Section 3.1.3 were used to perform both simulation and optimization analyses.

#### 3.2. Energy System Model

HOMER simulated and optimized several configurations of the hybrid power system sorted by Net Present Cost [23,67]. To do that, this software performed hundreds or thousands of hourly simulations/optimizations, matching supply and demand, to get the optimal system [109,110] and the least-costly option, using a proprietary derivate-free algorithm [66]. This analysis focused on comparing a wide range of equipment (previously described), including different constraints and sensitivities [110]. Firstly, the hybrid system was simulated to identify the real LCOE. Then, depending on the optimization scenario, this research applied the Advanced HOMER Optimizer or the HOMER Optimizer. The first one compares a range of capacities between upper and lower bounds, while the second one does not involve capacity limits [66]. The main indicators are defined as follows:

# 3.2.1. Net Present Cost (NPC)

The NPC, which is determined in Equation (1), is defined as the present value. The total NPC of a system is the present cost of the entire system over its lifetime, subtracting revenues. That includes capital, replacement, O&M and fuel costs [66,111].

$$NPC = \frac{C_{ann}}{CRF(i,N)} \tag{1}$$

where  $C_{ann}$  is the total annualized cost (USD/year) and CRF is the capital recovery factor, given by Equation (2).

$$CRF(i,N) = \frac{i(1+i)^{N}}{(1+i)^{N} - 1}$$
(2)

where *i* is the annual discount rate (%) and *N* is the project lifetime [66].

#### 3.2.2. Levelized Cost of Electricity (LCOE)

LCOE is the average cost per kWh of useful electrical energy produced by the system. HOMER divides the  $C_{ann}$  by the total electrical load served [66].

$$LCOE = \frac{C_{ann}}{E_{served,ACprim}}$$
(3)

where Equation (3), *E*<sub>served,ACprim</sub> is the ac primary load.

The RE potential of the hybrid system of the Galapagos Islands depends on the techno-economic feasibility of RE technologies and DG configurations and the demand. Furthermore,  $CO_2$  emissions result from the electricity produced by diesel generators. For the purpose of this paper, making decisions about different scenarios focused on the LCOE, taking care of the environmental conditions of these islands. Finally, it is worth mentioning that this paper considered a simplification on the batteries systems due to the fact that HOMER is not able to simulate two batteries simultaneously. The only simulated battery system considered the technical characteristics of lead-acid batteries (for optimization analyses, the maximum depth discharge was set at 70%).

#### 3.3. Description of Scenarios

This research performed multiple scenarios to provide reliable answers to the aforementioned research questions. First, the Baltra–Santa Cruz hybrid system was simulated to identify the real cost of electricity supply in 2018. Moreover, two additional simulations were performed to cover the projected load to 2030 with a growth rate of 7% and 3.5%, respectively. Second, the power system was optimized to cover the demand in 2030. To do so, "Renewable Energy Potential" (annual growth rate of electricity demand 7%) and "Energy Efficiency" (annual growth rate of electricity demand 3.5%) scenarios were applied. Furthermore, diesel capacity is not allowed to increase, according to the Zero Fossil Fuel Initiative. Third, "Distributed Energy" scenarios were applied to offer an alternative to the Zero Fossil Fuel Initiative due to the land use limitation and the necessity of this resource from large-scale generation systems. Figure 7 shows the different scenarios studied. Then, to guarantee the reliability of the optimal solutions, sensitivities analyses were carried out.



Figure 7. Simulation, optimization and distributed generation scenarios.

# 3.3.1. Status quo Scenarios

The "Status quo 2018" Scenario analyzes the Baltra–Santa Cruz Island system to estimate the real cost of the electricity supply. To do that, renewable energy resources, the hourly demand profile, characteristics of the current power system and economic information previously described in Section 3.1.3 are introduced in HOMER. In 2018, the electricity consumption and the peak demand were 32 GWh and 7.26 MW, respectively. Table 2 shows the simulation costs applied in this scenario.

In the "Status quo 7%" Scenario, the electricity demand and the peak demand are 73.7 GWh and 16.35 MW, respectively. The feasibility of this scenario needs 5% of capacity shortage for simulation [112]. In the "Status quo 3.5%" Scenario, the electricity demand is 49.45 GWh and the peak demand is 10.97 MW, considering the successful implementation of the National Plan for Energy Efficiency [51].

# 3.3.2. Renewable Energy Potential Scenarios

# Renewable Energy Potential: Boundary Conditions

Mahesh and Sandhu [73] showed that constraints are a crucial part to determine the most suitable solution in optimization processes. However, in most cases, constraints are related to technical aspects, e.g., installation capacity, leaving aside environmental or political concerns. On the other hand, a recent

study [8] focused on hybrid renewable mini-grids found that a successful RE implementation requires an in-depth understanding of the context. This entails taking into account technical, socio-economic, environmental and political criteria to define the limits of planning [8]. This scenario takes as reference these recommendations to optimize the hybrid system of Baltra–Santa Cruz through the identification of a list of boundary conditions shown in Table 4. Here, the ELECGALAPAGOS' Planning Directorate has also supported the definition of the listed constraints. In that sense, aspects related to the interconnection between Baltra and Santa Cruz, RE technologies, diesel capacity, stability issues and demand are analyzed to define the optimization constraints according to the criteria. These conditions are considered to limit the optimization process in HOMER. Therefore, HOMER is allowed to optimize the total capacity of PV and wind up to 21.83 MW, applying the Advanced HOMER Optimizer (see Section 3.2).

For this scenario, the aim is to supply 73.7 GWh of electricity demand in 2030, considering that the current annual growth rate of electricity demand is 7%. In this year, the peak demand is 16.35 MW. Hence, three configurations are analyzed: PV + wind + batteries + diesel; PV + wind + batteries + Ecuadorian biodiesel; and PV + wind + batteries + Chinese biodiesel. Table 3 shows the optimization costs applied.

#### Renewable Energy Potential: High RE Share

As the Zero Fossil Fuel Initiative lacks clear pathways to introduce RE technologies in the Galapagos Islands, this scenario evaluates the feasibility of high RE share. The objective is to achieve 70% of RE penetration by 2030 and supply an electricity demand of 73.7 GWh (peak demand: 16.35 MW). The HOMER Optimizer is applied in this analysis (see Section 3.2).

In contrast to the boundary conditions scenario, additional RE capacities, which overcome the remaining capacity of the Baltra substation (7.83 MW), involve an increase of \$1014 US/kW in investment prices for interconnection infrastructure. This value is added to the optimization costs of PV and wind technologies shown in Table 3. The configuration analyzed includes PV + wind + batteries + diesel. This ambitious scenario also aims to estimate the land required to install new RE power.

# 3.3.3. Energy Efficiency Scenarios

#### Energy Efficiency: Boundary Conditions

This scenario assumes that the National Plan for Energy Efficiency [51] has been applied effectively, reducing the annual growth rate of electricity demand to 3.5% (half of the current value and close to growth rates from other islands). This scenario optimizes the power system of Baltra–Santa Cruz to supply an electricity demand of 49.45 GWh (peak load: 10.97 MW) in 2030. The boundary conditions shown in Table 4 are also considered to optimize the system. According to that, the total capacity of PV and wind can achieve 21.83 MW through the application of the Advanced HOMER Optimizer. Three configurations are analyzed: PV + wind + batteries + diesel; PV + wind + batteries + Ecuadorian biodiesel; and PV + wind + batteries + Chinese biodiesel. Table 3 shows the investment costs applied.

#### Energy Efficiency: High RE Share

Again, a positive application of the National Plan for Energy Efficiency in the islands is assumed. Thus, the lower demand is supplied (49.45 GWh and 10.97 MW) in 2030. This analysis aims to achieve a RE fraction of 70%, regarding that PV and wind optimization investment costs (shown in Table 3) increase by \$1014 US/kW. Here, the HOMER Optimizer is used and one configuration is evaluated: PV + wind + batteries + diesel.

Factors	Technical	Socio-Economic	Environmental	Political	<b>Optimization Conditions/Constraints</b>
Interconnection of Baltra–Santa Cruz	7.83 MW is the remaining capacity of the Baltra substation to install additional RE power	Exceeding 7.83 MW involves an extra investment cost of \$1014 USD/kW to the RE costs shown in Table 3 to install additional RE capacity	According to ELECGAPAGOS, there is not specified the area available to install new RE power		Install a maximum power of 7.83 MW of PV or wind capacity in Baltra to avoid additional costs (\$1014 USD/kW) in RE investment
RE technologies			Solar and wind resources are seasonally complementary	Galapagos Islands Zero Fossil Fuel Initiative aims to increase RE capacity	PV and wind technologies along with battery systems are evaluated to optimize the hybrid system Baltra-Santa Cruz
		RE projects for the Galapagos Islands lack funding		The General Regulation of the LOSPEE (2019) promotes private participation to fund RE projects The PME 2016–2025 contains the proposal of RE projects	Table 3 shows optimization costs under market conditions. Keeping possible investment within those values could foster a free competition in the private sector
	According to ELECGALAPAGOS, 14 MWp of PV can be installed in 20 ha in Santa Cruz (based on the experience of previous projects)		In Santa Cruz, there is available 20 ha for new RE projects	The National Park of the Galapagos Islands institution makes decisions about available areas to install RE projects	Install a maximum power of 14 MWp in Santa Cruz
Gensets	Gensets are the main	Diesel is highly subsidized,	Reduction in	According to the Zero Fossil Fuel Initiative, gensets	Gensets capacity cannot increase
	generation systems	mining the competition of the	CO <sub>2</sub> emissions	The National Government is considering replacing diesel with local or Chinese biodiesel in Santa Cruz	Optimize the hybrid system with diesel and biodiesel (Ecuadorian and imported from China)
Stability	Operating reserve is 15%			Standard 006/00	Operating reserve is 15% for both diesel power plants and batteries
Demand	The optimized hybrid renewable power system has to be able to cover the demand in 2030	The annual growth rate of electricity demand is 7%, high value compared to rates from developed islands		The targets of the SDG7 must be achieved in 2030	Optimize the hybrid system to cover a demand of 73.7 GWh and 16.35 MW (peak load) in 2030

**Table 4.** Boundary conditions to optimize the hybrid system of Baltra–Santa Cruz (own elaboration).

#### 3.3.4. Distributed Generation Scenario

Rooftop integrated PV systems are more expensive than centralized power plants because of dedicated components [113] and soft costs [114]. Commonly, large systems are installed in more competitive markets where there are a few permitting requirements. These centralized systems are new infrastructures, are implemented by more experienced technicians and receive more incentives [114]. The common objective of designing PV grid-connected applications is to maximize electricity generation to supply the demand. Its generation potential differs because of the location, a crucial factor of PV operating conditions. This scenario assesses the feasibility of the PV microgeneration regulation [47,48] in the residential and commercial sectors, which represents 41% and 42% of the total electricity consumption, respectively, in 2018 [77]. The regulated electricity tariff is 9.8 USc/kWh in the residential sector, while it is 10.30 USc/kWh in the commercial sector [49]. The PV rooftop capacity  $P_{nomA}$  is calculated as follows [115]:

$$P_{nomA} = \frac{E_{PV}}{PR. Y_R} \tag{4}$$

where  $E_{PV}$  is the annual electricity produced by the PV generator. *PR* is the performance ratio between normalized electricity production and the available solar resource. For this case, *PR* is estimated as 0.75, regarding non-optimal locations and shadow effects in architectural integration. This is a conservative value compared to optimal designs of PV plants in the Galapagos Islands [40].

 $Y_R$  is the reference yield that characterizes the PV generator according to the available solar resource in terms of equivalent peak hours (equivalent to a constant incident irradiance of 1 kW/m<sup>2</sup>).  $Y_R$  is given by Equation (5):

$$Y_R = \frac{G_i \left( kWh/m^2 \right)}{1 \ kW/m^2} \tag{5}$$

where Gi is the Global Horizontal solar Irradiation measured by a sensor installed in Santa Cruz Island. In average annual terms, this is equal to 2080 kWh/m<sup>2</sup> [75].

The annual electricity consumption of one residential and commercial user was on average 2320 kWh and 12,575 kWh, respectively, in 2018 [78]. Here, the hourly load profiles of the residential [78] and the commercial user [79] are used. The Galapagos Islands are characterized by a moderate urban vertical expansion [116]. Houses and buildings, which represent 84% of infrastructure categories [117], occupy an area over 50 m<sup>2</sup>. Then, to install PV systems, it is assumed that most of the constructions have flat roofs. Given that Santa Cruz Island is in line with the equator, the optimal module tilt angle is equal to the latitude  $(-0.74^{\circ})$ . However, to avoid dust and dirt, 10° is the recommended tilt angle to install the PV system [40].

For this scenario, monocrystalline PV modules of 250 W with an efficiency of 15.46% were selected. The PV installation cost is \$1432 US/kW [102]; the replacement cost is 15% of the initial investment (15 years of inverter lifetime) [106]; and the O&M cost is 1.25%/year of the initial investment [105]. The PV generator's lifetime is 20 years. This scenario estimates the PV potential in residential and commercial sectors to avoid using large extensions of land, as in the case of ground-mounted power systems (high RE share scenarios). This analysis provides another possibility to support the Ecuadorian Zero Fossil Fuel Initiative.

## 4. Results and Discussion

#### 4.1. Results of the Status quo Scenarios

As mentioned before, the hybrid power system of Baltra–Santa Cruz produced 35 GWh (7.26 kW of peak demand) and the subsidized cost of electricity was 24.31 USc/kWh in 2018. The results of the simulations are shown in Table 5. In the "Status quo 2018" Scenario, the real electricity generation cost is 32.06 USc/kWh. In the generation side, the National Interconnected System subsidizes 24% of this cost. The economic impact for the electric power sector and the emissions of 18,662 tons of CO<sub>2</sub>/year of the current hybrid system point out how imperative it is to diversify the electricity generation mix (82% diesel).

			Currer	nt Capacity			Techno-Economic Results				
Scenario	Island	PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Unmet Load (kWh/year)	Fuel Consumption (million liters/year)	RE (%)	Fuel Cost (MUSD/year)	O&M (MUS/year)	LCOE (USc/kWh)
Status quo 2018	Baltra Santa Cruz	1.50 0.067	2.25	- 13.90	4.30 -	-	7.90	18	5.65	0.24	32.06
Status quo 7%	Baltra Santa Cruz	1.50 0.067	2.25	- 13.90	4.30 -	527.36	17.71	8.1	14.166	0.444	26.73
Status quo 3.5%	Baltra Santa Cruz	1.50 0.067	2.25	- 13.90	4.30 -	-	11.35	12	9.08	0.317	28.63

Table 5. Results for the status quo scenarios—real Levelized Cost of Electricity (LCOE).

Energy dependency would be intensified in the Galapagos Islands in the case where there are no new installations of RE. In the "Status quo 7%" Scenario, the current configuration of this island system cannot supply the 73.7 GWh of electricity demand in 2030. This scenario presents stability issues, which means 527.36 kWh of unmet load, lower LCOE (26.73 USc/kWh) and RE share (8.1%). The CO<sub>2</sub> emissions increase to 46,786 tons. On the other hand, in the "Status quo 3.5%" Scenario, the current configuration could supply the demand (49.45 GWh) in 2030. However, the generation price would still be high: 28.63 USc/kWh and the RE penetration would decrease to 12%. Moreover, the CO<sub>2</sub> emissions would be 29,998 tons. This scenario is not environmentally friendly and stands out that RE should be applied in parallel with energy efficiency initiatives.

Furthermore, while cheap hydroelectricity generation is practically subsidizing the generation costs of ELECGALAPAGOS, there are several reasons to increase RE penetration. First, a recent study [118] demonstrated that runoff availability for hydropower could be affected by climate change, demanding an increase in thermal power generation in the mainland. Second, the growth rate of electricity demand could intensify stability issues. Third, the economic impact on the electric sector would remain high because of the growth rate of the electricity demand that increases diesel consumption. Fourth, in 2001, the ecosystem of the Galapagos was affected by spills of 681 thousand liters of fossil fuel [8]. Finally, the pollution level of the hybrid system would be higher because of fossil fuel consumption. Thus, technical, economic and environmental impacts could be minimized if there is a considerable reduction in diesel consumption for electricity generation.

#### 4.2. Results of the Renewable Energy Potential Scenarios

#### 4.2.1. Results of the Renewable Energy Potential: Boundary Conditions

Table 6 and Figure 8 present the techno-economic characteristics of the optimized island system of Baltra–Santa Cruz to supply 73.7 GWh of demand in 2030 (16.35 MW is the peak demand). The boundary conditions applied are listed in Table 4.



**RE (%) -•-**LCOE (USc/kWh)

Figure 8. RE share and LCOE of the Renewable Energy Potential: Boundary Conditions Scenarios.

		Final Configuration and Technical Results							Economic Results				
Configuration	PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Diesel (million l	Biodiesel iters/year)	RE (%)	Capital (MUSD)	Fuel Cost (MUSD/year)	O&M (MUSD/year)	LCOE (USc/kWh)		
PV + wind + batteries + diesel	19.82	2.25	13.9	24.98	11.60	-	39.00	29.58	9.28	0.70	18.95		
PV + wind + batteries + Ecuadorian biodiesel	20.20	5.45	13.9	26.26	-	10.50	100.00	35.22	24.15	0.76	40.39		
PV + wind + batteries + Chinese biodiesel	20.03	5.45	13.9	25.62	-	10.77	100.00	34.82	13.15	0.75	25.19		

Table 6. Results of the Renewable Energy Potential: Boundary Conditions Scenarios.

The results show that the configuration "PV + wind + batteries + diesel" is the most techno-economically viable alternative. This solution proposes the installation of additional PV and battery capacity of 18.25 MWp and 20.68 MWh, respectively. This optimization keeps the power system stable and reduces the operation hours of DGs and fuel expenditures. The initial investment (\$29.58 million US) and O&M costs (\$0.70 million US) are the lowest of all the optimization results. Furthermore, LCOE would be 18.95 USc/kWh in 2030. The RE penetration is 39.00% and the CO<sub>2</sub> emissions are 30,651 tons.

The second configuration, "PV + wind + batteries + Ecuadorian biodiesel", introduces new PV (18.63 MWp), wind (3.2 MW) and battery capacities (21.96 MWh). The batteries compensate for the reduction in the operation hours of biodiesel gensets, whose cost is \$2.31 US/liter. Despite the fact the RE penetration reaches 100%, the LCOE become much higher—40.39 USc/kWh. Beyond that, this configuration is conditioned by jatropha production, which is insufficient to fuel gensets. In 2019, farmers expected jatropha price to increase [92], but there was a lack of public funding to support the development of this market. In Ecuador, there are no studies of cost internalization of environmental and social benefits of biodiesel. In fact, a life cycle analysis is not possible due to structural problems of the project [119]. Nevertheless, Mayorga et al. [120] noted that the Ecuadorian jatropha project could benefit the most vulnerable people in poverty in the coastal region. The same authors concluded that an increase in the price of biofuel would make the production of jatropha more attractive to farmers than other crops. However, it depends on promoters (IICA and Ministry of Energy) to make the jatropha project profitable, to generate a social impact and to build trust in local suppliers and communities. Before promoting biodiesel as an alternative fuel in the Galapagos Islands, the jatropha project should be audited to improve its structural limitations and to identify the real benefits to support the Zero Fossil Fuel Initiative. In other locations, such as Thailand, a related study showed that environmental externalities contribute from 3% to 76% to the total price of palm oil biodiesel [121]. All the weaknesses of the jatropha project should be clarified and solved before applying this scenario.

The "PV + wind + batteries + Chinese biodiesel" configuration builds new capacities of PV (18.46 MWp), wind (3.2 MW) and batteries (21.32 MWh). The LCOE is 25.19 USc/kWh and the RE share is 100%. Ecuadorian government should consider and verify the sustainability of this alternative in social and environmental terms. Authors have asserted that standards to ensure biodiesel quality are needed because of the great variety of raw material used in China for its production [122]. Meanwhile, Liu et al. [123] noted that it is difficult to quantify the environmental impacts of Chinese biodiesel due to several factors, including the need for standardizing methodologies of life cycle analysis, detailed specific-site evaluation and the need for defining more indicators to assess its environmental impact besides energy consumption and greenhouse gas (GHG) emissions, such as the cultivation and harvesting of biomass.

Comparing the results of these three scenarios, the configuration: "PV + wind + batteries + diesel" offers a more realistic perspective for the hybrid system of Baltra–Santa Cruz in 2030. This generation system has a RE potential of 18.25 MWp combined with a battery bank with a capacity of 20.68 MWh to reduce the LCOE to 18.95 USc/kWh. The use of diesel and batteries combined with the control system (also included in investment prices) ensures the system's stability. This total RE capacity should be split between Baltra and Santa Cruz according to the boundary conditions (Table 4). Regarding the limitations of the biodiesel fuel, it is verified that its promotion does not help the rapid energy transition in the Galapagos Islands.

# 4.2.2. Results of the Renewable Energy Potential: High RE Share

As was described in Section 3.3.2, this scenario analyzes the feasibility of the Zero Fossil Fuel Initiative through the achievement of 70% of RE share. In 2030, a demand of 73.7 GWh (16.35 MW-peak demand) should be covered. Table 7 presents the result of the optimized hybrid system of Baltra–Santa Cruz.

		Technica	l Results		Economic Results						
PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Fuel Consumption (million liters/year)	RE (%)	Capital MUSD/year	Fuel Cost (MUSD/year)	O&M (MUSD/year)	LCOE (USc/kWh)		
79.14	74.25	13.9	359.27	5.66	70	461.29	4.53	6.23	98.34		

**Table 7.** Results of the Renewable Energy Potential: High RE share Scenario.

In this case, the optimization process adds to the current capacity: 77.57 MWp of PV, 72 MW of wind and 354.97 MWh of batteries. This involves an extremely high total investment of \$461.29 million US and a considerable increase in the LCOE (98.34 USc/kWh) compared to the previous scenarios. This system would emit 14,963 tons of  $CO_2$  to the atmosphere.

It is demonstrated that achieving a high RE share of 70% does not offer a techno-economically viable solution for the islands. Another remarkable aspect is the area of land required to install large RE capacities, approximately 280 ha (extrapolation based on the area used by RE projects in Baltra and Santa Cruz). Installing this excessive RE capacity is environmentally infeasible in protected areas, e.g., wind technology is recognized to cause some critical environmental impacts on scenery, land use and biodiversity depletion [124]. In the Galapagos, the Zero Fossil Fuel Initiative should be oriented to safeguard a balance between development and environmental preservation, where large-scale RE projects could represent a threat to this sensitive territory. This points out that decision-makers should design effective and more progressive energy policies for a sustainable future, which, regarding RE deployment, should be supported by energy efficiency measures.

# 4.3. Results of the Energy Efficiency Scenarios

# 4.3.1. Results of the Energy Efficiency: Boundary Conditions

This scenario aims to supply 49.45 GWh of demand (peak load: 10.97 MW) in 2030, considering the effective adoption of the National Plan for Energy Efficiency and limiting the optimization process based on the boundary conditions listed in Table 4. The results of the configurations analyzed are depicted in Table 8 and Figure 9.





Figure 9. RE share and LCOE of the Energy Efficiency: Boundary Conditions Scenarios.

	Fi	inal Config	guration an	d Technical Re	sults			Economic Results				
Configuration	PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Diesel (million l	Biodiesel liters/year)	RE (%)	Capital (MUSD)	Fuel Cost (MUSD/year)	O&M (MUSD/year)	LCOE (USc/kWh)	
PV + wind + batteries + diesel	10.97	2.25	13.9	4.3	7.99	-	37.50	12.53	6.39	0.41	17.10	
PV + wind + batteries + Ecuadorian biodiesel	15.71	5.45	13.9	4.3	-	6.62	100.00	23.06	15.22	0.51	37.92	
PV + wind + batteries + Chinese biodiesel	12.25	5.45	13.9	4.3	-	6.99	100.00	18.87	8.53	0.47	23.22	

Table 8. Results of the Energy Efficiency: Boundary Conditions Scenarios.

The first configuration, "PV + wind + batteries + diesel", installs a new PV capacity of 9.40 MWp. This alternative does not add batteries because diesel capacity is enough to cover the peak demand and ensure the operating reserve of the system. Wind turbines are not competitive, given the lower demand and lower operating diesel costs. The additional PV capacity requires an investment of \$12.53 million US and the LCOE would be 17.10 USc/kWh by 2030. The RE share would reach 37.50% and the CO<sub>2</sub> emissions would be 21,102 tons. These indicators are much better than those of the Renewable Energy Potential: Boundary Conditions Scenarios. This scenario demonstrates that it is imperative that there is a reduction in the current growth rate of electricity demand to make a plausible higher share of RE, which requires policy willingness, effective energy efficiency programs and social awareness about the use of energy.

Based on the results, the Ecuadorian government should commit to push and reinforce the implementation of the National Plan for Energy Efficiency. While this plan considers the adoption of a building standard, a labeling scheme for energy-efficient appliances and the standard ISO 50001 [51], the plan lacks a detailed mechanism to disseminate a general awareness about the use of energy and the benefits of RE. Currently, education campaigns focus on the commercial sector [51], while only 35% of residential users relate RE initiatives to environmental care [40]. The Galapagos Islands can learn from successful experiences from Atlantic and Mediterranean small islands to reduce energy consumption and increase RE share [8]. Therefore, the National Plan for Energy Efficiency should be part of a complete package on sustainability, where targets on RE, energy efficiency and reduction in  $CO_2$  emissions are well-integrated.

The second configuration, "PV + wind + batteries + Ecuadorian biodiesel", installs a new capacity of PV (14.14 MWp) and wind (3.2 MW), while stability is ensured by the biodiesel power plant. The necessary investment is \$23.06 million US. While there is 100% of RE share, the LCOE is higher (37.92 USc/kWh) because of the use of biodiesel compared to the previous scenario. The discussion coincides with the explanation of Section 4.2.1. The reliability of this scenario needs a full evaluation of the economic, social and environmental impacts on the promotion of the national biofuel industry.

The third configuration, "PV + wind + batteries + Chinese biodiesel", adds an additional PV capacity of 10.68 MWp and 3.2 MW of wind, that, together with the use of biodiesel, achieve 100% of RE penetration. The LCOE would be 23.22 USc/kWh by 2030. In spite of the fact that this configuration gives positive indicators, under the logic of the Zero Fossil Fuel Initiative, the Chinese biodiesel production should comply with a set of quality criteria and clarify social and environmental benefits. Thus, Ecuador should establish biofuel standards for importation. However, importing biodiesel could cause a side-effect on the Ecuadorian jatropha sector, where farmers with low incomes are involved [120]. A comprehensive study is needed to clarify possible advantages and risks for future promotion of biodiesel.

To conclude, energy efficiency measures are essential in the path to hybridize the power system of Baltra–Santa Cruz and to make the introduction of new RE capacity more competitive. The energy transition is more than an economic matter. Thus, policies should prioritize social and environmental concerns. Biodiesel scenarios are not recommended for the Galapagos because of the lack of information about externalities. Quantifying social and environmental benefits is needed to support decision-making and promotion of biodiesel. In that sense, the first configuration (PV + wind + batteries + diesel) offers a sustainable techno-economic potential solution for the power system of Baltra–Santa Cruz as long as the National Plan for Energy Efficiency could be well-implemented in the islands.

# 4.3.2. Results of the Energy Efficiency: High RE Share

For this scenario, the Baltra–Santa Cruz hybrid power system is optimized analogously to the previous High RE Scenario, but in this case, to supply 49.45 GWh of demand (peak load: 10.97 MW) in 2030. Table 9 shows the results of the optimization process of the island system of Baltra–Santa Cruz.

		Technical	Results		Economic Results						
PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Fuel Consumption (million liters/year)	RE (%)	Capital (MUSD/year)	Fuel Cost (MUSD/year)	O&M (MUSD/year)	LCOE (USc/kWh)		
58.35	47.85	13.9	90.30	3.79	70	268.00	3.03	3.64	85.03		

**Table 9.** Results of the Energy Efficiency: High RE share Scenario.

For achieving 70% of RE share, 56.79 MWp of PV capacity, 45.60 MW of wind and 86 MWh of batteries should be installed. While the demand is hypothetically lower, the investment (\$268 million US) and LCOE (85.03 USc/kWh) are extremely high. What is more, the use of land could also cover an area of 170 ha; again, this is an extrapolation based on the area used by RE projects in the islands currently.

According to the results, in the Galapagos Islands, adequate planning should consider environmental concerns to avoid contradictions with climate change actions. The Zero Fossil Fuel Initiative should include structured and holistic planning, since its goal mostly focuses on the reduction of fossil fuel consumption. The Ecuadorian Ministry of Energy should regulate and promote the identification of social, economic and environmental benefits of RE projects in order to analyze non-conservative initiatives in the future. Furthermore, social awareness about the linkage between environmental preservation and energy is needed to become the islands a resilient territory.

#### 4.4. Results of the Distributed Generation Scenario

The goal of this analysis is to identify the PV potential in the residential and commercial sectors. The PV capacity is determined by applying the calculation process described in Section 3.3.4. For this analysis, the installation of conventional PV technologies is considered (crystalline silicon modules with a conversion efficiency of 15.46%). Table 10 summarizes the results and Figures 10 and 11 present energy flows of one residential and commercial consumer, respectively. These reflect that the amount of electricity sold to the grid is higher in the cold season (lower electricity consumption between June and November).

		Technical F	Results		E	conomic Resul	ts
-	PV (kWp)	Electricity Purchased (kWh/year)	Electricity Sold (MW)	RE (%)	Capital (USD)	O&M (USD/year)	LCOE (USc/kWh)
tial	1.50	1289	1328	64.70	2148	23.13	8.37
cial	8.00	7000	7005	64.20	11,456	143.47	8.42
30 25 20 15 10 5	00 00 00 00 00 10 10 10 10 10	runs wash parit wash	h)	soverher or	obet per	50 40 30 20 10 0 -10 -20 -30 -40 -50	Electricity Charge (USD)
	ial cial 30 25 20 15 10 5	PV (kWp)         ial       1.50         cial       8.00         300       250         200       100         150       100         50       0         yasuaxy       yasuaxy         type       Elector        >Net	Technical H         PV (kWp)       Electricity Purchased (kWh/year)         ial       1.50       1289         cial       8.00       7000         300       300       300         250	Technical Results         PV (kWp)       Electricity Purchased (kWh/year)       Electricity Sold (MW)         ial       1.50       1289       1328         cial       8.00       7000       7005         300       250       7000       7005         150       100       100       100       100         50       100       100       100       100         50       100       100       100       100         50       100       100       100       100         50       100       100       100       100         50       Electricity purchased (kWh)       100       100         50       Electricity purchased (kWh)       Electricity purchased (kWh)	Technical Results         PV (kWp)       Electricity Purchased (kWh/year)       Electricity Sold (MW)       RE (%)         ial       1.50       1289       1328       64.70         cial       8.00       7000       7005       64.20         300       250       0       0       0         150       100       0       0       0         50       0       0       0       0         100       50       0       0       0         100       50       0       0       0         100       50       0       0       0         100       50       0       0       0         100       50       0       0       0         100       50       0       0       0         100       50       0       0       0         100       50       0       0       0         100       100       100       100       100         100       100       100       100       100       100         100       100       100       100       100       100         100 </td <td>Technical Results       E         PV (kWp)       Electricity Purchased (kWh/year)       Electricity Sold (MW)       RE (%)       Capital (USD)         ial       1.50       1289       1328       64.70       2148         cial       8.00       7000       7005       64.20       11,456         300       700       7005       64.20       11,456         300       700       7005       64.20       11,456         300       700       7005       64.20       11,456         300       700       7005       64.20       10,456         100       700       700       7005       64.20       10,456         100       700       700       700       700       700       700         100       700       700       700       700       700       700       700         100       700       700       700       700       700       700       700       700         100       700       700       700       700       700       700       700       700         100       700       700       700       700       700       700       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Results       E         PV (kWp)       Electricity Purchased (kWh/year)       Electricity Sold (MW)       RE (%)       Capital (USD)         ial       1.50       1289       1328       64.70       2148         cial       8.00       7000       7005       64.20       11,456         300       700       7005       64.20       11,456         300       700       7005       64.20       11,456         300       700       7005       64.20       11,456         300       700       7005       64.20       10,456         100       700       700       7005       64.20       10,456         100       700       700       700       700       700       700         100       700       700       700       700       700       700       700         100       700       700       700       700       700       700       700       700         100       700       700       700       700       700       700       700       700         100       700       700       700       700       700       700       700 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ResultsEconomic ResultPV (kWp)Electricity Purchased (kWh/year)Electricity Sold (MW)RE ( $MW$ )Capital ( $S$ )O&M (USD)ial1.501289132864.70214823.13cial8.007000700564.2011,456143.47300 $7000$ 700564.2011,456143.47 $250$ $64.20$ 11,456143.47 $250$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $200$ $64.20$ $11,456$ 143.47 $100$ $64.20$ $11,456$ 143.47 $100$ $64.20$ $10.00$ $0.00$ $100$ $64.20$ $10.00$ $0.00$ $100$ $64.20$ $10.00$ $0.00$ $100$ $64.20$ $10.00$ $0.00$ $100$ $64.20$ $10.00$ $0.00$ $100$ $9.00$ $9.00$ $9.00$ $100$ $9.00$ $9.00$ $9.00$ $100$ $9.00$ $9.00$ $9.00$ $100$ $9.00$ $9.00$ $9.00$

#### Table 10. Techno-economic results for distributed generation scenarios.

Figure 10. The net-metering scheme applied in the residential sector.



Figure 11. The net-metering scheme applied in the commercial sector.

For a residential consumer, the PV generator capacity is 1.5 kWp to supply an average electricity demand of 2320 kWh. This capacity represents an investment of \$2148 US and requires approximately 10 m<sup>2</sup> for its installation. The electricity generation cost is 8.37 USc/kWh, which is a lower value than the electricity tariff in the residential sector: 9.8 USc/kWh. For solar adopters, there is a reduction of 57% in the total bill (\$230 US/year) and a positive energy balance of \$3.87 US for the next year.

For a commercial user, whose electricity consumption is 12,575 kWh, the PV capacity is 8 kWp (51 m<sup>2</sup> of the required area). This represents a total investment of \$11,456 US. The electricity generation cost is 8.42 USc/kWh, while the regulated tariff is 10.30 USc/kWh. The application of the PV microgeneration regulation would reduce the annual bill (\$1300 US) by 56%. There is only an energy balance of \$0.50 US for the next year.

Schelly [125] observed that owners can adopt solar technology, regardless of whether they are environmentally concerned or not, whereas other people can be only interested in bill reductions, or they are indifferent because of the lack of environmental motivations. Likewise, some authors [126] found solar power adoptions could also influence home/building value and electricity consumption. According to ELECGALAPAGOS, only one homeowner and one commercial user have started to install PV systems since the PV microgeneration regulation was launched. The total rooftop PV solar potential in the residential (1.5 kW/user × 5905 users) and commercial (8 kW/user × 1093 users) sectors is approximately 18 MWp. Given this potential, to achieve wider dissemination of this technology, innovation, environmental culture and mechanisms to make distributed generation more affordable are needed. This scenario is an attractive and feasible alternative to intensive ground systems. Cities can generate electricity, increase their self-resilience and reduce their environmental impact.

In the Galapagos Islands, further research could be addressed to identify dwelling types with the application of Geographic Information Systems to obtain an accurate evaluation of the existing PV potential for electricity generation in urban areas. There is a good illustration in Vitoria-Gasteiz, the capital of the Basque country, located in the north of Spain. Vitoria-Gasteiz presents a PV potential of 1258 MWp in urban areas, of which 82% is on inclined roofs and the remaining is on flat roofs. What is more, in this city, the annual Global solar Horizontal Irradiation (1390 kWh/m<sup>2</sup>) [127] is even lower than the solar resource in the Galapagos Islands (2080 kWh/m<sup>2</sup>).

#### 4.5. Sensitivity Analysis

Sensitivity analysis allows us to prove the robustness of the scenarios described in Section 3.3, verifying how a solution changes depending on a group of sensitivity variables. Investment prices of PV, wind and batteries are falling, making RE technologies the competitive backbone of energy transition [102]. Moreover, fuel cost is expected to increase by 30% in 2030 [128]. Thus, this study chooses investment prices and fuel cost as its sensitivity variables. First, a sensitivity analysis of the "Status quo 2018" Scenario is performed to evaluate the LCOE depending on the diesel fuel price (80 USc/liter and \$1 US/liter—including taxes). Second, to avoid underestimations in optimization results, a reduction of 20% in investment prices of RE technologies and batteries is assumed and diesel cost is set \$1 US/liter. Here, the LCOE and RE share are analyzed. Third, in the case of the distributed generation scenario, the sensitivity analysis considers an increase of 20% in investment prices of the PV generator, taking into account the lower profitability of small domestic projects [129,130], as well as a sensitivity analysis with a decrease of 20%. Based on the results of the scenarios analyzed in the simulation and optimization processes, sensitivity analyses are applied to the following: (i) The "Status quo 2018" Scenario with the current demand; (ii) the Renewable Energy Potential: Boundary Conditions Scenario, configuration: PV + wind + batteries + diesel; (iii) the Energy Efficiency: Boundary Conditions Scenario, configuration: PV + wind + batteries + diesel; (iv) The Distributed Energy Scenarios.

(i) Table 11 shows the sensitivity results of the "Status quo 2018" Scenario to supply the current demand: 32 GWh (7.26 MW of peak demand).

In case the diesel price reaches \$1 US/liter, the LCOE would increase from 32.06 USc/kWh up to 36.37 USc/kWh. This analysis shows the high dependency of the hybrid system of Baltra–Santa Cruz on fuel prices and it reveals that changing from a conventional system mainly based on diesel generation to another one with more RE capacity is relevant for environment preservation. This dependency on foreign oil markets becomes an economic pressure on the Ecuadorian electric power sector.

 (ii) Table 12 shows the results of the sensitivity analysis of the "Renewable Energy Potential: Boundary Conditions Scenario, configuration: PV + wind + batteries + diesel" to cover 73.7 GWh of demand in 2030 (16.35 MW-peak demand).

According to the optimization constraints, HOMER is allowed to optimize the hybrid system of Baltra–Santa Cruz, adding up to 21.83 MW of PV and/or wind. As it is expected, lower PV costs (–20%) lead to an increase in PV and battery capacities and consequently to lower initial investment and LCOE and higher RE share compared to the base scenario. A reduction in wind costs (–20%) facilitates the introduction of this technology and battery capacity, reducing the PV power by 41%, regarding the base scenario. The total hybridization investment is lower, but the LCOE increases because DGs operate for additional hours. Thus, the RE share is reduced by 12%. Cost reductions in batteries (–20%) boost the installation of additional wind turbines and reduce the PV and battery capacities by 41% and 3%, respectively. On the other hand, an increase in fuel price (\$1 US/liter) increases the PV and battery capacity to reduce the operating hours of DGs. Despite this, the LCOE increases by 20%. Moreover, RE penetration is higher compared to the base scenario.

Comparing all results of these sensitivity analyses, a reduction in battery investment costs is more convenient in terms of LCOE and RE share for the island system of Baltra–Santa Cruz. The opposite happens with wind technology; although a lower investment cost allows the installation of wind turbines, the LCOE becomes higher due to the necessity of higher fuel consumption. It is verified that the relationship between the sensitivity of the variables and the results is not linear in the optimization process when a complex power system is optimized to supply a high demand. In HOMER, an energy system is a multivariable system in which the change in an input variable interacts with several output variables. This fact is noticed in the results from Table 12 where, for example, lower battery prices do not lead to a higher installation rate of this technology.

		Cu	rrent Capac	city		Te				
Sensitivity Variables		PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Fuel ConsumptionRE(million liters/year)(%)		Fuel cost (MUSD/year)	O&M (MUSD/year)	LCOE (USc/kWh)
Fuel price	Base scenario	1.57	2.25	13.9	4.3	7.90	18	5.65	0.24	32.06
i dei pilee _	\$1 US/liter	1.57	2.25	13.9	4.3	7.90	18	7.06	0.25	36.37

**Table 11.** Sensitivity results: Status quo 2018.

 Table 12. Sensitivity results of the Renewable Energy Potential: Boundary Conditions Scenario.

Sensitivity	v Variables	Final Configuration and Technical Results						Economic Results					
(costs)		PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Fuel Consumption (million liters/year)	RE (%)	Capital (MUSD)	Fuel Cost (MUSD/year)	O&M (MUSD/year)	LCOE (USc/kWh)		
Base s	cenario	19.82	2.25	13.90	24.98	11.60	39.00	29.58	9.28	0.70	18.95		
PV	-20%	19.95	2.25	13.90	33.30	11.58	39.10	27.79	9.26	0.75	18.71		
Wind	-20%	11.68	5.45	13.90	27.54	12.50	34.30	24.34	10.00	0.66	18.98		
Batteries	-20%	16.58	5.45	13.90	24.34	11.30	40.60	28.80	9.04	0.71	18.49		
Fuel	\$1 US/liter	19.95	2.25	13.90	33.30	11.57	39.10	32.24	11.57	0.75	22.64		

 (iii) Again, Table 13 summarizes the sensitivity results of the "Energy Efficiency: Boundary Conditions Scenario, configuration: PV + wind + batteries + diesel" to supply 49.45 GWh (peak load: 10.97 MW) in 2030.

Similarly to the previous scenarios, a maximum power of 21.83 MW of PV and/or wind can be added to the current capacity of the Baltra–Santa Cruz Island system. Compared to the base scenario, a reduction in PV costs (–20%) increases the PV capacity by 8%, reducing the operation hours of DGs. Thus, RE increases by 4% and the LCOE is lower. More affordable wind prices (–20%) increase the installation of wind turbines significantly and decreases the PV capacity slightly. Then, there is less diesel consumption, a higher RE penetration and a small reduction in the LCOE compared to the base scenario. Based on this result, wind technology becomes more competitive when the demand to be supplied is lower: 49.45 GWh. As regards the reduction in battery costs (–20%), the PV capacity increases by only 1% compared to the base scenario. There is a small positive impact on the RE share and LCOE. Lastly, increasing the fuel price (\$1 US/liter) forces a reduction in operating hours of DGs through the installation of additional PV and wind capacities. This increases the RE penetration but also increases the LCOE by 17% since the initial investment is higher compared to the base scenario. In this case, any reduction in investment prices limits the installation of greater battery capacity due to stability assurance is being covered by the diesel power plant. Comparing all possibilities shown in Table 13, lower investment costs in PV technology make the LCOE more affordable.

Moreover, it has been possible to verify that HOMER gives correlative results when a complex hybrid system supplies a lower demand of 49.45 GWh (compared to 73.7 GWh, demand used in the Renewable Energy Potential Scenario). Furthermore, it is demonstrated how energy efficiency measures can reduce the impact of volatile fuel prices on the island system.

Finally, in both sensitivity cases—the renewable energy and energy efficiency boundary conditions scenarios—in general terms, the PV is the most competitive technology, the battery capacities are conditioned by the stability criteria and the demand. Wind has a positive effect on the LCOE under the following conditions: Lower battery costs and higher demand, lower wind costs and lower demand and higher fuel price and lower demand. Investment prices and electricity demand are decisive in the optimization process. Thus, the reinforcement of energy efficiency policies can reduce the necessary initial capital and LCOE. Similarly, considerable reductions in investment RE costs encourage the implementation of RE technologies. Furthermore, in reference [8], it was demonstrated that public policies support the definition of adequate business models, which, in turn, support the achievement of higher RE shares. These mechanisms are crucial to increase the hybridization levels of the Baltra–Santa Cruz power system.

Based on these findings, future research should focus on the optimization of real applications such as the hybrid system of Baltra–Santa Cruz, regarding complexity in data treatment, optimization software and the modelling of hybrid storage systems. To do this, the use of modelling tools based on open software could be the best option. As a reference, there are recent studies [131–133] that have simulated and optimized hybrid systems through the python-library Open Energy Modelling Framework (oemof), which offers a platform to model a great variety of energy systems.

Sensitivity Variables (costs)		Final Configuration and Technical Results						Economic Results			
		PV (MWp)	Wind (MW)	Diesel (MW)	Batteries (MWh)	Fuel Consumption (million liters/year)	RE (%)	Capital (MUSD)	Fuel Cost (MUSD/year)	O&M (MUSD/year)	LCOE (USc/kWh)
Base so	cenario	10.97	2.25	13.9	4.30	7.99	37.50	12.53	6.39	0.41	17.10
PV	-20%	11.89	2.25	13.9	4.30	7.81	38.90	11.15	6.25	0.42	16.46
Wind	-20%	10.00	5.45	13.9	4.30	7.39	42.20	15.19	5.91	0.44	16.90
Batteries	-20%	11.07	2.25	13.9	4.30	7.97	37.70	12.42	6.37	0.41	17.04
Fuel	\$1 US/liter	11.34	5.45	13.9	4.30	7.13	44.20	17.78	7.13	0.46	20.08

Table 13. Sensitivity results of the Energy Efficiency: Boundary Conditions Scenario.

(iv) Other applicable solutions are the "Distributed Generation" Scenarios in residential and commercial sectors and Table 14 shows the results of the sensitivity analyses.

From a solar adopter perspective, lower PV investment costs (–20%) would foster new installations. In contrast, increasing investment costs by 20% represents an additional investment and higher electricity generation costs, which could discourage solar adoption. For residential users, higher investment costs could make PV installations not profitable due to a lower electricity tariff: 9.8 USc/kWh. While commercial adopters could be not affected by a higher investment cost because of its electricity tariff (10.30 USc/kWh), PV installations are not guaranteed at all without the application of reliable business strategies. On the other hand, lower prices would allow users to install rooftop PV systems and reduce the installation of large-scale projects, avoiding the negative impacts on the use of land and local biodiversity.

Encouraging islanders to install rooftop PV generation systems is relevant in order to make the archipelago self-sufficient in terms of energy [134]. Nevertheless, passive social acceptance by the consumer or the market side could not embrace the dissemination of distributed energy [135]. Additionally, the market may not be interested in bringing products to a remote territory, where installing small PV capacities cannot be representative for the business. According to reference [136], social acceptance can be improved by innovative business models to build trust between the market and users. Moreover, financing facilities that fit island conditions could support distributed generation [126,129]. However, beyond that, distributed generation faces other challenges, such as the electricity exchange assurance between users and the electrical grid. Here, smart grids and flexible demand are crucial to reduce the impact on electrical networks and to guarantee the client's energy security. For instance, Demand Side Management in the low voltage network has been determined as a feasible smart strategy for the Galapagos Islands [134]. In terms of distributed generation, the Ecuadorian Ministry of Energy and the electric power sector, in general, have a great mission to incorporate technical, economic, social and environmental requirements within effective policies.

	Sensitivity Variables		Technical Results				Economic Results			
User			PV (kWp)	Electricity Purchased (kWh/year)	Electricity Sold (MW)	RE (%)	Capital (USD)	O&M (USD/year)	LCOE (USc/kWh)	
Residential	PV cost	-20%	1.50	1289	1328	64.70	1718	17.73	6.67	
		Base scenario	1.50	1289	1328	64.70	2148	23.13	8.37	
		+20%	1.50	1289	1328	64.70	2578	28.53	10.10	
Commercial		-20%	8.00	7000	7005	64.20	9165	114.67	6.73	
	PV cost	Base scenario	8.00	7000	7005	64.20	11,456	143.47	8.42	
		+20%	8.00	7000	7005	64.20	13,747	172.27	10.10	

# Table 14. Sensitivity results of the Distributed Energy Scenarios.

#### 5. Business Model Proposal for RE Introduction

The Ecuadorian government and international cooperation agencies have supported RE introduction in the Galapagos Islands; however, despite this, the Zero Fossil Fuel Initiative still seems to be a hard goal to achieve. Indeed, reference [137] found that the principal barriers for 100% renewable electricity are political, institutional and cultural. For instance, in the archipelago, this is reflected by the application of RE and energy efficiency policies in an isolated manner, limited private investment and the high growth rate of electricity demand. Based on that and the scenarios discussed, the authors present a business model proposal to facilitate RE introduction through centralized power plants and distributed generation, involving multiple actors to overcome the aforementioned limitations.

In the Galapagos Islands, regarding the large scale of RE projects, the most attractive identified business models are competitive auctions [8]. For guaranteed success, this mechanism considers "a schedule, volume disclosure, price ceilings, penalties, streamline of administrative procedures and information provision to the participants", but it depends on the government's priorities, implying a trade-off between criteria [138]. This competitive bidding process also involves upfront guarantees to reduce the financing risk, especially in developing countries [139]. In mainland Ecuador, the Ministry of Energy has recently launched an auction scheme to leverage resources for 500 MW of PV, wind and hydro projects through Power Purchase Agreements (PPAs) for 20 years. This initiative has received around 22 Expressions of Interest (EoI) from different countries, such as Germany, Spain, the United Kingdom, the United States, Canada, China, Colombia, France and Portugal [140]. Thus far, there are nine qualified companies to implement 310 MW [141]. In the Galapagos Islands, the national authority plans to apply the same scheme to install 26 MW of PV and wind for \$55 million US [142]. While there are no details on planned projects, this capacity represents 11% of the total capacity shown in the Country's Electricity Master Plan 2016–2025 [44].

Regarding distributed generation, Horváth and Szabó [129] claimed that the bottlenecks of this mechanism are financial issues and low electricity tariffs, which means longer payback periods and liquidity risk for RE technologies. Therefore, to attract distributed generation investment, the government is expected to define adequate (higher) purchase prices and incentives. Nevertheless, in Ecuador, economic changes in the subsidized electricity service usually generate social discontent. Hence, reducing investment costs for possible solar users should be the first step to support this initiative. The community-shared model (also known as shared solar, community solar or community-owned) is a good opportunity for innovation and to increase the competitiveness of RE technologies. Its biggest advantage is the economy of scale to bring down the PV system costs [129,143]. This model helps communities to acquire and manage their rooftop PV systems, sharing capital and O&M costs [143,144]. Policy-makers favor the establishment of cooperatives to involve a wider population through solar access distribution [143]. This model would lead to a sustainable society via green power generation, but policies need to be inclusive to meet the PV project's feasibility for every kind of prosumer [144]. The community model has been widely applied in Europe, e.g., the case of Samsø Island, characterized by government support, community responsibility, expert assistance and social networks [145]. In the framework of the energy transition, the European Union has recently embodied their extensive experience in the "energy citizen community concept" as a legal entity to cover the energy value chain, involving the participation of public and private sectors and civil society [146]. Energy community models provide social, economic and environmental benefits for members and local areas [146].

Since the national and international energy markets are evolving to cover energy needs and environmental concerns, this research presents a mix-business model approach to facilitate RE introduction. Here, people are the core of new actions. Figure 12 shows schematically the proposal that is characterized by:

- The auction business model supports the widespread installation of RE power and provides the capacity required by the residential and commercial sectors for distributed generation. Here, the private sector is in charge of installing, operating and maintaining a large RE capacity.

At the residential and commercial levels, the private sector ensures maintenance as an incentive for prosumers. The Power Purchase Agreement should collect all these aspects. The auctions concession period can be 20 years, including guarantees for renewal. Otherwise, when there is no private continuity over time, business models tend to be unsuccessful [8].

- The residential and commercial sector creates cooperatives through a citizen energy community model based on a net-metering scheme for PV rooftop installations. The auction scheme ensures the maintenance of PV systems. Solar adopters can be homeowners, building owners or tenants. The people set up cooperatives to facilitate the acquisition and management of solar systems. This model also enables conditions which involve other actors/sectors within energy communities.



Figure 12. A business model proposal for the RE implementation at large and small scales.

Political willingness at the national, regional and local level is required to go beyond fossil fuel reduction. This implies a strong horizontal and vertical coordination of the public sector. Nevertheless, the public sector is not the only agent responsible for generating and promote business models. It is very important to support this proposal through the participation of international cooperation, banking facilities, private entities and civil society:

- The Ministry of Energy (MERNNR) is the main promoter and is responsible for energy policies (RE and energy efficiency), management and funding.
- The Agency for Regulation and Control of Electricity (ARCONEL) is responsible for the control of RE projects and for the design of technical and economic regulations that build an appropriate environment for business model application.
- The Government Council for the Galapagos Special Regime (CGREG) works as a facilitator and supports energy policies implementation.
- The local municipality designs strategies for enabling PV integration adapted for the beneficiary.

- The Ministry of Environment (MAE) and the Galapagos National Park Directorate (PNG) fund the auction process through tourism contributions. Tourism taxes vary from \$3 US for Ecuadorians to \$100 US for international tourists [147]. Since this is the most important activity of the islands and relates to environmental impact, a tourism energy fee could be designed to support energy initiatives with the participation of the partners of this proposal. It is recognized that a comprehensive understanding of the dynamics of tourism is relevant in terms of management effectiveness and efficiency on small islands [148,149]. Here, ecotourism, which is conceived for biodiversity preservation by reducing the impact of mass tourism, also implies the adoption of RE technologies for guaranteeing a sustainable energy supply [150,151]. Ecotourism is widely supported by international cooperation and environmental organizations through incentives and funds, which helps to mobilize the tourism market [150]. Similarly, revenues derived from tourism taxes can also support money flow in ecotourism and the quality of the service [152]. Authors [153–156] have asserted that well-informed and environmentally aware tourists are willing to pay an additional fee for environmental conservation actions or to spend in a green hotel equipped with energy saving and RE installations. A previous study showed that, in the Galapagos Islands, visitors are willing to pay an additional fee of \$50 USD per visit for a reduction in the carbon footprint [156]. This shows that sustainable actions in tourism-based environments, as in the case of the Galapagos, can generate direct benefits on the tourism sector, the local economy and environmental protection. Then, the national and local decision-making have the main responsibility to encourage RE investments in the tourism sector via effective policies and business proposals.
- Electricity Corporation of Ecuador (CELEC EP) supports grid connection and the O&M of diesel power plants.
- ELECGALAPAGOS supports management, PV residential grid connections, control and electricity fees collection and the O&M of previous RE projects installed.
- International cooperation works on advising RE and energy efficiency policies and supporting awareness campaigns and capacity building at the institutional and community levels.
- The private sector invests in large capacity projects and provides the PV capacity required by the residential and commercial sectors and other actors. Moreover, it is in charge of technical training and O&M.
- Banking facilities provide credits to homeowners, building owners, tenants or other members of energy communities to acquire PV systems. In fact, there is a pioneer bank, ProCredit Bank Ecuador, that has implemented a credit line to support PV system acquisition [157].
- Prosumers are responsible for the adequate management of their installations and changing traditional and inefficient ways of energy consumption.

Supporting the Zero Fossil Fuel Initiative and, at the same time, the Agenda for Sustainable Development is a big challenge. This demands effective policies, a generalized awareness and the commitment of each partner to ensure the proposal application and its sustainability. Enabling an adequate political environment for the conservation of the Galapagos ecosystem and adopting an energy identity beyond economic savings are crucial in implementing the decarbonization process.

#### 6. Conclusions and Policy Implications

The Galapagos Islands are highly dependent on imported fossil fuels, which makes the cost of electricity high. Furthermore, their high growth rate regarding electricity demand makes it a challenge to support the Zero Fossil Fuel Initiative and, in turn, the SDG7 by 2030. In the Galapagos, diesel subsidies, weak policies and the lack of private participation and social awareness about the use of energy have limited RE contribution. For this reason, to make these islands more resilient to the current challenges of climate change and development, this research presents multiple pathways towards the stepwise decarbonization of the hybrid renewable mini-grid of Baltra–Santa Cruz. To meet the

research's target, the specialized hybrid renewable mini-grid HOMER Pro software is used to perform several techno-economic assessments. HOMER has been widely applied for analyzing realistic islands systems. The analysis focuses on different electricity demand scenarios to understand the implications of the load growth by 2030 and the installation of additional capacities of RE such as solar and wind, or the replacement of diesel with biodiesel. Furthermore, technical, socio-economic, environmental and political constraints are taken into account to limit some optimization analyses. Likewise, the feasibility of distributed generation is analyzed in residential and commercial sectors.

The simulation of the current Baltra–Santa Cruz power system confirms that the RE share is only 18% and reveals that the current real cost of electricity is 32.06 USc/kWh. Moreover, it is verified that this system needs to incorporate more REs and storage capacity to maintain performance stability by 2030.

Considering optimization scenarios, it is demonstrated that PV is the most techno-economically viable technology for Galapagos because of solar resources and investment prices. Its implementation makes the LCOE more affordable. For the "Renewable Energy Potential: Boundary Conditions Scenario, configuration: PV + wind + batteries + diesel", to cover a demand of 73.7 GWh by 2030, the installation of 18.25 MWp of PV combined with 20.68 MWh could be economically installed in Baltra and Santa Cruz Islands. The RE share and the LCOE would be 39% and 18.95 USc/kWh, respectively. On the other hand, for the "Energy Efficiency: Boundary Conditions Scenario, configuration: PV + wind + batteries + diesel", the outcomes are much more positive when there is a significant reduction in investment prices of RE technologies and the electricity demand. This requires the commitment of the government to rethink policies and also from the islanders to change their traditional electricity consumption habits. Based on the assumption that the Ecuadorian National Energy Efficiency Plan is successfully implemented, 49.45 GWh would be supplied in 2030. Then, the PV potential would be 9.40 MWp to achieve 37.5% of RE penetration and reduce the LCOE to 17.10 USc/kWh. In this case, the stability is ensured by the diesel power plant. Regarding boundary conditions scenarios with biodiesel, it is proven that this resource is not techno-economically competitive since its cost is high and there are no studies of cost internalization of the environmental and social benefits. Similarly, High RE Share Scenarios were also evaluated. However, their applications are infeasible because of the high electricity generation costs and the intensive use of land required for the implementation of large RE capacities. Some limitations in the use of the HOMER software have been identified, showing that future research is needed to improve and adapt energy system modelling tools to more complex cases.

As regards the evaluation of the distributed generation scheme in the residential and commercial sectors, this study demonstrates that the total rooftop PV potential is 18 MWp. According to the results, the electricity bill would be reduced by more than 50%. For this reason, and due to the low availability of land, a distributed generation is posited as the most attractive alternative to support the Zero Fossil Fuel Initiative. Further research could be addressed to identify dwelling types in urban areas in Santa Cruz and Baltra Islands and to identify the PV potential of distributed generation with higher accuracy.

The feasibility of different pathways is effectively demonstrated by this research. However, energy transition demands more than feasibility analyses. Reliable and innovative policies and the willingness of multiple actors are essential to move away from pollutant energy generation systems and inadequate methods of energy consumption. The Galapagos Islands require a proposal that combines different business models to facilitate the installation of RE at a large and small scale to move rapidly towards the least carbon-emitting energy system. A combination of auctions and a citizen energy community model could be the most attractive solution, prioritizing people and the ecosystem of the islands. This inclusive business model leaves aside the traditional methods of RE implementation on the islands. There is a great opportunity for the public and private sectors and for users to become prosumers in the decarbonization process of the Galapagos Islands. The achievement of the Zero Fossil Fuel Initiative is only possible if there is an energy culture that engages the participation of national and local governments, the private sector, international cooperation and civil society. This also demands better and stronger coordination between public institutions. Policies should promote the development

of a specific, holistic and sustainable energy plan for the Galapagos Islands, designing measures based on the local needs and the context. This challenge implies establishing a strong link between energy, environment and society.

Author Contributions: Conceptualization: A.A.E.-A. and M.A.E.-A.; methodology: A.A.E.-A., M.A.E.-A., P.B., S.B., E.C. and E.G.-A.; software: A.A.E.-A., M.A.E.-A., P.B., S.B., E.C. and E.G.-A.; validation: A.A.E.-A., M.A.E.-A., P.B., S.B., E.C. and E.G.-A.; validation: A.A.E.-A., M.A.E.-A., P.B., S.B., E.C. and E.G.-A.; investigation: A.A.E.-A. and M.A.E.-A.; methodology: A.A.E.-A.; methodology: A.A.E.-A.; methodology: A.A.E.-A.; M.A.E.-A., P.B., S.B., E.C. and E.G.-A.; validation: A.A.E.-A., M.A.E.-A., P.B., S.B., E.C. and E.G.-A.; validation: A.A.E.-A.; methodology: A.A.E.-A.; methodology: A.A.E.-A.; methodology: A.A.E.-A.; methodology: A.A.E.-A.; M.A.E.-A.; methodology: A.A.E.-A.; methodolog

**Funding:** This research was funded by the UNIVERSIDAD POLITÉCNICA DE MADRID through the XVII Funding Call from Social Council for Promotion of Training and Internationalization of PhD Researchers for the Course 2018–2019 (XVII Convocatoria de Ayudas del Consejo Social para el Fomento de la Formación y la Internacionalización de Doctorandos para el Curso 2018–2019).

Acknowledgments: The authors would like to thank Engineer Hernando Merchán from the Ecuadorian Ministry of Energy and Non-Renewable Natural Resources (MERNNR) for supporting this study. The authors gratefully acknowledge the support from the Ecuadorian Electricity Company ELECGALAPAGOS through Engineer Juan Carlos López, Chairman of the company and especially the support and information provided by Engineer René Chumbi from the Planning Directorate of the company. The conclusions and recommendations of this study do not reflect the point of view of MERNNR or ELECGALAPAGOS.

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

#### Abbreviations

The following abbreviations are used in this manuscript:

ADS	Autonomous Desalination Systems
ARCONEL	Ecuadorian Agency for Regulation and Control of Electricity
BMU	German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
CELEC EP	Electricity Corporation of Ecuador
CGREG	Government Council for the Galapagos Special Regime
CRF	Capital Recovery Factor
DG	Diesel gensets
ELECGALAPAGOS	Electricity Company Galapagos
EoI	Expressions of Interest
GDP	Gross Domestic Product
GEF	Global Environment Facility
GHG	Greenhouse gas
GHI	Global Horizontal solar Irradiation
GIZ	Germany International Cooperation Agency
GSEP	Global Sustainable Electricity Partnership
HOMER	Hybrid Optimization of Multiple Electric Renewables
IICA	Inter-American Institute for Cooperation on Agriculture
INDC	Intended Nationally Determined Contribution
JICA	Japan International Cooperation Agency
KOICA	Korea International Cooperation Agency
LCOE	Levelized Cost of Electricity
LOSPEE	Organic Law of Public Electricity Service
MAE	Ecuadorian Ministry of Environment
MERNNR	Ministry of Energy and Non-Renewable Natural Resources
MBOE	million barrels of oil equivalent
NEC	Ecuadorian Building Standard
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
oemof	Python-library Open Energy Modelling Framework

O&M	Operation and maintenance
PME	Ecuadorian Electricity Master Plan 2016–2025
PNG	Galapagos National Park Directorate
PPA	Power Purchase Agreement
PV	Photovoltaic
RE	Renewable energy
SDG7	Sustainable Development Goal number 7
SNI	National Interconnected System
SOC	State of charge
UNDP	United Nation Development Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNF	United Nations Foundation

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