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Cornerstones for greater participation of smart renewable energy on clustered islands; the case of Guayas in Ecuador towards 2050

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ABSTRACT

This article presents a new approach to long-term energy planning based on the concept of smart energy systems. Unfortunately, fossil fuels have had a negative impact on fragile ecosystems, including the coastal islands in the Guayas province of Ecuador considered in this case study. The objective is to structure an energy system that responds to the growing demand by taking advantage of the renewable energy potential of the islands. The cornerstones that support the generation system are based mainly on wind and photovoltaic energy that follows a multisectoral approach, including the heating and cooling, transport, desalination, gas and electricity sectors. The analyses were applied with the support of the EnergyPLAN tool in an intelligent energy structure according to the land use plans, elements that put together the puzzle to design the path towards the 100% renewable transition that is much friendlier to the environment. This is a novel study that seeks to take advantage of the renewable energy potential available on the islands themselves. Finally, after analyzing the results, it is concluded that the energy mix for 2050 can consider 49.12% wind power and 38.59% solar photovoltaic, as well as in smaller proportions 7.02% biomass and 5.26% biofuels, thereby achieving 100% of renewable energy in the grouped islands thanks to their energy potential. Decision makers may consider this study a reference before committing resources and carrying out modern energy planning.

Keywords: Smart energy; 100% Renewable energy; Energy Planning; Energy transition

Nomenclature

CO_2	*Carbon Dioxide*
DC	*Direct Current*
DSOC	*Discharge*
ENSO	*El Niño Southern Oscillation*
GHG	greenhouse gas
GIS	*Geographic Information Systems*
IPCC	*Intergovernmental Panel on Climate Change*
LMP	*Land Management Plan*
LPSP	Loss of Power Supply Probability LPSP
MSC	*Machine-Side Converter*
NISC	*National Institute of Statistics and Censuses*
NOAA	*National Oceanic and Atmospheric Administration*
NZE	*Net Zero Emissions*
TPO	*Tropical Pacific Ocean*
PPO	*Pure Pinion Oil*
PE	*Primary energy*
PV	*Photovoltaic*
PVC	Present Value of Costs
RE	*Renewable Energy*
RES	*Renewable Energy Sources*
SDG	*Sustainable Development Goals*
SOC	*State of Charge*
TAC	Total cost
TOP	*Territorial Ordering Plan*
TPO	*Tropical Pacific Ocean*
TPP	*Total Power Plants*
UN	*United Nations*
WMO	*World Meteorological Organization*

Formulae

DE(t)	Electric power deficit in hour t
$P_{t,k}^{res}$	Residual capacity
$P_{t,k}^{new}$	New installed capacity
t'	Installation period
t	Operation time
n	Life cycle
$INV_{t,\Omega}$	Investment costs
R	Residual value
$O\&M_t$	Total cost of operation and maintenance
Y	Number of years
Ω	New capacity of technology
$Salvage_{t,\Omega}$	Salvatage value
$Cost_{cum}$	Accumulated costs
CO_{2cum}	Accumulated emissions
ESR	Energy Supply Ratio
$P_{rene-2050}$	Renewable power generated in 2050
P_{DEMAND_2050}	Load demand in 2050.
E_{bat}	Battery capacity
η_{cbat}	Charge efficiencies
η_{dbat}	Discharge efficiencies.
η_{bc}	Battery bank efficiency
E_{bat}^{T}	Battery charge at time *T*
E_{bat}^{T-1}	Battery charge at time *T-1.*
η_{inv}	Inverter efficiency.
τ	Autonomy time.
P_{PV}^{T}	Electrical power provided by the solar panel.
P_{l}^{T}	Electrical power absorbed by the demand in a certain time.

P_{WT}^{T} Electrical power provided by wind turbine.

$P_{OTHERS\ RENE}^{T}$ Electrical energy provided by other small-scale renewable sources.

P_{tot}(t) Total power in the time t

$P_{pv}(t)$ Photovoltaic power in the time t

$P_{wg}(t)$ Wind power in the time t

1. Introduction

In most parts of the world, various strategies are being developed to increase levels of renewable energy generation. Among the Sustainable Development Goals (SDG) is Goal 7, which guarantees access to reliable, sustainable, affordable and modern energy [1]. Energy systems must be accessible to the entire world population [2], and to achieve this, its leaders must work intensively, especially in favor of the towns, communities and islands that have the greatest difficulties in developing [3]. In the mid-twentieth century, fuels were an essential source of development and well-being for countries, especially public works took off strongly [4]. Although fuels were an essential source of growth, the indiscriminate exploitation of this resource has caused irreversible damage to species in different areas of the world and has irrationally contributed to increasing global warming. Its effects are evident in the rise in sea level due to the melting of the poles, torrential rains in some areas and others, the high proportion of forest fires and the fact that the burning of fossil fuels is one of the elements that threaten life on the planet [5]. There is hope to improve these conditions, among many others, by increasing the use of renewable energy and, on the other hand, by progressively reducing the use of fossil fuels. There are also other petroleum derivatives that, due to their misuse, are causing problems, especially environmental ones, in the case of plastic, a harmful product that has been introduced into the fragile ecosystems of the islands and has caused the death of thousands of species, among the many cases are the Galapagos Islands [6], the coasts of Chile [7], the Canary Islands [8], the Caribbean Islands [9].

Several researchers have identified major benefits of renewable energy, noting that increasing their proportions could prevent a more significant increase in global temperature [10]. The recent Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 ∘C has assessed a wide range of scenarios that achieve the 1.5 ∘C limit [11]. These pathways are characterized by a substantial increase in near-term action and total greenhouse gas (GHG) emission levels approximately 50% lower than implied by current NDCs [12]. This would cause a crisis for the global ecosystem, many species of animals and plants would disappear, including coral reefs [14]. In this unfavorable scenario, it is essential that countries and regions are predisposed to propose an energy transition with clear roadmaps and allocating sufficient resources to renew energy systems [15]. Meanwhile, energy systems at the continent level are being restructured, and it is possible that at the island level they will also develop clean energy schemes and replace historical fossil fuels [16]. At the island level, their ecosystems are fragile and must be valued and protected; efforts must be made as soon as possible [17]. Currently, few islands have high levels of renewable energy in high proportions; Costa Rica's case is exceptional, reaching practically 100% clean energy generation in 2021 [18]. Most of the world's islands continue to depend directly on the importation of fossil fuels for their daily lives, which has consequences on the islands, especially regarding energy security, its economy and its ecosystem. The main limitation of introducing renewable energy in these territories is the intermittent nature of these resources, so relying on a single source may not be adequate. Hybrid systems are typically recommended between wind and solar PV, most of which should be accompanied by energy storage systems [19]. One of the main aspects to consider when adopting these solutions based on renewable energy is to design technological combinations that allow maintaining the balance between energy generation and demand [20]. The fact that islands are solitary and small in size is a significant barrier to such solution [21].

The TILOS project [22] epitomizes a reference to energy installations on islands, where successful implementation of green transition projects has been accomplished. Notably, an innovative solar-wind hybrid and molten salt (NaNiCl2) battery energy storage system was deployed within the actual grid environment on Greece's Tilos island. The battery system facilitates grid-independent and grid-connected operations, ensuring demand-side management and interoperability with the other microgrid components. Another exemplary undertaking in the energy transition processes is observed on Fernando de Noronha Island in Brazil as a critical participant in the 'Smart Islands' environmental initiative [23]. This action provides innovative mobility solutions across diverse territories to achieve carbon neutrality. It has boosted the island's supply of clean and renewable resources. In order to implement 100% renewable energy systems, it is imperative to thoroughly consider several issues, such as renewable energy penetration rates, energy resource utilization, and fossil fuel reductions. The work by CG Meza et al. [24] serves as a pivotal reference in this field, as it analyzes the case of the energy matrix of the Ometepe islands in Nicaragua, provided that they have an important renewable energy potential. This research furnishes technical insights to revamp the island's energy planning, particularly emphasizing the integration of diversified renewable energy penetration rates, with storage systems that are the basis for counteracting the natural variability of its renewable sources. The wind and solar resource assessment results indicate wind energy densities of 147 W/m^2 and 178 W/m^2 at elevations of

80 m and 120 m, respectively, and an irradiation level of 5.3 (kWh/m²/day). Another case aiming to realize 100% renewable energy systems materializes in the renowned Canary Islands, as extensively discussed in reference [25]. Like many other small islands and archipelagos, the Canary Islands rely heavily on energy imports. This study examines a hypothetical trajectory toward achieving complete RE supply across the islands by 2050. It shows in its analysis that the locally available technology potentials amply suffice to meet the islands' total renewable energy, heat, and land transport demands.

In Ecuador there is a first good experience in the Galapagos by interconnecting nearby islands that complement each other very well [21]. In this aspect of the present study, having five nearby islands can increase the reliability of the entire system. Henning Meshchede et al. [22] conducted an exhaustive review of islands that have as a reference to achieving 100% renewable energy. This review highlights the importance of using specialized software, highlighting EnergyPLAN, Homer, H2RES and TIMES, with the EnergyPLAN tool widely used by researchers. Revealed in several studies on a progressive increase in renewable energy on islands [23]. Island-level studies provide a framework to map the status of islands globally and embrace good practices and roadmaps outlined in energy planning and the progress they can bring to island systems [24]. Research carried out in various parts of the world is an excellent reference for this study, among which are Lusaka in Zambia [25], the Åland Islands in Finland [26] and Gran Canaria Island in Spain [27] are just a few examples that they use a systematic methodology to transform including 100% renewable energy in the islands in the long term.

With the exact purpose of carrying out an energy transition, other approaches have been studied that, above all, evaluate land use and renewable energy potentials on site, which implies the use of Geographic Information Systems (GIS) [28]. The analysis of information from diverse sources based on case studies can lead to highlighting specific energy generation experiences; this does not mean that other methodologies are less valid. In the end, tools such as EnergyPLAN allow the evaluation of smart energy systems considering that in the future, land use conditions may be reorganized and not necessarily have the same current patterns. The strengths of optimization techniques allow renewable energies to be integrated in a flexible and adaptable way [29]. From this arises the design proposals for the generation of energy in the islands that are grouped in the province of Guayas, a place that requires the necessary attention in energy issues from which the proportion of energy needed in the long term is outlined, maximizing in this case the Renewable Energy Sources (RES) [30]. The manuscript presents the novelty of taking advantage of the renewable energy resources available on the islands that are grouped on the Ecuadorian coast in the Guayas Province. The procedures developed in this study can serve as a reference for others who have the vision of decarbonizing their energy systems and who include storage systems. In this study, the roadmap for state decision-making has been developed, specifically by the Ministry of Environment, Water and Ecological Transition of Ecuador.

1.1. Review of previous work

There is a diversity of studies on the European and Asian continents that focus on the energy transition both at the continental level and on islands. However, it is striking that little research in America seeks a sustained energy transition to renewable energies. Even the tools available to analyze these systems go beyond maximizing the penetration of renewable energies generally focused on the electricity sector. Among the most notable references are those provided by Alena Lohrmann et al. [31], S. Pokhrel [32], M Liu et al. [33], L Li et al. [34] and P Sorknæs et al. [35]. These authors take advantage of the surplus electrical energy generated by renewable sources and allocate it to make better use of collateral systems such as lighting in tourist areas or give heat to specific areas such as swimming pools, supply the desalination plant and water pumping units to achieve greater use of these resources. Research that addressed a regional energy transition with 100% renewable purposes was presented by DF Dominković et al. [36] for South East Europe, Dmitrii Bogdanov and Christian Breyer and Simon [37] for North-East Asia and Daniel Icaza et al. [38] for South America. They all trace the path towards modernizing the 100% renewable electricity system by 2050.

Other research focused on the interconnection of the different islands using submarine cables of energy and grouped to transfer their energy surpluses to the surrounding islands; among the most representative investigations are those provided by P. N. Georgiou et al. [39], M Alves et al. [40] and Shin'ya Obara et al. [41]. This solution is beneficial; however, the costs involved are quite high when the islands are very far from each other. In addition to the technical power losses due to the distance factor, which makes it challenging to achieve this type of system [42]. Consequently, each study has its particularities, and they are still substantial contributions to consider; meanwhile, research at the island level continues to be developed, and new approaches are being specified each time that address the link between fossil fuel reduction, energy storage and penetration of renewable energies [43].

The storage role is crucial in renewable energy systems, mainly when autonomous, as in the case of islands. JK Kaldellis et al. [44] conducted a techno-economic comparison of energy storage systems for islanded stand-alone power systems. It was concluded that increased renewable energy sources (RES) exploitation on islands, facilitated by appropriate energy storage systems, presents a feasible scenario that safeguards consumers. Conversely, JX Jin et al. [45] devised a hierarchical cooperative control strategy for an island's hybrid energy storage system in a DC microgrid. Their findings revealed that during instances of 400 kW voltage sags and spikes in the DC microgrid, the maximum DC bus voltage overshoot recorded at 5.6% and 5.3% under MSC control. In contrast, overshoot increased to 26.9% and 8.2% under filtering control. In another recent noteworthy study, J. Deng et al. [46] designed an energy router based on a multi-hybrid energy storage system featuring a coordinated energy management strategy, all operating in an islanded mode. The results verify the feasibility and effectiveness of the proposed coordinated energy management strategy, damping power oscillation within 0.1 s in different RE buses, with a 2% fluctuation observed in bus voltages when changing operating scenarios. Iñigo Bonilla-Campos et al. [47] analyzed the typical profile of renewable energy generation and surplus electricity and proposed using diverse energy storage groups. These energy balance technologies have been modeled and subjected to economic evaluations under varying conditions, yielding returns of moderate investment significance. Notably, despite a substantial investment in storage facilities and considering the exported energy, surplus energy is anticipated to exceed 35%. This surplus energy abundance implies high energy availability in storage systems or injection of energy into adjacent power systems. Alam Hossain Mondal and Manfred Denich [48] proposed that surplus production can be utilized in the street and ornamental lighting, grounded on an interesting methodological scheme based on smart lighting. Ali Raza Kalair et al. [49] presented duck curve smoothing in integrated renewable energy networks using the Internet of Relays. It is concluded that it is important to integrate big data technologies into the home energy management system (HEMS). Heidar Jafarizadeh et al. [50] presented a synthesis of how to address the challenges of large-scale renewable energy storage, recognizing the barriers and possible solutions and innovations.

According to Ecuador's Electrification Master Plan [51] for electricity generation purposes, the country's gross wind-electric potential is 1,691 MW, considering areas with an average annual wind speed exceeding 7 m/s, which would generate an average energy of 2,869 GWh. The feasible potential in the short term has been estimated at an installable power of 884 MW and average annual energy of 1,518 GWh. Notably, this potential could increase if areas with low average annual wind speeds (between 5 and 6 m/s) are included. According to the Solar Atlas of Ecuador for electricity generation purposes, the average direct insolation value of continental Ecuador is 2,543 (Wh/m^2/day); the average diffuse insolation stands at 2,032 (Wh/m^2/day); and the average global insolation is reported at 4,575 (Wh/m^2/day). Furthermore, the United Nations (UN) in Ecuador [52] has reaffirmed its commitment to the Sustainable Development Goals (SDGs) and declared Agenda 2030 as a public policy of the National Government. Likewise, the National Assembly has also adopted a resolution pledging to implement the SDGs and considering them a mandatory reference. At the local level, several decentralized autonomous governments have defined their planning to fulfill the global agenda. The private sector, civil society, and academia have unified their efforts to advance toward common goals to ensure equal opportunities and dignified life for all individuals. According to the Ministry of Energy and Mines, Ecuador updated the renewable energy block to 500 MW with a potential investment of USD 968 million [53].

Regarding the policy framework that is suggested to be implemented especially in various island regions, among them the proposal to reduce the environmental effects produced by the generation of electricity in the islands to comply with the state policy of “Zero fossil fuels” [54]. Important proposals have been considered, such as implementing carbon tax policies [55], a cap-and-trade regulatory program [56], policies that in other countries have proven their usefulness in promoting the use of renewable generation sources. International commitments can also cover the Guayas Islands in addition to the list of Natural World Heritage Sites, declared Biosphere Reserves, or Marine Reserves, considered within the Ramsar Sites Network for the conservation of wetlands [57]. It should be noted that there is a new trend to promote the exploitation of photovoltaic systems is the development of integrated systems. Federico Minelli et al. [58] presented a study regarding an integrated and modular tracking photovoltaic shading device for large sustainable urban spaces. The tracking mechanism is carefully designed, 3D printed on a small scale. The realization of the physical prototype confirmed the viability and correct functioning of the conceived system, opening it up to real-scale applications.

The scientific methodology is organized as specified: In this first section is the introduction. Section 2 analyzes the case study of the Islands grouped in the Province of Guayas, analyzing the renewable energy potential available after applying the long-term energy transition model. Section 3, analyzes the results obtained when performing the optimization in steps of 10 years with a view to 2050, the proportions of renewable energy are evaluated from the technical point of view and their economic impact. Then, in section 4 the Analysis and Discussion is presented. Finally, in section 5, the case study's conclusions are provided.

1.2. Methods

This section details the design of the energy system for the islands grouped in the Guayas Province, object of study. In the first instance, it is necessary to have the main data of the base electrical system, which are the input data to the EnergyPLAN software. In this part, the selected tool performs the simulations respecting period by period, and the scenarios are built up to the year 2050. EnergyPLAN is an easy-to-use tool recommended by various researchers who propose roadmaps towards zero carbon in regions and countries [59]. In the final part of this study, the analysis scenarios will be presented from the technical and economic point of view to achieve an adequate energy transition for the Guayas Islands. Wind and solar energy are essential in this study and can form an energy mix with other renewable sources at lower rates, in the case of biomass.

1.2.1. Essential particularities of the method

The analysis method begins by knowing the energy potential of the islands. Although there are no significant disparities in the islands' elevation above sea level, it is crucial to understand the conditions conductive to deploy technologies such as wind and solar photovoltaics on each island. Despite their close proximity to the mainland, the analysis will remain on treating them as 'islands'. The approach encompasses the areas related to the island's energy system. The study includes electricity, desalination, heating and cooling, transportation, and natural gas. The main objective is to capitalize on the interrelationships between the areas of the energy system and their feasibility. Upon understanding the energy potential, it is also necessary to recognize that the islands obey an exceptional analysis due to the fragility of their ecosystems; the isolated electrical system must have a balanced and environmentally friendly structure so that the technologies are harmoniously adapted to the islands' ecosystem. It implies that the electrical system should be as diversified as possible, mitigating reliance on a singular energy source that can affect energy security. Finally, a short-term (hourly) approach becomes indispensable to identifying how the energy system will evolve, considering the intermittency of RES from the outset, as is the case of wind and solar energy.

1.2.2. Long-term projection model

Currently, there are specialized tools for long-term energy analysis and projection. In this case study, the EnergyPLAN [60] tool is used, conceived as a flexible and adaptable analysis tool to the conditions and energy potentialities of the study area under deterministic control conditions in an input/output scheme, and Fig 1 is presented with more detail. Its design aims to structure an effective long-term energy planning, primarily seeking planning attached to the protection of ecosystems and clean energy production without impeding economic growth and rather comforting it for the good of the countries and the humanity [61]. Researchers at Aalborg University in Denmark developed EnergyPLAN. In 2000, the development of EnergyPLAN bega; it was born to be a support tool to transform energy markets with a 100% renewable perspective. Its libraries have been adapted to the demanding investigative demands, which entails a significant evolution until the actuality [62]. Unquestionably, one of the main objectives of the EnergyPLAN tool is to help design completely carbon-free systems. It is released as free software on its official page [63] and is widely used by many researchers, consultants and government decision-makers worldwide, among them highlighted on the EnergyPLAN website [64]. The explanations of the algorithm are presented in detail in the manuals, and a large number of research products are available by specific area and country. There is rich literature available, with case studies, explanatory videos and, therefore, the success achieved by the tool. In addition, it has not stopped innovating and updating, it already has version 33, and the latest is V16.2 of May 2022 to make it even more dynamic and applicable to different regions and countries.The latest publication by Poul Alberg Østergaard et al. [65], behind the EnergyPLAN model, discusses model validation and EnergyPLAN model validation more explicitly. The article highlights an overview of the 315 articles identified in the literature that were studied and had a high application of EnergyPLAN.

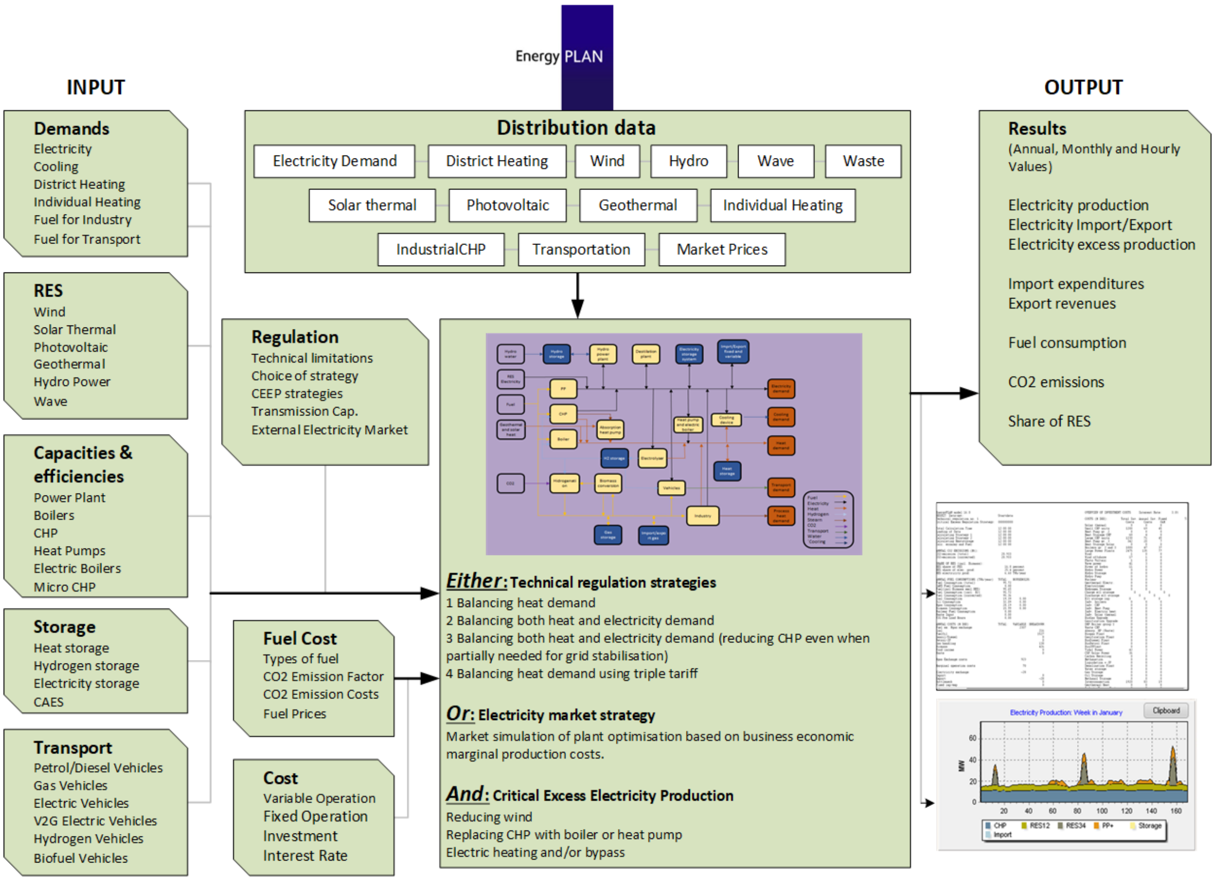


Fig. 1. General structure of the EnergyPLAN model for smart energy analysis [63].

2. The case of the Islands clustered in Guayas

It is located south of the Guayas province, between the Santa Elena peninsula and Cabo Blanco (Peru). Francisco Pizarro discovered it in August 1527. Its entrance has a mouth of approximately 250 km, and within it is Puná Island, which divides it into two significant navigation channels: Morro and Jambelí, the latter at the mouth of the Guayas River. In addition to Isla Puná, which is the main island, the Gulf of Guayaquil is home to several smaller islands, but they are still important for the high production of mangroves, such as Mondragón, Verde, Matorrillos, Ingleses, Escalante 1, Escalante 2, among other small. The Gulf of Guayaquil includes the mass of water and islands with an area of 13,701 km^2 (11,711 km^2 of water surface and 1,990 km^2 of islands and islets), constitutes a unique geomorphological feature of the entire Ecuadorian coastline profile, is located between latitudes 2° 0' and 3° 23' S, longitude 81° 00' 30" and the continental limit and is the westernmost prominence of the South American Pacific coast. The energy source for its supply is thermal to drive combustion engines, as seen in Fig 2. Unfortunately, no government was concerned about providing an adequate service to the islands despite being highly producers of shrimp; much worse has been sought to generate clean energy to maintain a permanent benefit to its inhabitants. It is here where this study aims to give a more ecological sense and support safer production.

Analyzing the energetic systems in Ecuador is of vital interest to the region and the world. The following fact provides a more precise vision of the Ecuadorian context: in the protected territory of Yasuní, there are more than 660 species of native plants living in a single hectare, compared to the 1000 species of plants species existing in all of North America [66]. If we go further and study the case of the Galapagos Archipelago, it is here that the English naturalist Charles Darwin proposed the theory of evolution [67]. These islands showcase the evolution and are valued as living museums; they cover an area of 147,135.4 km^2, of which around 97% is considered Cultural Heritage of Humanity [68]. Highlighting the benefits of this South American country entails a much broader study and the need to protect these ecosystems that are so special to the world. The threat to human beings is evident, especially of the energetic systems based on fossil fuels; based on this problem, there is the motivation in this research regarding the group of islands of the Province of Guayas in Ecuador [69]. A recommendable realistic option is proposed to carry out an energy transition from this research shore for the 100% renewable transformation.

The authors consider that this study can be an essential reference for the case of other islands in the world that are in the same line to promote the energy transition. In this study, notable increases in renewable energy rates are identified by the year 2050, considering that in Ecuador, a significant problem is an economic part, and a similar situation can occur in other parts of the world. However, countries or islands that do not have this difficulty can accelerate the energy transition in the medium term, depending on their reality.

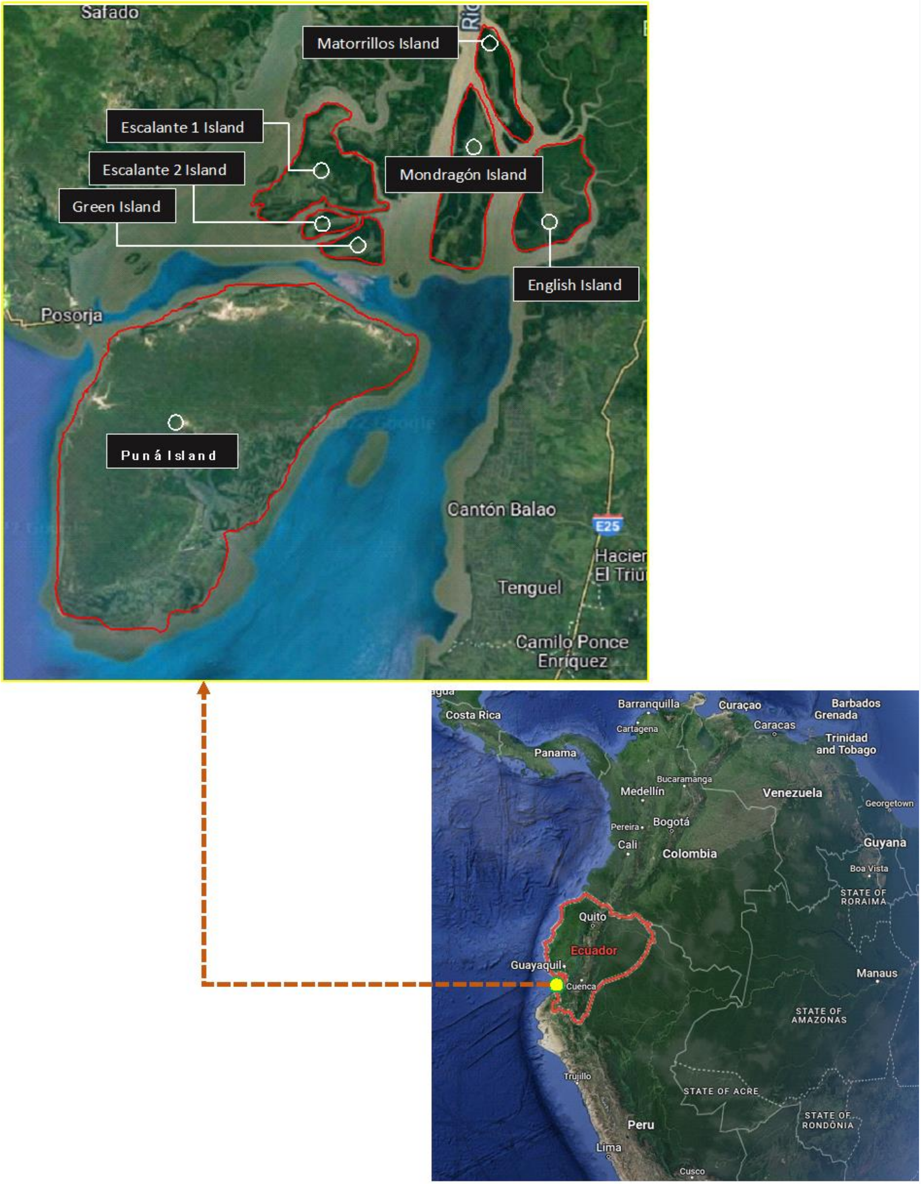


Fig 2. Identification of the islands grouped in Guayas-Ecuador.

One of the significant alterations in the Ocean-Atmosphere system in the Indo-Pacific region is the Southern oscillation, and related to it on the South American coast, the El Niño Phenomenon [70]. The world scientific community groups these two events under a single term: Event El Niño Southern Oscillation (ENSO) [71]. El Niño has been classified as an atypical, acyclical, but recurrent event since its manifestations do not always have the same pattern of behavior nor appear in a certain period. However, Mathematical Models of the National Oceanic and Atmospheric Administration (NOAA) of the United States suggest that the presence of this anomaly is between 7 and 8 years. El Niño describes a large-scale ocean-atmospheric anomaly generated in the western tropical Pacific, fundamentally characterized by the non-periodic flow of hot waters (28°C – 30°C) in the eastern tropical Pacific, particularly in Ecuador and Peru. These water invasions of abnormally warm climates produce dramatic changes in weather, ocean and biological, climatic regimes. To this, the burning of fossil fuels and the use of fuels carry a high risk of new spills, such as those that have occurred countless times according to references [72]. In Oceanographic terms, these events can be considered as the dynamic response of the Tropical Pacific Ocean (TPO) to the fluctuations of the pressure systems in the atmosphere. On the contrary, man's hand is harsh with nature, which is why this research proposes an energy system that is friendly to the environment and promotes development following the international agreements in which Ecuador is immersed and committed to achieving Net Zero Emissions (NZE) by 2050.

2.1. Renewable energy potential

2.1.1. Wind and solar energy

Although periodically there are these adverse effects due to the El Niño phenomenon as a result of global warming, it is no less accurate that opting for a more environmentally friendly energy system will help mitigate its effects, as they have already been working hard in various countries. In this sense, the seven islands considered in this study and belonging to the Gulf of Guayaquil are characterized by their excellent energy potential. If something can be highlighted between one island and another, Puná Island can be essential for articulating more special equipment and supporting of the other islands, especially with higher production and storage levels due to its more significant potential in the wind. In fact, in Ecuador there are good experiences both in the Galapagos Islands and the Villonaco de Loja in wind energy production [73]. In these islands, it can contribute significantly to supplying their populations and shrimp production systems, avoiding dependence on supply of energy coming from the barges that constitute a significant problem in the area due to the continuous fuel spills and the high costs derived from provisioning. The solar radiation in the seven islands is quite similar; logically, being close to each other is the fundamental reason and can be identified in Fig 3. The annual average daily value of solar radiation is approximately 4.7 kWh/m^2. Analyzing the same Fig 3, it is observed that the region is characterized by a considerable wind potential with its particularities in each island that due to variations in the terrain and wind inputs to the Gulf, there is a greater potential between one island and another, being an excellent resource to exploit it. The highest annual average wind speed of 7.6 m/s, Puná with 7.3 m/s, Mondragón with 5.4 m/s; meanwhile, Escalante 1, Escalante 2, English, Green and Matorrillos have the lowest wind speed, around 2.6 m/s. The wind speed values are taken at the height of 10 m, and at a higher rates can be achieved at a higher altitude, as seen in the reference [74].

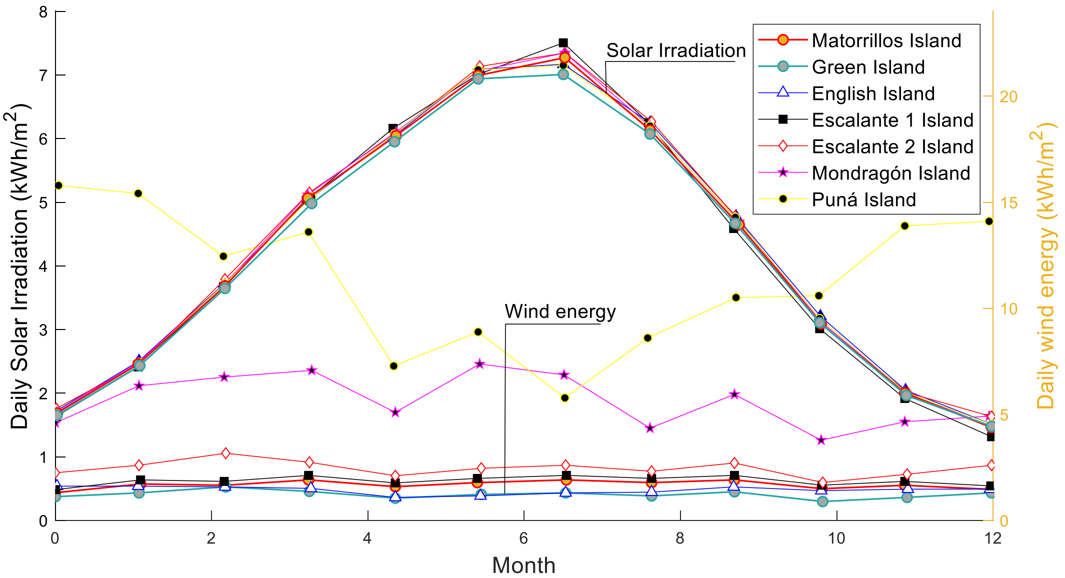
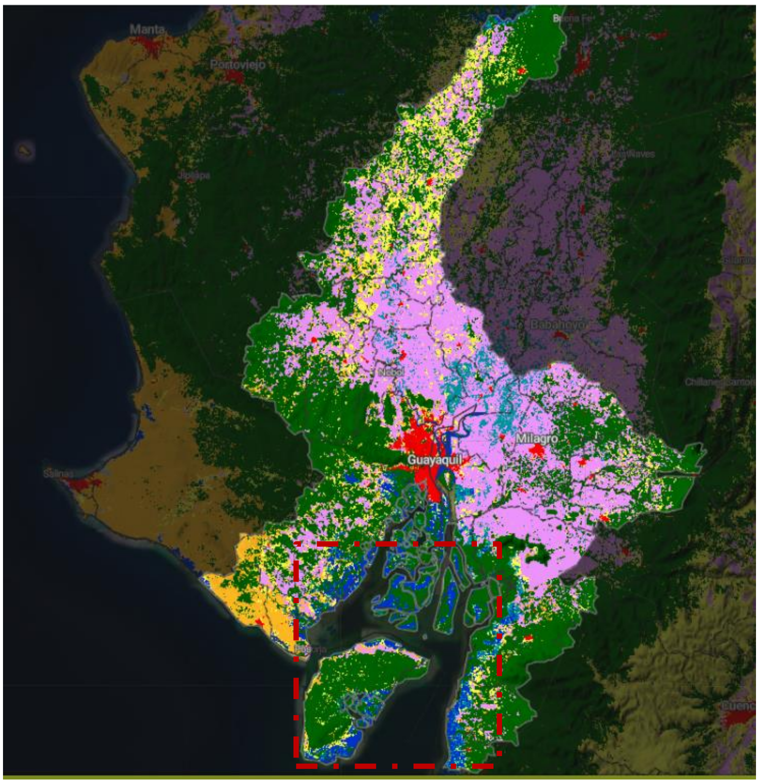


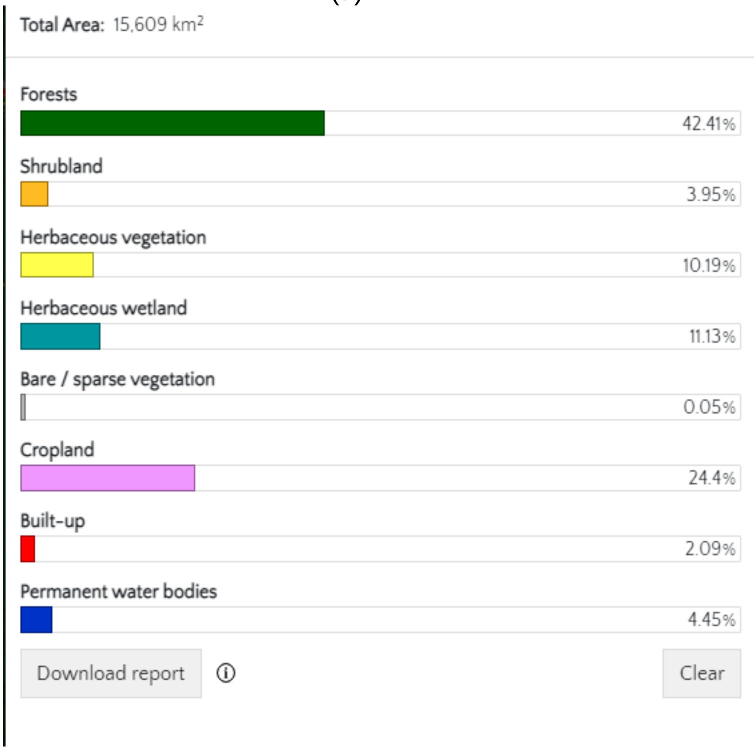
Fig 3. Wind and the solar PV energy potential in the grouped islands of Guayas

2.1.2. Biomass

On the other hand, when studying the classification of land use in the Province of Guayas through the Global Land Cover tool [75], it can be seen in Fig 4a and Fig 4b that 42.41% of the territory is made up of Forest and 21.32% by herbaceous which is very significant that there is a large number of plants of different sizes in the province. If studied more in detail, the islands under study have many areas rich in vegetation, which leads to taking advantage of the resources that are harvested from the plants to generate biomass as they have more than 62% of the plants in the territory. Good planning and treatment of the harvest resources is a potential source of energy that should not be overlooked and be part of the energy mix in the long term.



(a)



(b)

Fig 4. The territorial layout of the Guayas Province. (a) Green (forest) and yellow_green-blue (vegetation) predominate (b) Territorial distribution rates according to [75].

2.2. Structure of the inputs

The technologies directly coupled to the seven islands under study are wind and solar; as previously explained, biomass would be on a smaller but more important scale. Due to their potential, these three primary energy sources are called to revolutionize the energy system under study. Achieving this requires first a decisive decision by the national and local governments, and then the resources are necessary to make it a reality. Later on, a recommended realistic scenario is presented based on its energy potential. However, it is not rigid that other renewable sources can also enter the energy mix; among them may be tidal and wave energy [76,77], to mention, but from the financing point of view, they will be a little more complicated to start up due to the high costs they represent, and it is difficult to achieve significant reductions in their prices. Concerning energy storage, it can be indicated that it is vital in this design because having intermittent sources becomes essential to provide battery banks on each island and jointly to be able to repay energy to neighboring islands in the event of shortages. Meanwhile, since there is an energy surplus, high storage levels can be maintained, and, if possible, the infrastructure can be built to inject the national interconnected ring for export purposes to neighboring countries such as Colombia and Peru.

The energy system extension's limitations have been considered to create a much more realistic scenario concerning the optimization performed to project the entire electrical system. Therefore, the installed capacity of the technologies was structured about future demand by interpolating data from the National Institute of Statistics and Censuses (NISC) to reflect much more realistic investments. It is important to indicate that several sectors such as transport, heating and cooling, etc. have not yet been developed, but it cannot be restricted that they will not be developed in the future. For this reason, in this study, a complete renewal of the energy system is considered; it is conceived that a clean generation also implies a demand that rewards the efforts made and evolves in the same order.

It must be recognized that an orderly and well-structured energy transition takes time, and for this reason, the year 2050 is a good benchmark; not accelerating the energy transition can we neglect critical aspects such as the cost of technologies, improvements in legal regulations, etc. EnergyPLAN considers intelligent transport, electrification, the use of hydrogen, heating and cooling as fundamental elements to be developed.

2.3. Mathematical model

Running the EnergyPLAN tool in each period considered and taking into account its evolution, a temporary structure is defined based on site data because EnergyPLAN requires defining the base year. Based on theexisting energy potentials on the islands, the so-called energy transition function is structured. The energy transition function interacts with EnergyPLAN and bases its extraordinary value of the tool, and in each execution, it performs the following operations. The main aspects related to the mathematical model are presented below.

1) The reference energy scenario is defined to be entered into the EnergyPLAN tool, from which the transition begins and which contains the energy capacity data by source. In this aspect, the base year is not necessarily the most recent year or the year experienced, but the year in which the information and data are available; in this particular case, it is 2020. Fig 5 is presented below.

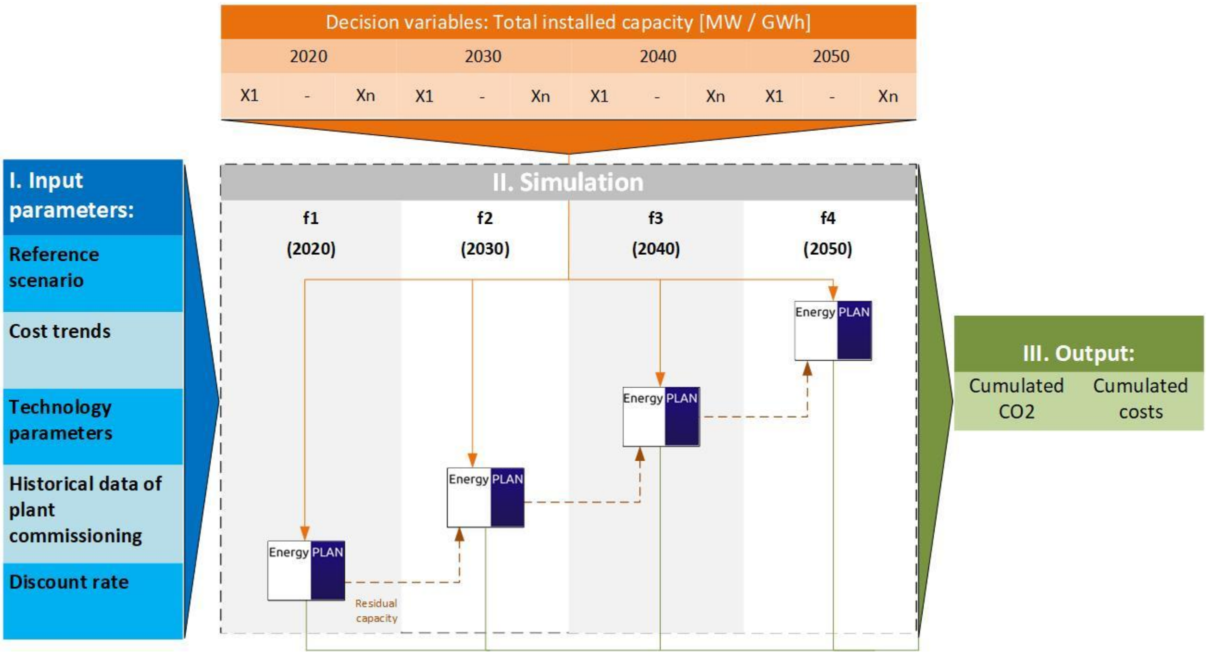


Fig. 5. The systematic process of analysis in long-term scenarios in periods of 10 years with EnergyPLAN.

2) Execution of EnergyPLAN includes the reference scenario and obtaining new scenarios with greater participation of renewable energies. Annual Operation and Maintenance (O&M) costs are also included.
3) The costs of the technologies are essential; the greater penetration of renewable energies and their renewal of the island's energy system depends on them and will depend a lot on the learning curves of the costs. In this case, wind and solar technologies are crucial and will be discussed in more detail in the results section.

Below, equation (1) represents the typical installed capacity conservation constraint. The total power installed *P* for technology Ω in the time step t is the sum of: The new installed capacity $P_{t,k}^{new}$, at that time step. On the other hand, there is the residual capacity $P_{t,k}^{res}$, which represents the available capacity at the beginning of the time horizon and which continues to operate in the time *t*. Life cycle *n* is greater than the difference between t and its installation period *t'*, therefore, the new power installed in the previous steps continues to operate in the time step *t*.

$$P_{t,\Omega} = P_{t,\Omega}^{new} + P_{t,\Omega}^{res} + \sum_{t'=t-n_{\Omega}}^{t} P_{t',\Omega}^{new} \tag{1}$$

To determine the annual costs of O&M and CO_2 emissions. The investment costs relative to the reference period must also be calculated. Eq. (2) is presented below:

$$Costs_t = O\&M_t + \sum_{\Omega}^{K} INV_{t,\Omega} \tag{2}$$

Where the parameter $O\&M_t$ represents the total cost of operation and its respective maintenance, both fixed and variable, of the electrical system in *t*. $INV_{t,\Omega}$ refers to the investment costs in the acquisition of the new technology, represented by the new capacity of technology Ω added in *t*. The total annual costsare only determined by multiplying the annual costs by number of years *Y*. Equation (3) is then applied, where *r* is the discount rate and *y* is the generic year.

$$O\&M_t = O\&M_y * \sum_{y=1}^{Y} (i + r)^{(1-y)} \tag{3}$$

Regarding investment costs, lump sum payments are considered. Equation (4) determines the investment costs $INV_{t,\Omega}$ for technology Ω in relation to *t* as a function of the new power capacity $P_{t,\Omega}^{new}$.

$$INV_{t,\Omega} = inv_{t,\Omega} * P_{t,\Omega}^{new} \quad (4)$$

The identified drawback of using investment costs is that at the end of the horizon, there is a surcharge value for the replacement or dismantling of the fuel and derivatives disposal centers, which may incur a potential penalty at the end of *t*. The salvage value has been introduced to avoid this penalty. A proportional depreciation of the asset Ω was assumed to calculate this value. Its valueconstantly decreases in *t*. It starts from an initial value equal to the investment cost $INV_{t,\Omega}$ at the beginning of the cycle of life. An approximate residual value of the parameter *R* at the end of the valuable life cycle is considered. For purposes of application and to simplify the model for Ecuador, an *R* = 0 was considered. It is then presented in mathematical terms in (5) and (6):

$$Salvage_{t,\Omega} = INV_{t,\Omega} * \left[1 - \frac{T-t}{n_\Omega}\right] \quad (5)$$

$$CO_{2t} = CO_{2y} * Y \quad (6)$$

For obtaining the accumulated costs of the entire time horizon, the sum of all the costs and emissions is made. It is represented mathematically in equations (7) and (8). Note that the recovery value at the end of the last time step is subtracted.

$$Cost_{cum} = \sum_{t=1}^{T}\left[(i+r)^{Y(1-y)} Costs_t\right] - (1+r)^{-YT} * \sum_{\Omega=1}^{K} Salvage_\Omega \quad (7)$$

$$Salvage_\Omega = \sum_{t=T+1-n_\Omega}^{T} Salvage_{t,\Omega} \quad (8)$$

The temporary emissions can be integrated into a single equation, according to equation (9) to obtain the accumulated emissions.

$$CO_{2cum} = \sum_{t=1}^{T} CO_{2t} \quad (9)$$

The Energy Supply Ratio (ESR) is an important parameter that allows for evaluating the level of incidence for the demand in the desired period, this study is evaluated to 2050. The time range is considered from *0* to *t*, and the following is the equation (10).

$$ESR = \sum_0^t \frac{P_{rene-2050} - P_{DEMAND\_2050}}{P_{rene-2050}} \quad (10)$$

Where $P_{rene-2050}$ is the renewable power generated in 2050, while P_{DEMAND_2050} is the load demand in 2050.

The global electricity demand in Guayas reached 1,126 MW registered [78], of these according to the data registered in the CNEL EP portal [79] it has been determined that in the islands of Guayas around 22.5 MW would be consumed. However, according to predictions declared by official entities, these values are expected to increase in the islands by approximately 1.26% [80,81], representing a demand close to 28.5 MW by 2050.

Surplus energy is commonly stored in battery banks, strategically located in the islands under analysis. The excess energy production from renewable sources usually occurs during daylight hours, thereby facilitating the charging process of the batteries. Meanwhile, during nighttime, when the sources' production is reduced due to their intermittent nature, the batteries supply electric energy to meet the demand, engaging in the discharge process. Mathematically the state of charge (SOC) and discharge (DSOC) are expressed by equations (11) and (12) respectively.

$$SOC(T) = SOC(t-1) + \frac{E_{bat}(t) * \eta_{cbat}}{P_{bat}} * 100 \quad (11)$$

$$DSOC(T) = SOC(t-1) + \frac{E_{bat}(t) * \eta_{dbat}}{P_{bat}} * 100 \quad (12)$$

E_{bat}: Battery capacity with charge and discharge η_{cbat} and η_{dbat} efficiencies.

Another reason to install battery banks in addition to storing energy is to maintain the balance between energy supply and demand. Equilibrium is fulfilled over time under the following two conditions:

- $P_{PV}^{T} + P_{WT}^{T} + P_{OTHERS\ RENE}^{T} = P_{DEMAND}^{T}$ It maintains a complete balance.
- $P_{PV}^{T} + P_{WT}^{T} + P_{OTHERS\ RENE}^{T} > P_{DEMAND}^{T}$ The hybrid system generates more electrical power than is necessary at the extreme of demand. The battery bank maintains its full charge over time and is expressed by equation (13).

$$E_{bat}^{T} - E_{bat}^{T-1}.(1-\tau) + \left[(P_{PV}^{T} + P_{WT}^{T} + P_{OTHERS\ RENE}^{T}) - \frac{P_{l}^{T}}{n_{inv}}\right]\eta_{bc} \quad (13)$$

Where:

η_{bc}: Battery bank efficiency
E_{bat}^{T} and E_{bat}^{T-1} : Battery charge at time *T and T-1.*

η_{inv} : Inverter efficiency.
τ: Autonomy time.
P_{PV}^{T}: Electrical power provided by the solar panel.
P_{l}^{T}: Electrical power absorbed by the demand in a certain time.
P_{WT}^{T}: Electrical power provided by WT.
$P_{OTHERS\ RENE}^{T}$: Electrical energy provided by other small-scale renewable sources.

- $P_{PV}^{T} + P_{WT}^{T} + P_{OTHERS\ RENE}^{T} < P_{DEMAND}^{T}$ The power absorbed by the demand exceeds the levels of electrical power generation generated by the three renewable sources. In this condition, the battery provides enough electrical power stored, as identified in the mathematical relationship (14).

$$E_{bat}^{T} - E_{bat}^{T-1}.(1-\tau) + \left[\frac{P_{l}^{T}}{\eta_{inv}} - (P_{PV}^{T} + P_{WT}^{T} + P_{OTHERS\ RENE}^{T})\right]\eta_{bf} \quad (14)$$

η_{bf}: Performance of the energy storage system.

2.3.1. Technical and economic evaluation criteria refer to sources of high participation

In order to analyze a flexible combination between the two primary sources of generation (wind and PV) for the seven islands mentioned in this case study and meet the growing demand in 2050, an evaluation based on the reliability and economics of electricity service es performed. The methodologies used for the evaluation are presented below:

2.3.1.1. Technical criteria

It is clearly known that the parameters of wind speed and solar radiation are of intermittent origin, however, at the level of demand, service guarantees are required both in quality and continuity, this is where the success of the design of energy systems lies. The concept of system reliability in terms of Loss of Power Supply Probability (LPSP) is adopted and applied to the present case study [82]. The LPSP bases its concept as the direct relationship between all energy deficits and the load demand. The mathematical relationship that expresses what is indicated is presented below in (15):

$$LPSP = \sum_{t=1}^{T} E(t) \Big/ \sum_{t=1}^{T} P_{load}(t)\Delta t \qquad (15)$$

Where *DE(t)* corresponds to the electric power deficit in hour t. This can happen when the total generated power available in a time range *[(t-1),t]* and the power stored in the battery bank are insufficient at the beginning of this time range to supply the energy demand.
The energy deficit equation (16) can be applied at any time as expressed below:

$$\frac{\partial DE(t)}{dt} = P_{load}(t) = P_{tot}(t)) \qquad (16)$$

Where P_{tot}(t) depends on the partial contributions of electrical power from the different generation sources and the level of power stored in batteries at the inverter output. Below equation (17) is shown:

$$P_{tot}(t) = \left(\left(P_{pv}(t) + P_{wt}(t) + P_{others\ renew}(t)\right) + C_{bat}(t-1) - C_{bat\ min}\right) * \eta_{inv} \qquad (17)$$

2.3.1.2. Economic criteria

In this study, an economic criterion is also issued; it is based on the LCOE determined as the relationship between the total annualized system cost and the annual energy supplied by the system.
Equation (18) is presented below to estimate the LCOE of the renewable energy system.

$$LCOE = \frac{TAC}{E_{tot}} \qquad (18)$$

Where, TAC is the total cost and E_{tot} is the total annual energy.
The TAC is determined in (19), taking into consideration the Capital Recovery Factor (CRF) and Present Value of Costs (PVC).

$$TAC = CRF(i, N) * PVC \qquad (19)$$

i = annual interest rate;
T = Project useful life in years.

The *CRF* mathematically is defined in equation (20):

$$CRF = \frac{i(1+i)^{T}}{(1+i)^{T} - 1} \qquad (20)$$

During the operation of the hybrid system, it is necessary to comply with the objectives of maintaining the continuity of the electric power service, which requires adhering to a set of restrictions. This implies satisfying the conditions in all system operations for any possible solution.

Considering a minimized cost scheme $MinM_t\left(P_{pvD}(t), P_{pvA}(t), P_{wt}(t), P_{Bat}(t), P_{others\ rene}(t)\right)$ each contribution seen from the point of view of its own constraints is evaluated through equation (21):

$$MinM_t\left(P_{pvD}(t), P_{pvA}(t), P_{w}(t), P_{Bat}(t), P_{others\ rene}(t)\right) = Min\left(M_{pvD}(t), M_{pvA}(t), M_{wt}(t), M_{Bat}(t), M_{others\ rene}(t)\right) \qquad (21)$$

Where M_t is the renewable system cost.

$M_{pvD}(t), M_{pvA}(t), M_{w}(t), M_{Bat}(t), M_{others\ rene}(t)$ Parameters that refer to the individual costs of each technology and its complements for the integrated operation of the hybrid system. These costs encompass the photovoltaic system, wind turbines, other renewable energies, and batteries.

2.4. Base year 2020 and long-term projection 2050

The electrical system of the seven islands under analysis in the Province of Guayas is supported by a high rate of thermoelectricity from specific points on the islands as well as from barges located strategically to increase the energy supply (See Table 1). Electicity production for water pumping and recirculation during shrimp and fish harvesting is also included.

Table 1. Main data of the islands of the Gulf of Guayaquil provided by [83] [84] [85].

Island	Surface (km^2)	Population	Main activity	Source
Mondragón Island	511.8	1020	Mangroves	4MW, Thermal
Puná Island	920	6500	Tourism, Mangroves	8MW, Thermal
English Island	472	970	Mangroves	3MW, Thermal
Matorrillos Island	364	220	Mangroves	4MW, Thermal
Escalante 1 Island	448	384	Mangroves	1.5MW, Thermal
Escalante 2 Island	84	30	Mangroves	1MW, Thermal
Green Island	97	15	Mangroves	1MW, Thermal
			Total Installed Power	22.5 MW, Thermal

In Fig 6, the results of the optimization are obtained in an hourly scheme, as is characteristic in EnergyPLAN. The primary sources of energy production called to dominate the energy mix of the seven islands under study by 2050 are solar and wind, while biomass and biofuels will also be present in a smaller proportion. The results identified are RES1, which includes wind and biomass, meanwhile RES2 for solar and biofuels. These results lead us to identify that the two main sources complement each other very well with the smaller ones. In this software, the contribution of small increases is highly valued, and it is not only limited to evaluating high proportions, but even its combinations are made in pairs to obtain a resulting energy generation later [86]. It is also observed that the demand curve at some specific moments is at the limit in proportion to the generation (20 MW); this implies that a battery backup system can be an excellent option to guarantee the security of the energy service towards the demand. Naturally, generation levels are reduced at certain times when trying to configure 100% renewable generation sources, which are intermittent, and it is precisely there that battery backup systems play a prominent role in increasing the reliability of the overall electrical system [87]. In the results obtained, according to Fig 6, it can be observed that at certain hours there is a flexible surplus of energy (flex) and high availability of power for export (Exp EEEP + Exp CEEP) with 43 MW and 53 MW, which makes the system more dynamic, enabling interconnections with other energy systems in the future [88]. In this particular case, there is ta possibility of making these interconnections with other systems, since upstream there are other island groupings, including the Ecuadorian mainland.

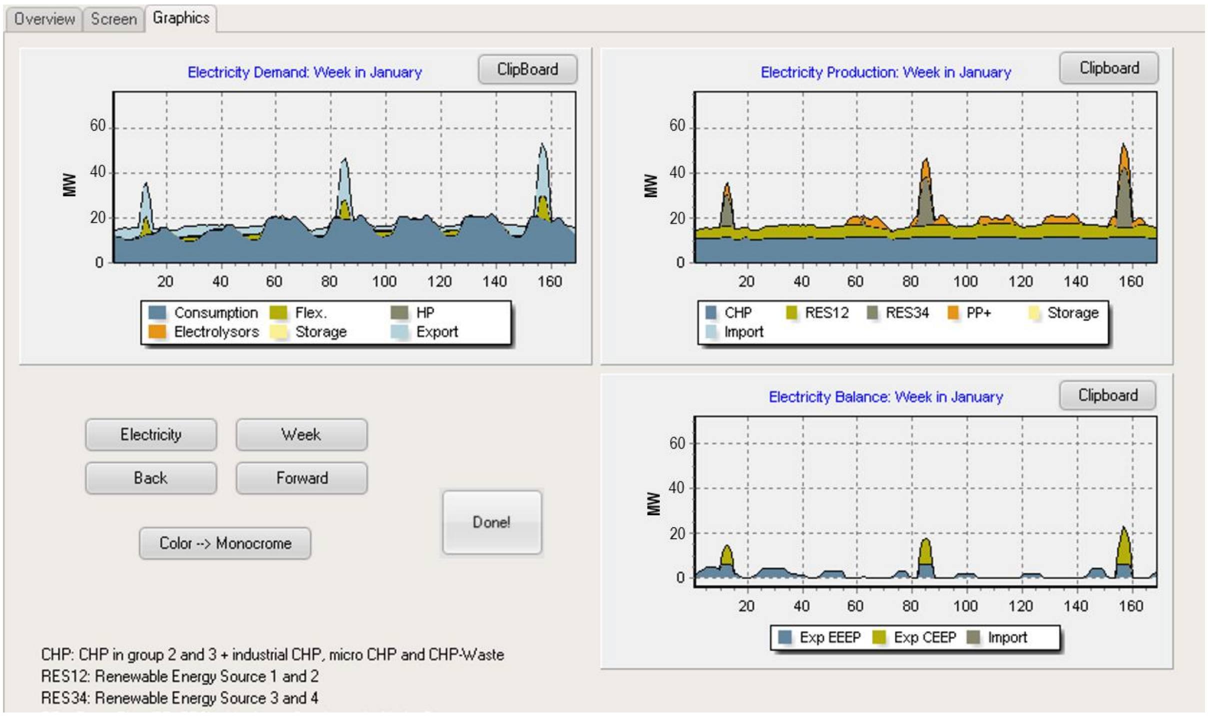


Fig 6. Production-consumption ratio for the 7 Grouped Islands of the Gulf of Guayaquil per week in January 2050.

It is reasonable that wind and solar technologies are the future technologies in the islands due to the high primary energy potential available. From the experiences acquired worldwide about electrified islands with these technologies, even with lower primary energy potentials, they have achieved the desired success for those who live or carry out productive activities. There is the example of Ometepe in Nicaragua [89]. The wind power densities are 147 W/m^2 and 178 W/m^2 at 80m and 120m, respectively, and an irradiation level of 5.3 (kWh/m^2/day). Another interesting case is that of São Vicente of Cape Verde [90], an island in West Africa with 540,000 inhabitants, with wind power densities around 154 W/m^2 and an irradiation level of approximately 4.85 (kWh/m^2/day). Additionally, it becomes desirable that the production costs of wind turbines, solar panels, converters, batteries and additional infrastructure to configure hybrid systems tend to decrease significantly [91]. With this, it is achieved that the islands with dispersed populations have greater access to these technologies. Wind energy is highly valued in Ecuador in different power plants, such as Villonaco, with 16.5 MW of power; it has 11 wind turbines with 1.5 MW of nominal power [92] and Minas de Huascachaca with 50 MW [93]. On the other hand, on islands, there are already successful experiences in the Galapagos Archipelago on San Cristobal island, with a capacity of 2.4 MW formed by three 2.25 MW wind turbines located on Tropezón Hill [94], and Baltra, with three 750 kW wind turbines [95]. Biomass will be helpful in low proportions, mainly due to the existence of forests and thick vegetation that can be well treated for electricity generation purposes, without implying the irresponsible felling of forests and green spaces. Proper planning and recycling of solid waste are essential at the island level to make them healthier and more attractive for visitors and what a better option to generate energy [96]. The production of biofuels on the islands should not be overlooked; in the Galapagos Islands, the production of Pure Pinion Oil (PPO) is already being promoted as a substitute for diesel for electricity generation [97], it is probably an effective solution in these islands to carry out responsible electric mobility with the environment at affordable costs.

Industry experts and researchers recommend the diversity of electricity generation sources [98], thus avoiding dependence on point sources and increasing energy security on the islands by diversifying sources. Their expected impacts are very encouraging when it comes to committing economic resources to these technologies Having nearby and diversified sources of generation will avoid additional payments for transportation to their inhabitants; in many cases, people transport the fuel in heavy containers on their shoulders to supply their diesel or gasoline generators.

Below is the reference model summarized in Table 2 that will be used to enter the main data in EnergyPLAN as expressed in this section.

Table 2. General description of the reference model for the case study of Islands grouped in the Gulf of Guayaquil.

Main Factors	Solar Energy	Wind Energy	Biomass	Biofuels	Oil
Time of life (years)	25	35	35	35	30
Total units 2050	11 MW	14 MW	2 MW	1.5 MW	-
Trend	Increase	Increase	Increase	Increase	Progressive Disappearance
Financing Capacity (%)	80 ↑	60 ↑	40 ↑	60 ↑	50 ↑
Order of merit	1.5	1.5	1.5	1.5	2
Fuel costs in $/TOE	-	-	-	-	426.8
Availability (%)	46	68	22	36	70
Capital Costs in thousands of US$ per MW					
2020	3426	5135	2130	720	1040

2050	23350	8100	1740	2200	N/A
O&M Cost in thousands of US$ per MW					
2020	19	52	167	105	9.4
2050	9.4	48	43	69	N/A

EnergyPLAN calculates and integrates energy generation capacities with a vision for 2050. When designing the energy system, there are several routes to determine the final scenario; this depends on the available energy potential and the design criteria introduced below, described in this section, and evaluated by EnergyPLAN. The tool's strength is that it is flexible tool and allows different analyses without needing to reconfigure the entire data matrix, precisely this aspect is relevant for designers and researchers and distinguishes EnergyPLAN from other energy planning tools. The tool catalogues its results under a favorable operating scheme; as expected, it does not contemplate political or regulatory aspects, so the conditions must be established well for technological deployment in real life. Under these conditions, it is essential to have clear policies for the complete technological transformation and to achieve favorable results. It is also necessary to have an updated Land Management Plan (LMP) [99] and, as far as possible, to contemplate the energy transition to avoid delays during the transition [100]. In the Province of Guayas, there is an LMP; however, before initiating processes of this type, it must be clear that the route is the transformation of the electrical system and, if necessary, update the plan. Particularly in the the Gulf of Guayaquil islands, it is a fundamental necessity to generate citizen welfare, environmental protection and economic development.

3. Results

Figure 7 presents the results of this case study, considering the main aspects of the socio-technical and economic viability of the electrical system designed until 2050. In addition to seeking the transition of the electrical system, the aim is always to safeguard the growing electricity demand and under no circumstances be the one that perceives the poor quality of service and much worse outages. Within the long-term planning, a substitution of renewable energies for thermal ones is contemplated; however, this process that must be well focused and socially responsible, seeking to protect the jobs of people who have been working for several years. Instead, they should be trained for this systematic transformation. This designed system has a particularity that it does not contain hydroelectricity, as is usual in other studies. It is a unique case of islands that do not have significant springs on the mainland for energy use. The energy sources considered in this case study are not usually constant, so it is necessary to diversify them and create energy backup systems through battery banks. Interpreting the results with precise values in Fig 7 and Table 3, it is observed that solar and wind technologies are the protagonists in 2050 with 11 MW and 14 MW, respectively. It is observed that biomass can be installed to a lesser extent with at least 2 MW and biofuels with 1.5 MW, thus reaching 28.5 MW of 100% renewable installed capacity in the seven islands. The scenarios every 10 years are established as recommended realistic. In the islands it is possible to take better advantage of the available resources such as wind and solar radiation. At some points, it may even lead to the inclusion of floating systems. However, they are not considered in this study and therefore avoided since mangrove areas or, in turn, the people who carry out the work of harvesting sea products, especially shrimp, can cover the panel surfaces with nets or serve as anchors for canoes. This would affect the system's efficiency and put the levels of electricity production at risk in the stated proportions.

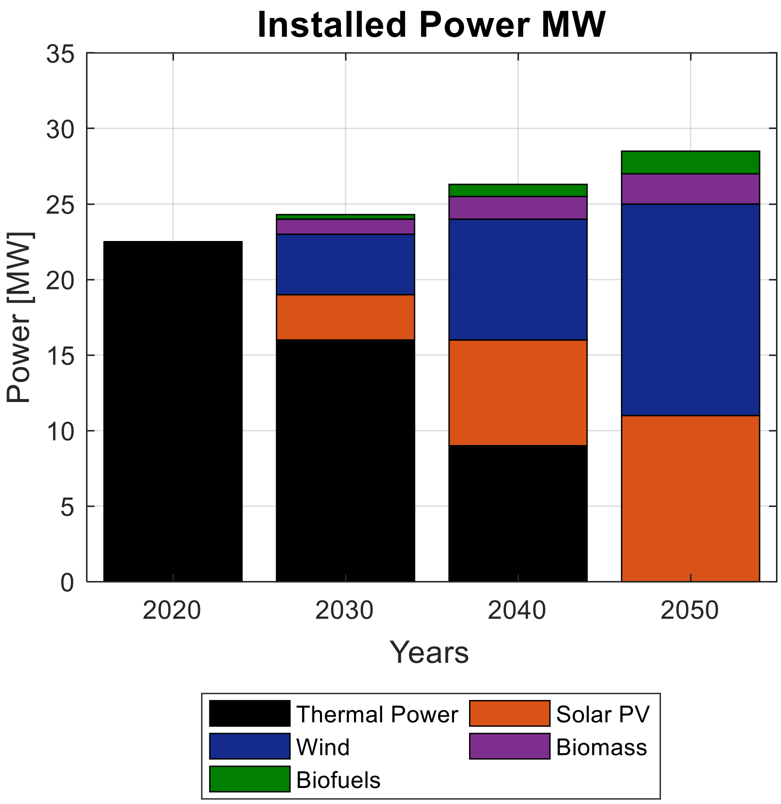


Fig. 7. Installed power in MW with steps of 10 years until 2050 for the case of the Islands of the Gulf of Guayaquil.

Table 3. Projection of Installed Power (MW) in periods of 10 years

Source	**2020**	**2030**	**2040**	**2050**
Thermal	22.5	16	9	0
Solar		3	7	11
Wind		4	8	14
Biomass		1	1.5	2
Biofuels		0.3	0.8	1.5
TOTAL	**22.5**	**24.3**	**26.3**	**28.5**

In Fig. 8 and Table 5, the feasible electricity generation levels are presented in time steps of 10 years until 2050. In the year 2050, the seven islands will achieve a 100% renewable energy supply.

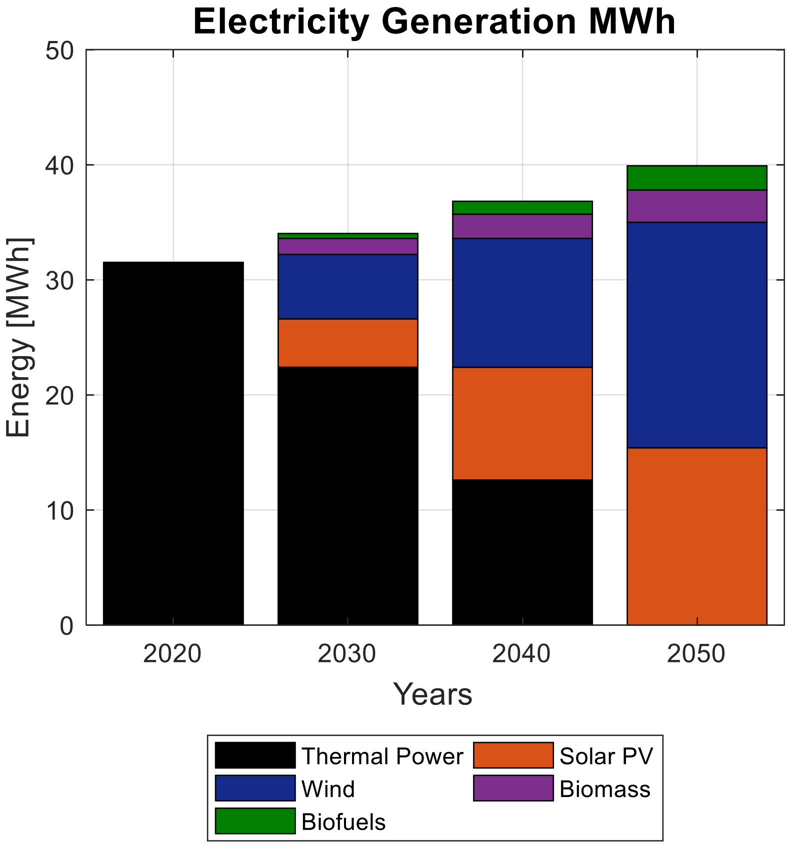


Fig. 8. Scenarios of energy produced in MWh with steps of 10 years until 2050 for the case of the Islands of the Gulf of Guayaquil.

Table 4. Projection of Energy (MWh) in steps of 10 years

Source	**2020**	**2030**	**2040**	**2050**
Thermal	31.5	22.4	12.6	0
Solar		4.2	9.8	15.4
Wind		5.6	11.2	19.6
Biomass		1.4	2.1	2.8
Biofuels		0.42	1.12	2.1
TOTAL	**31.5**	**34.02**	**36.82**	**39.9**

Below, in Fig. 9, the percentages of contribution by source are presented until 2050.

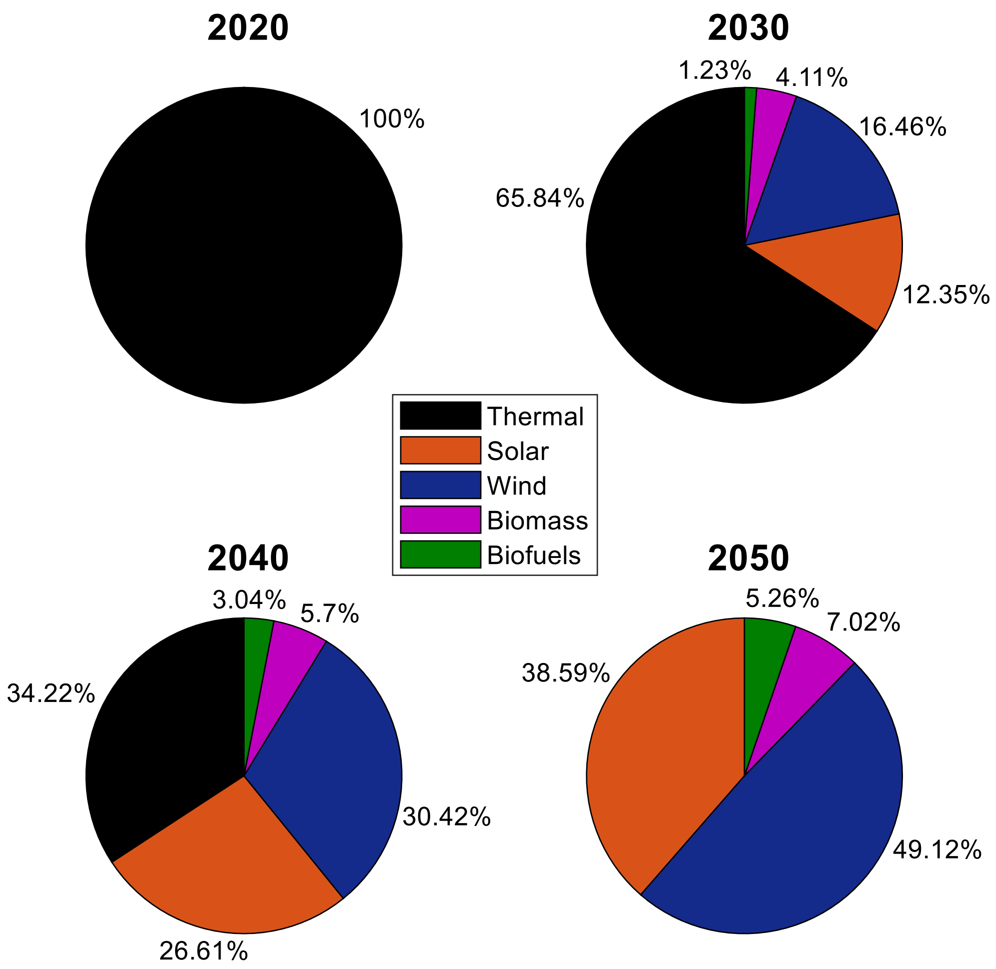


Fig. 9. Percentage of Installed capacity for a period towards a 100% renewable model by 2050 in the Islands under study.

As has already been fully described in this section, the electrical system designed with a view to 2050 is based on a high installed capacity of the two sources, solar and wind, which together account for 87.61%, while biomass and biofuels account for 2.29%. The two components, wind and solar, have been analyzed separately in the search to maintain production levels according to projections. For evaluation purposes of the two sources mentioned, the two smaller-scale sources (biomass and biofuels) are considered fixed.

Fig. 10 shows the curves of installed wind energy versus installed solar PV energy power for three days of storage for the seven islands. Each combination in each plotted curve guarantees electrical energy service on demand in total energy autonomy within one year. The results of the optimization indicate that the potential renewable resources are used objectively and that the relationship between wind and solar can be adjusted.

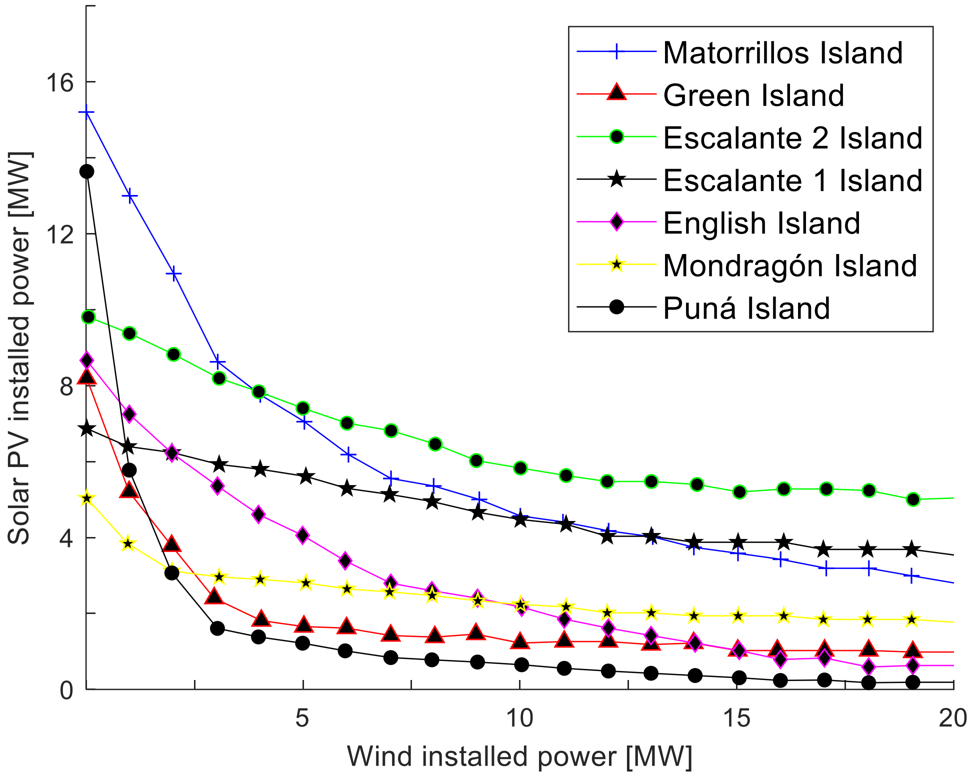


Fig 10. Combinations of wind and solar PV capacities for the desired 0% LPSP across the various islands with 3-day storage.

The electrical energy system for the set of islands that guarantees a zero LPSP it depends to a large extent on the renewable energy potential of each island individually to meet demand. Wind potential was identified on each island; while intermittent, it also occurs at night, even at low levels at specific periods, which are best complemented by the solar energy system and its battery bank as a backup, which is much more effective. When analyzing the energy potential of Puná Island, the wind potential on this island is really important since it receives currents from the Pacific; the first isle that receives these wind currents precisely is Puná. A high-intensity wind tunnel is also formed on the island of Mondragón, which is precisely one of the places where more wind energy can be generated. Above all, these two islands were identified as having the most significant wind potential, more than 32% of the total energy production, concerning the other five islands with less wind potential. However, they are not negligible either and represent around 17% of the total energy production. The results of the optimization for the set of islands with just the lowest LCOE point occurred when there was less wind energy production/total (<30%) on the two islands (Puna and Mondragon). The wind energy/total energy production ratio is represented below in Fig. 11. In a multi-day energy storage scheme, a zero LPSP is guaranteed with a minimum LCOE. It should be noted that the more days of storage contemplated in the design, on the one hand, the more the continuity of the electrical service will be guaranteed; however, the LCOE tends to increase progressively.

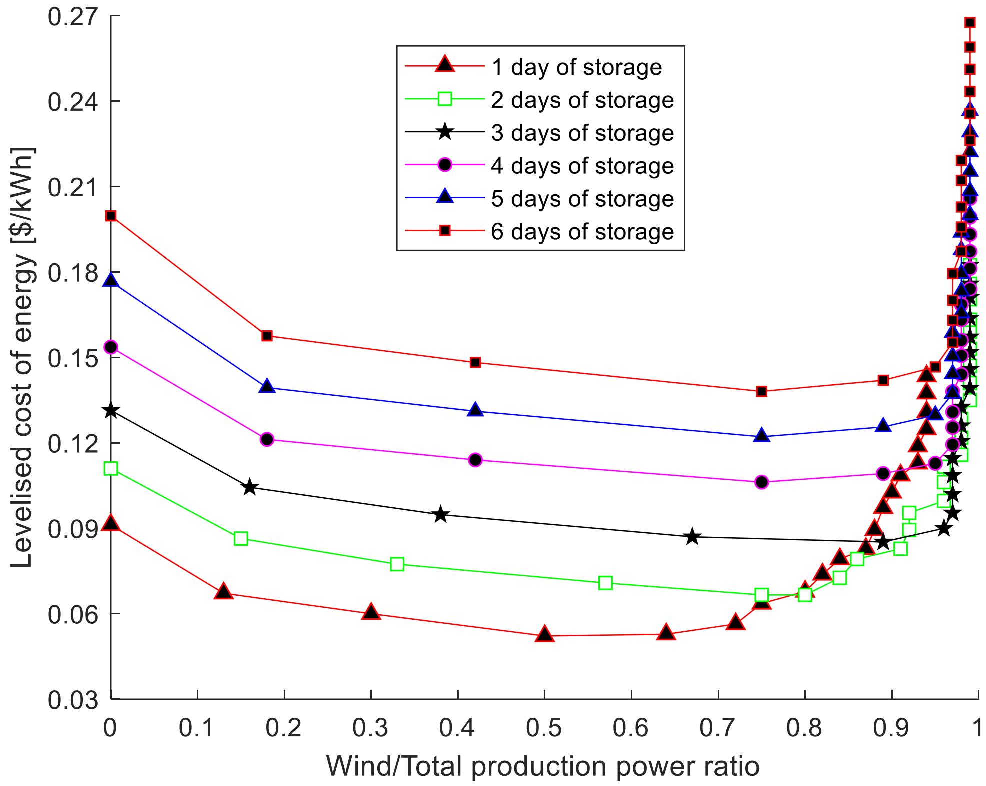


Fig 11. The expected impact of wind energy on the total power generated in the Levelized cost of energy

The costs considered in this study are included in Table 5. However, this table serves as a reference and is subject to change as technology tends to decrease costs. Therefore, it will require updating to obtain more accurate data. The costs of the various technologies are detailed below:

Table 5. Summary of assimilated costs associated with the technologies to be implemented

Equipment	**Power Required (MW)**	**Cost (USD)**
Solar photovoltaic system	11	2’300,000
Wind energy system	40	6’500,000
Biomass system	2	1’600,000
Biofuels systems	1.5	1’500,000
Indirect costs	-	5’000,000
Equipment replacement	-	6’000,000
Transportation	-	5’500,000
TOTAL (USD)		28’400,000

Starting a planned energy transition process on the islands can be a momentous step. Firstly, following the Constitution and the Law of the Ecuadorian Electric Sector Regime. It is observed that around 8.3 MW of renewable energy can start being part of the transformation in the Islands, while around 6.5 MW can be reduced in thermal capacity. Once the energy transition is underway by 2040, it is possible to reduce 13.5 MW and increase 17.3 MW according to measured growth in demand, for which t ordinances must be carried out to limit the increase in demand population of these islands to avoid disorders and alterations in both energy and land use planning. By 2050, which is the long-term planning, a 100% renewable energy system is expected where the four wind sources, solar PV, biomass and biofuels, are called to directly influence the production of renewable energy in the islands. It is expected that 28.5 MW will be required to supply the demand of the islands under an energy storage scheme using batteries. Acceptable energy production levels for 2050 are shown in Fig 8 and consist of 39.9 MWh. The country and its territorial constituencies are responsible for meeting these social requirements by promoting the use of clean energy. According to the constitution of the republic, nature is endowed with rights. Figure 10 shows that the Puná and Mondragón islands are a substantial base for producing wind energy due to their much more constant and stronger wind currents. They are even much firmer islands to be located with wind generators of considerable sizes. Combinations between wind and solar photovoltaic are presented for the different islands, taking great advantage of PV solar energy; in reality, the two sources will be the basis for the islands' transformation without neglecting the importance of other sources such as biomass and biofuels.

Another vital part of the designed system is storing of energy through batteries. Figure 11 shows that the more days of storage the energy design contains, the more expensive the energy value tends to be. It should be noted that the value in $/kWh expressed in each curve with wind power/Total Production power ratio tends to be higher than the reference value in Ecuador, which is approximately 9 cents on the dollar. However, it must be recognized that the analysis of this study does not include subsidies. Nevertheless, it is very favorable concerning the benefits achieved in regular mangrove harvesting activities. It can also be noted that achieving a 100% renewable system would guarantee the protection of fragile ecosystems on the seven islands. Tourism could also be an industry that could take off notably in the future, similar to the Galapagos Islands.

4. Analysis and Discussion

The study was conducted with the assistance of the EnergyPLAN tool in a smart energy structure aligned with land use plans. These elements were considered to design the pathway towards a 100% renewable transition, inherently more environmentally friendly. After analyzing the results, it is concluded that the energy mix for 2050 can consider mainly 49.12% wind energy and 38.59% solar photovoltaic, complemented by a smaller proportion of 7.02% biomass and 5.26% biofuels, thus achieving 100% renewable energy in the islands of Guayas. The cost of implementing this energy system in the islands amounts to US$28,400,000, which is still low compared to the disasters that can occur from the indiscriminate use of fossil fuels. This study is the first to be analyzed on the Ecuadorian coasts to achieve an orderly transition, as intended by Ecuador.

Those responsible for making decisions should integrate several sectors, including: The central government exercising the greatest leadership and managing economic resources, the Academy with advice and research, the National Assembly supporting the laws, the business sector executing the projects, the salesperson providing the most appropriate and high-quality offers. Participatory decision making is the most appropriate and avoids imbalances that can range from technological, economic, environmental or social. This study can be considered as a reference and discussed before committing economic resources to carry out the energy transition processes on these islands.

The financing of projects in Ecuador has been challenging due to its lack of internal investment and economic liquidity. However, since these are long-term projects, it is possible to plan with a certain margin of uncertainty due to various situations, such as the variation in technology costs. The closestconnection between financing programs and the electricity public service law could lead to lower financing costs and also make the implementation of renewable energy projects more attractive. The task is undoubtedly arduous for Ecuadorian decision-makers, who in their profiles, must remain free of links to project providers in terms of goods and services to avoid conflicts of interest. The granting of loans by international organizations is a good option. However, the conditions must be established based on the lowest interest rates, and the management must be in charge of Ecuador to avoid forcing external conditions. There is frequent interest in financing this type of project, especially by development banks within the framework of a financing program. As long as there are clear regulatory conditions, once the roadmap is clear, the execution routes can be undertaken under the scheme presented in Fig. 12. The participation of new renewable energy generation plants would make the Ecuadorian economy more attractive and dynamic.

Fig 12. The simplified regime for the financing of renewable power plants.

As in the Galapagos islands, a regulated demand on the islands has been considered to prevent overpopulation in these sensitive sites. Currently, a national regulation aims to protect marine ecosystems, avoiding human interventions in these vulnerable areas. Therefore, there is a limit on the electricity demand projected for 2050, estimated at approximately 18,000 inhabitants, according to the National Planning Secretariat.There should be no shortages based on projections considering energy potential and backup systems; instead, there is potential for increased energy consumption. Future research may involve exploring floating solar photovoltaic systems. Additionally, interconnections between islands are specified to maintain energy availability among them. Implementing policies centered aroung Demand Side Management (DSM) is recommended. For instance, the RENOVA Plan should achieve a more significant impact on the population; incentives should also be created to discourage disproportionate consumption during peak hours, mitigating the repercussions of excessive consumption on the entire electricity system.

On October 27, 2024, the Organic Law to promote private initiative in energy generation was approved, classified as urgent in economic matters. This Law aims to promote economic solutions and renewable energy generation in order to overcome the energy crisis that has greatly affected the country due to prolonged droughts. It has been called to optimize the use of public resources associated with the electricity sector and incentivize private investment throughout the national territory, prioritizing the diversification of the energy matrix to achieve a sustainable and resilient transition. This Law opens a range of possibilities to exploit clean energies in which this study, like many others, can be put into practice for the benefit of society.

Diana D'Agostino et al.[101] in their study emphasizes the importance of achieving a new robust decision-making framework when exposed to conflicting interests of stakeholders. The importance of seeking the highest performance from different alternatives, including thermal insulation, is discussed, and decision-making should not be superficial. The comparative analysis of the interested parties shows that the global rankings obtained for the different decision-makers show some similarities, but also significant deviations, and a fully compromise solution is not achieved. In this sense, decision-making between the public and private sectors should be as consensual as possible, knowing these scientifically proven repercussions. The focus should always be on ensuring that the energy transition processes experienced by the different territories are orderly. The case study analyzed should be considered of special interest, as is that of the Galapagos Archipelago.

5. Conclusions

This study presents essential details of the roadmap for the transformation of the electrical system of seven islands in the Gulf of Guayaquil located in the Province of Guayas, which is currently based on thermal energy in high proportions, and a roadmap toward 100% renewable energy is proposed for 2050. It is reasonable that one thing is to design an energy system with fiscal liquidity, and another is when there are not enough resources and that often there are other priorities such as food subsistence or covering health demands in the public sector. Under this perspective and awareness of the situation that Ecuador and the islands under study are experiencing, a flexible and adaptable roadmap is provided if it must not neglect the energy transition. For this design, the strengths of EnergyPLAN as a highly reliable tool have provided the general guidelines for this radical change in the energy structure to 100% renewable. Not only is the study there, but a financing mechanism was also presented and not only remains in a proposal but is launched from the Ecuadorian spheres of decision. It can even support new studies at the island level in other parts of the world seeking to transform their energy systems. The proposed design references abandoning the dependence on thermal energy and being the second island-level project in Ecuador after Galapagos entrusts its energy system to renewable energies, avoiding affecting health of people, and the production processes are more friendly to the environment.

The scenario outlined for the group of islands is to become a pole of economic development in the Gulf of Guayaquil, serving as a reference for other countries or regions where there are islands. The extractable energy can be used in these proportions to which it has been made known, it can even be used to a much greater extent, but it has been avoided since it seeks to supply energy in a measured but sufficient way to cover the electricity demand. A Territorial Planning Plan for Guayas must be updated and incorporate these aspects that integrate energy sustainability and sustainability for all its territories, especially for these islands that are fragile ecosystems and need the protection of all those who are immersed in the productive part and particularly energetic. It should be noted that political aspects are not included in this study. Technical, legal and economic conditions are assumed to be adequately channeled and achieve success over time. As in other development projects in Ecuador, it is important to socialize these proposals to the majority of the population involved with direct communication channels to avoid errors in the information disseminated.

The Electricity Master Plan (PME) 2018-2027 is not being fulfilled, so a “road map” with a medium and long-term vision must be proposed, including legislative measures and corrective actions. An incentive policy is also important to increase the use of alternative sources such as wind and solar photovoltaic plants, providing legal security for investors who identify business opportunities in the electricity sector in the Ecuadorian coastal region. In future work, it is recommended that researchers conduct studies on implementing floating solar panels in the vicinity of the islands of Guayas and investigate their potential long-term impacts.

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