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Smart energy transition with the inclusion of floating wind energy in existing hydroelectric reservoirs with a view to 2050. Ecuadorian case study

Daniel Icaza-Alvarez(1,2)*, Francisco Jurado(1) and Marcos Tostado-Véliz(1)

(1) Department of Electrical Engineering
University of Jaen
Linares, SPAIN

(2) Department of Electrical Engineering
GIRVyP Group
Catholic University of Cuenca
Cuenca, ECUADOR

* Corresponding author: dicazaa@ucacue.edu.ec (Daniel Icaza)

Abstract

Ecuador promotes an energy matrix with zero net emissions by 2050, knowing that hydroelectric power from a reservoir has been fundamental in the electrical system. The reservoirs comprise large unused areas, in many of these sites there are interesting wind speeds thanks to the wind tunnels that are formed between hill and hill and can be used by installing floating wind turbines. This research presents an alternative to increase the driving actions of Ecuador to structure its 100% renewable energy system in a diversified way. For this reason, the resulting impact is analyzed by including Floating Wind Power (FWP) systems and four points of interest are analyzed in this study: Mazar, Coca Codo Sinclair, Manduriacu and Delsitanisagua. The energy mix is evaluated using EnergyPLAN software, a specialized tool to evaluate diversified smart systems of completely renewable electricity in the long term. This study is novel, breaks the traditional schemes in Ecuador and provides a different vision for decision makers, such as investors, legislators and researchers to discuss before committing economic resources. The results show that in 2050 floating wind energy would be contributing 11.13% of the total electricity in Ecuador and 16.27% of the wind component. Interpreting these values, the floating wind component may be significant and would further diversify energy production in this South American country.

Keywords: Floating Wind Turbines; Energy Planning; Wind energy; Smart energy

Nomenclature

APEC	Asia-Pacific Economic Cooperation
FOWP	Floating offshore wind power
FWT	Floating wind turbine
GEP	Generation expansion planning
GHG	Greenhouse gases
IEA	International Energy Agency
NCRE	Non-conventional renewable energies
O&M	Operation and maintenance
OSeMOSYS	Open Source Energy Modeling System
PEG	Planning of the Expansion of Generation
RE	Renewable energy
RES	Renewable energy sources
Temoa	Tools for Energy Model Optimization and Analysis
TLP	Tension leg platforms
WT	Wind turbine

1. Introduction

In recent years, there has been a growing global agreement to combat global warming and minimize GHG (greenhouse gases) emissions. A sample case is Hong Kong, which has set itself the goal of achieving a reduction in energy magnitude of at least 25% by 2030, which corresponds to the objective of APEC (Asia-Pacific Economic Cooperation) [1].
To reach the goal of zero emissions by 2050, a large increase in renewable energy is necessary to supply demand in sectors such as transport and industry. About 80% of global offshore wind resources are located in waters deeper than 60 m, where bottom-mounted wind turbines have high complexity when anchored. This creates a fundamental possibility to continue studying ways to couple floating offshore wind energy at depths less than 60m to continue with energy transition processes [2].
Floating wind technology is being developed more and more with the purpose of taking advantage of the widely available physical space at sea level, lagoons, gulfs or reservoirs and taking advantage of existing wind currents in sectors with a high concentration of wind resulting from the formation of tunnels of wind [3] during several hours of the day, capable of moving the blades of wind turbines that exceed 3 m/s. The designs of these machines have been moving towards a higher power per unit. Projects in various countries of the world, scheduled for construction over the next 5 years already include wind farms with Floating Wind Turbines (FWT) from 8 to 13 MW [4], while wind turbines with a nominal power of 14 MW and 16 MW are reaching commercial maturity [5].

The literature will later show that there are different models of energy planning and define long-term scenarios that include proportions of wind energy within the energy mix with variable renewable energies. However, there is rarely a study that focuses on capacity planning for a 100% renewable energy system that includes floating wind energy in reservoirs in a disaggregated way to kick-start energy transition processes. In this manuscript the guidelines are given to carry out a systematic process of inclusion of floating wind energy in reservoirs where hydroelectric generation is also intended and that under this scheme hybrid systems can very well be formed with connection to the main trunk of a country or region. The methodology that is detailed later and that is supported by EnergyPLAN as long-term planning software, will determine the long-term scenario. is required to be address the contributions of floating wind as well as solar PV and hydro which typically lend themselves to introducing higher energy proportions to the overall mix. The different technologies can be complemented very well with floating wind power in a flexible way so that in this way they can contribute with less energy from fossil fuels and achieve a 100% renewable system by 2050.

1.1. Context and motivation.

In Ecuador there are hydroelectric generation plants by reservoirs precisely in the inter-Andean and Amazon region where the winds are considered quite good [6], which is why it is intended that these places can take advantage of using other types of renewable energy such as in this case wind energy. This type of technology is constantly developing, however it is not entirely new since in various parts of the world they are a reality and a real contribution. It seeks to take advantage of these areas for their availability, it is even possible to form hybrid systems between wind and hydroelectric in different reservoirs in the country. Another action to consider in this type of study is to locate the wind turbines properly, maintaining sufficient distance between one and the other for proper long-term operation. The energy supplied is 100% renewable and contributes to the protection of the environment. On the other hand, it stimulates a responsible economy and opens options for the creation of new sources of work. From this perspective, it is motivating that a country like Ecuador can take advantage of this type of technology for its decarbonization processes and achieve the long-awaited zero fossil fuels by

2050 with the increase in renewable energies in accordance with the current National Development Plan.

Diversified energy systems are the most suitable option to not depend on exclusive sources, this type of technologies that are combined with hydroelectric energy and others such as photovoltaic solar energy can very well be used, they have been widely addressed in the last decade. One of the benefits of these systems is the greater access that hydroelectric plants allow to the network. This concept transmits flexibility to adjust to the needs of the consumer.

2. Methodology

In the present investigation, the impact of the FWT within the Ecuadorian energy mix is presented, for which 4 specific analysis sites are considered, including the reservoirs of the Mazar, Coca Codo Sinclair, Manduriacu and Delsitanisagua hydroelectric plants located in Ecuador after an analysis of the wind potential in these sites. This study allows to be a contribution to include a new technology in Ecuador and to diversify the energy mix with contributions of electricity that are friendly to the environment. For this transition to be effective, the methodology considers, after its respective analysis, the availability of resources for the incorporation of these new renewable technologies and subsequently evaluates the impacts.

In the methodological analysis, three phases can be identified: The first is the data entry phase of the available renewable energy resources and the data on fossil fuels used. The second adjustment phase with the contribution of the EnergyPLAN software. It is necessary to indicate that for the adjustment phase, aspects that need to be taken into account are included and can directly influence the energy transition process as drivers or barriers, these aspects are: Political, economic, technical and social as presented in Fig 1. The parameters to be considered are explained below:

- Policy: This environment deals with different government regulations and policies to facilitate power generation from different RES.

- Economic: Analyzes the impact of collaborations on the energy grid, that is, how the supply chain influences the levelized costs of electricity.

- Technical: This part includes geographic aspects such as the average wind speed, which determine the generation capacity, the function of the infrastructures and the technological potential.

- Social: It deals with the interaction of the general public with the development of RE, and starts from the commitment of suppliers, for reasons of income, to the acceptance of consumers, taking into account issues such as the degradation of environment.

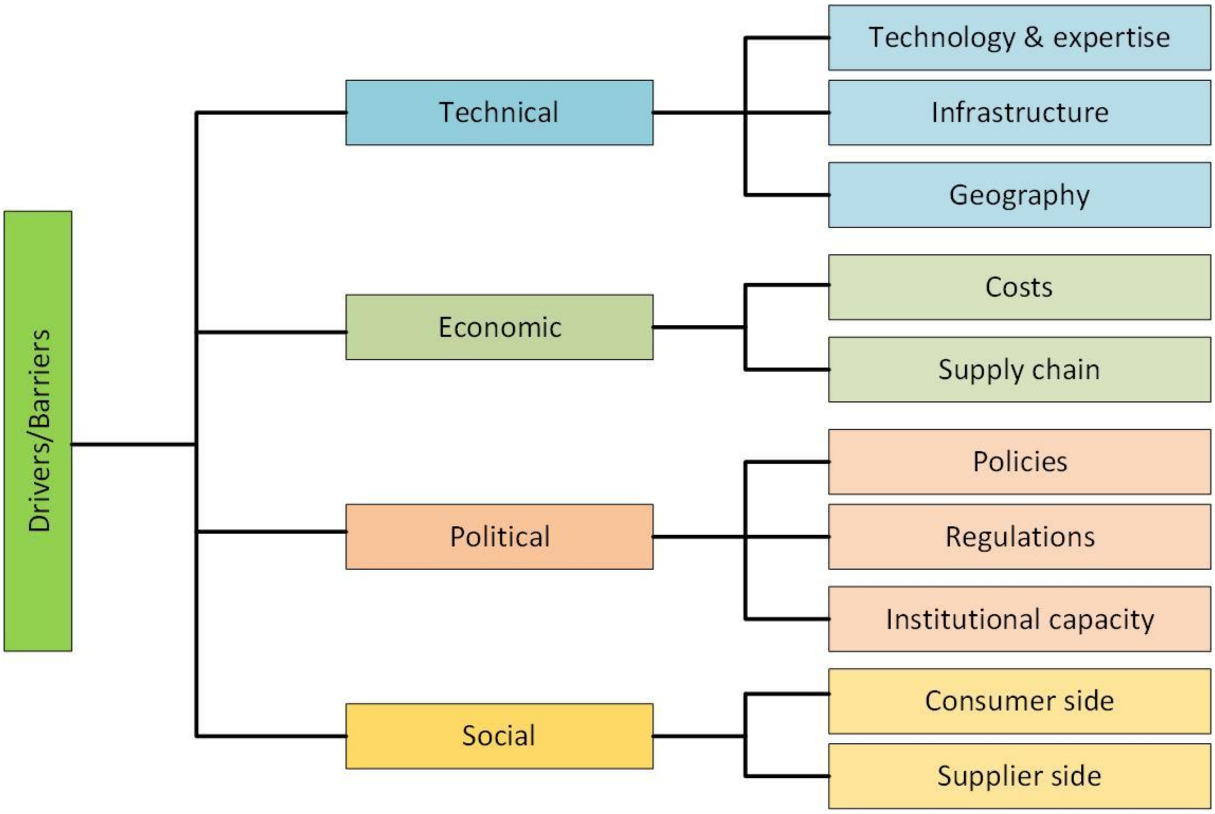


Fig 1. Framework for analysis of drivers and barriers to FWT [7].

Finally, in the third phase, the results are presented considering the inclusion of floating wind technology.

2.1. EnergyPLAN model.

EnergyPLAN is a platform that has been developed at the University of Aalborg, it emerged as version 6.0 in January 2004, progressively new functionalities have been incorporated and currently this tool is widely used worldwide, 15 versions have passed until reaching the version 16.2 currently available at [8]. EnergyPLAN is inspired by the concept of smart energy systems, giving rise to countless market investigations that seek an orderly and long-term energy transition, among the most recent studies [9–13] stand out. The main structure of the model is presented in Fig. 2. The software performs feasibility studies, transition analysis, market research for peer-to-peer energy exchange, among others. The challenge of progressively integrating variable energy based on RE is a policy of the Ecuadorian state, this implies previous studies and basically in this study the feasibility of including floating wind energy is presented and the impact that would be achieved in 2050 within the energy mix. In the end, as results, long-term energy scenarios are obtained, the production components of the complete renewable energy system are detailed.

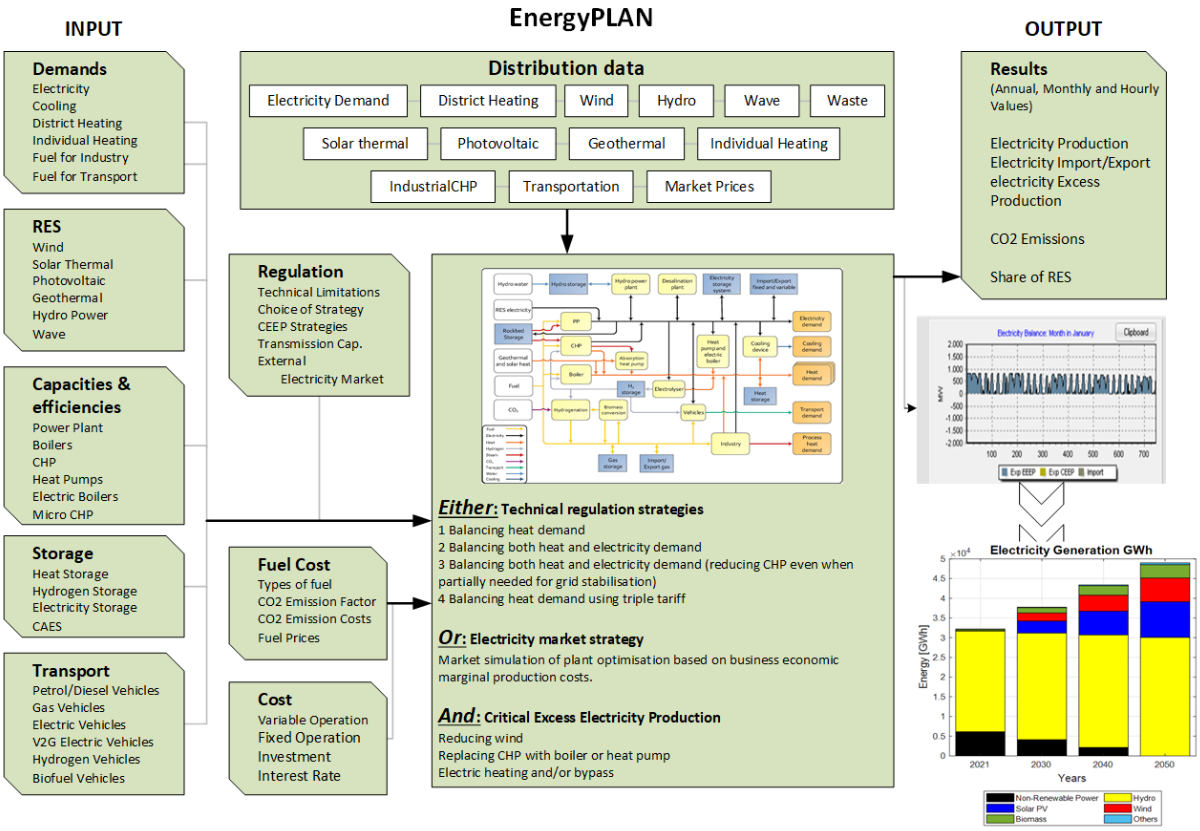


Fig 2. EnergyPLAN data inputs and outputs. Adapted from [14].

The conceptual scheme of EnergyPLAN has been applied in this study referring to the exposed Ecuadorian case. It can be seen in Fig. 3, a temporal structure with time jumps every 10 years with a view to 2050. The EnergyPLAN tool is used as a support to systematically evaluate the configuration of the energy system at each time step. It adopts a bottom-up static simulation approach that involves all energy sectors: cooling and heating, electricity, and transportation. EnergyPLAN is able to perform hourly energy balances in the examined system, on an hourly structure related to the availability of renewable energy sources (RES) and energy requests. A dispatch priority system ensures that the RESs are used based on demand requirements by remaining accessible in the evaluated time slot [15].

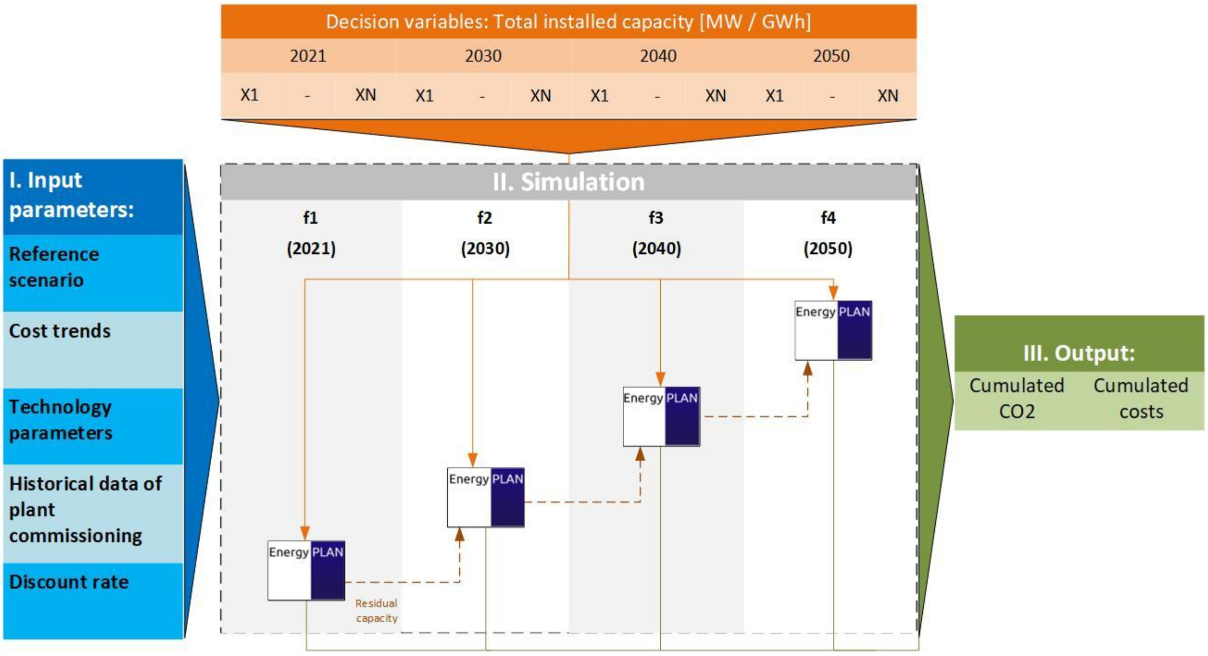


Fig 3. Analysis process in long-term scenarios with EnergyPLAN.

The scientific methodology is organized: The first section contains the introduction, in section 2 the methodology used in this study. In section 3 a review of the literature is carried out. Section 4 presents the mathematical model and the use of EnergyPLAN to carry out the design of the scenario to 2050. The results are presented in section 5. Section 6 discusses the results obtained. Finally, in section 7 the conclusions are presented.

3. Literature review

One of the most debated issues in the world and among those responsible for the energy sector is the Planning of the Expansion of Generation (PEG). The inclusion of renewable energy sources (RES) in the overall energy mix is closely related to the integration of these energies in the electricity sector, since currently RES applications are not as competitive with respect to other energy subsectors. EnergyPLAN is a tool that allows analyzing energy systems, created to encourage research and provide future sustainable energy developments, especially oriented towards energy systems with renewable energy sources. In the same way, it is possible to analyze the conversion of renewable energy into other energy vectors (hydrogen, heat, green gases); as well as the execution of policies to implement energy efficiency actions [16].

In 2020, the European Commission in its Offshore Renewable Energy Strategy has made a publication indicating that Floating Offshore Wind Power (FOWP) is a sector that is rapidly evolving with the aim of becoming a key market factor in the coming years [17]. Due to the increase in the world's offshore wind power generation capacity, wind turbines with large power production capacity are being used. For example, the new offshore wind turbine of the International Energy Agency (IEA) has a capacity of up to 15 MW and a total weight of 2,319 tons [18]. At present, countries are beginning to include in their electricity systems a greater number of floating wind farms that are in operation, it is expected that new projects will be developed around the world in the future [7].

For example, in Mexico, wind power is one of the most promising renewable energy sources. The results show wind power densities of 250–400 Wm−2 for most locations in the Gulf of Mexico and the Caribbean, while most locations in the Pacific Ocean have wind power densities of less than 250 Wm−2. This is because they have abundant wind resources [19].

On the other hand, Germany has established ambitious policies to increase the use of RE and thus abandon nuclear energy. Although there are still scientific gaps in relation to how this transition will develop, particularly by including all energy sectors. With the studies carried out, they seek to advance in the knowledge of the transition of the German energy system to a 100% renewable energy with a vision of 2050 [20].

Operations and installations in floating offshore wind turbines are complex actions due to the accessibility of the site and the availability of equipment [21]. In this regard, several countries have considered including FWT at strategic points where there are transportable access roads or accesses can be built [22]. Reason to promote the development of floating wind farms in wide rivers, lakes or dams that allow them to be better used to contribute to the purpose of decarbonizing local or national energy systems [23].

W Shi et al. [24] performed a fully coupled time-domain analysis of three different semi-submersible floating offshore wind turbines (semi-FOWT). The impact of second-order wave hydrodynamic loads combined with aerodynamic loads on normal and extreme dynamic responses was investigated. Three water depths (50, 100 and 200 m) were considered. The simulation results showed that second-order hydrodynamic loads play an important role in motion and structural responses in extreme marine conditions. Meanwhile, aerodynamic loads significantly affect the dynamic responses of all semi-FOWTs under normal operating conditions. Wave and pitch motions decrease as water depth increases. Tower base loads tend to be lower for deep water, while mooring line stresses are the opposite. These findings will surely benefit the floating wind turbine industries for further promotion and commercialization and consequently be a key element to speed up energy transition processes. Weiyu Yuan et al. [25] conducted a life cycle assessment of the environmental impacts of floating wind power in deepwater areas. The results showed that the carbon footprint of the floating wind farm was 25.76 g CO2-eq/kWh, which was relatively low in terms of global warming potential. Xing Chen et al. [26] tested a floating wind turbine model in an integrated wind and wave environment. They developed an innovative turbine system with a modular design philosophy to improve the spatial and temporal quality and the controllability of the generated wind fields. Stationary/dynamic and uniform/non-uniform wind fields were reproduced, with wind speeds ranging from 0 to 12 m/s. The FWT dynamic performances agreed well with those expected from the numerical simulation, demonstrating that floating wind systems may technically prove essential in the future to take advantage of currently unused aquatic spaces.

Xinbao Wang et al. [3] presented a new similarity criterion and design method for wind tunnel model testing of floating wind turbines. The authors consider that these technologies have received great attention in recent years and numerous experimental studies have been carried out on them and will be of great interest to take advantage of aquatic sites and become another of the essential elements in the decarbonization plans of the countries. In their research, they delved into a new criterion for wind tunnel model testing based on mapping the optimal top speed ratio (TSR) and relative TSR rate-of-change similarity. One factor to take into account is the influence that the structural movement exerts on the people who carry out maintenance activities and its implications for personal safety, since it can be conceived as a hostile environment [27]. Extensive simulation studies on structural movement have been carried out in order to assess whether work on floating wind turbines may be compromised. In reality, the conditions may be somewhat different from activities carried out in wind turbines installed on land. However, they do not imply high risks, but qualified personnel should be considered to carry out activities such as maintenance of floating wind turbines. Focusing on the financial sector, the potential losses that materialize due to some turbine failure may be somewhat higher compared to mainland turbines [28].

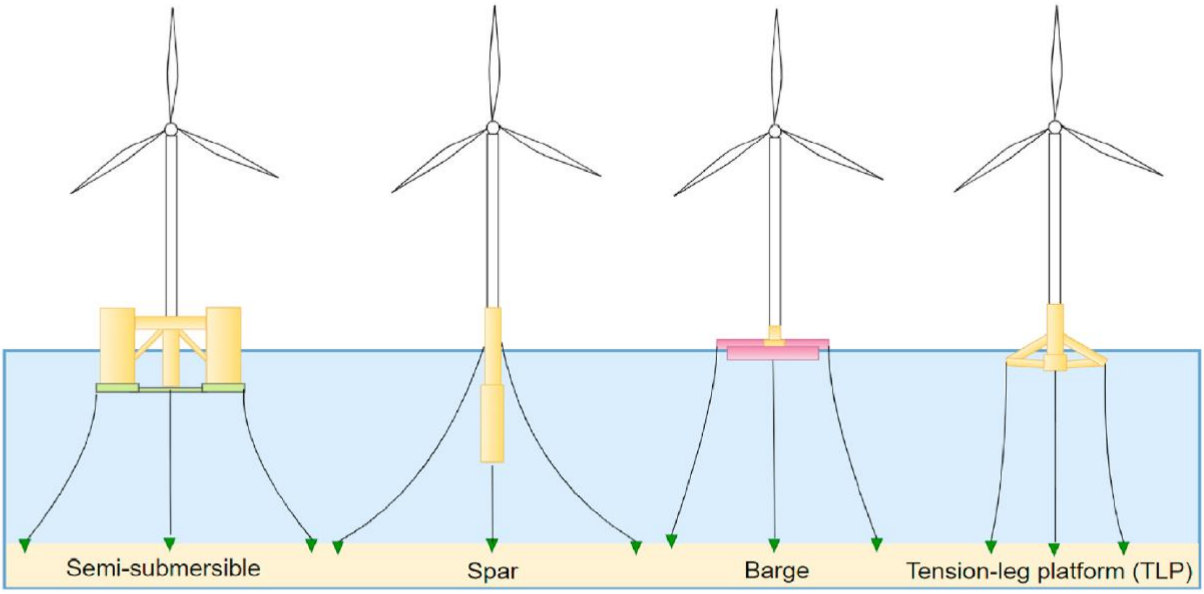


Fig 4. Design classes for floating wind turbine substructures.

In most cases, outrigger substructures are quite insensitive to wave excitation or one-way water circulation, but thanks to their small water plane area (hydrodynamically transparent structure) subjectively small movements are detected. The semi-submersible is stabilized to some extent by the ballast and to some extent by the water plane area. The barge terminus stabilizes primarily in the plane of the water; a mechanism comparable to that of a ship. In addition, the barges can be equipped with resources that increase damping and decrease movements such as a moon pool or wave plates [29]. Tension Leg Platforms (TLPs) remain stabilized by a tendon system, with tensioned vertical synthetic, steel wire or tubular steel tendons connected to anchors fixed to the seabed [30].

For some time now, the combined energy of wind and waves has been a hot topic in this field. C Pérez-Collazo et al. [31] highlighted the option of integrating offshore wind and wave energy during the past decade. In this study, the hybrid system was classified based on the degree of integration between the technologies and the type of substructure to improve efficiency in energy conversion. In Oceania several investigations have been carried out with hybrid systems. Australia has been studied by Qiang Gao et al. [32], the characteristics and potential of wind and wave energy for hybrid energy exploration were evaluated. In his comprehensive review he states that assessments of wind and wave resources have been developed separately in Australia, and the potential for diversified wind and wave energy has not been systematically explored. Mixed wind and wave energy farms are analyzed in this study using commercial models of wind turbines and various prototype models of wave energy converters. Power availability, capacity factor, idle time, and power leveling effect on these mixed power farms are also discussed [33].

Christina Kalogeri et al [34] also conducted the European offshore wind and wave energy resource assessment for their combined exploitation. The wind and wave fields in open sea areas reveal the lowest correlation in the field examined in contrast to those located in semi-closed and closed basins that exhibit the highest. In their results it is noted that the adequate energy conversion system for a specific area depends to a great extent on the local characteristics of the available resource. It is very attractive to take advantage of large areas for the production of wind energy, which is the one that can be generated in the greatest proportion. Fulya Islek and Yalcin Yuksel [35] conducted an assessment of wind power potential and its projected changes in the Black Sea to identify possible stable locations for wind farms. The temporal variability of wind power density (WPD) was investigated by spatial and local analyzes for the future period (2021-2100). For more predictable future developments of wind power potential, 15 benchmarks along the Black Sea were mapped using intra- and inter-annual variability.

Derrick Kwadwo Danso et al. [36] analyzed the possibilities of generating energy in open fields and for this, it evaluated the possibilities of generation through wind and photovoltaic solar energy. Their study took place in the Akosombo Reservoir, Ghana. Additionally, the flexibility of hydropower to integrate solar and wind power in West Africa was assessed using dynamic programming and sensitivity analysis. The flexibility of hydroelectric plants with large reservoirs is beginning to be taken advantage of and is a reason to integrate large proportions of variable and intermittent renewable energy sources into electrical systems. In this study, we assessed the flexibility that large hydroelectric dams in West Africa could provide to cope with future planned solar and wind power generation in the region.

Ammar Alkhalidi et al. [37] studied carefully the installation of cantilever wind turbines to harvest accelerated wind in hydroelectric dams (floating hybrid PV – Wind system). This development was carried out in the face of the lack of fossil fuel that led to the search for unique innovations to produce renewable energy in Jordan. Large bodies of water, such as dams, provide the opportunity to use both solar and wind energy for this purpose. The Wadi Al Mujib dam located in Jordan was chosen as the location for this study. Cantilevered wind turbines hanging horizontally facing the dry side of the dam combined with floating photovoltaics were found to be capable of producing up to three GWh per year. In particular, on the water dam side, there is a significant amount of space available to build a wind farm, especially since this area is located between two mountains, which creates a wind tunnel effect that increases wind speed and unifies the direction of the wind [38].

Since 2018, the nominal power in Ecuador has been 8,676.89 MW; of which, 60.75%, that is, 5,271.74 MW correspond to power plants with renewable energy sources, while both thermal power plants correspond to 39.24% (3,405.14 MW). The renewable energy sources that the country used to generate electricity in 2018 were: hydraulic, biomass, photovoltaic, wind and biogas [39].

Next, the sites where there are hydroelectric plants with reservoirs and that have a power greater than 50MW and their reservoir is large enough were defined. In addition, they have significant wind speeds with the capacity to generate energy taking advantage of the enbalces, for this purpose it was based on the wind atlas of Ecuador. Although most of the projects in Ecuador take advantage of the hill effect, it is also possible to take advantage of the wind tunnels available in the hydrographic basins, specifically in the inter-Andean or Amazon region. For this case study, the four sites specified in Fig 5 were determined for floating wind generation purposes.

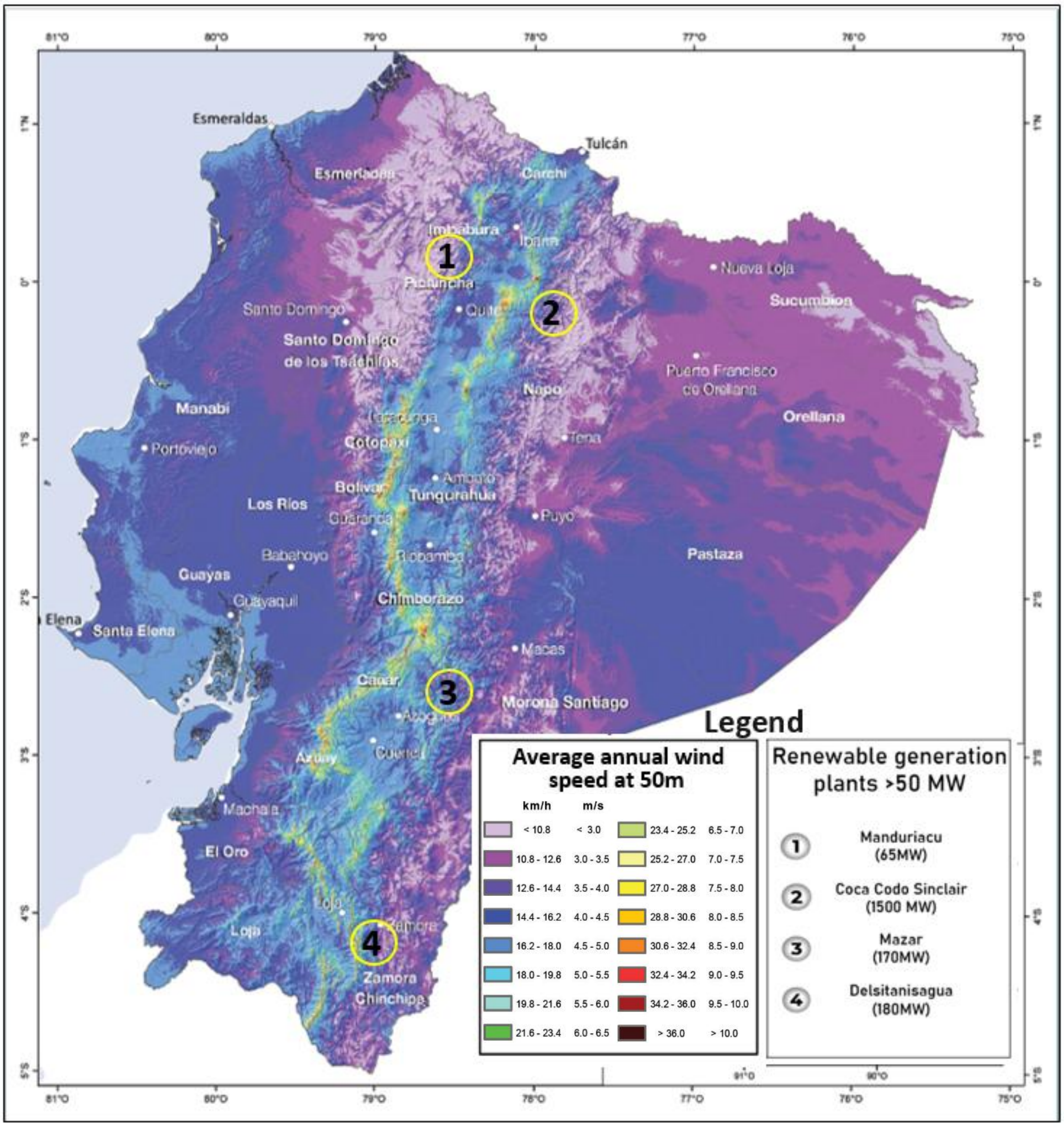


Fig 5. Sites determined for the implementation of floating wind energy

4. Mathematical model

To execute EnergyPLAN software for each period of time considered and defined the proposed time horizon. The software in the first instance collects all the input data, for this reason the EnergyPLAN reference scenario is defined, which represents the base energy system for the development of the energy transition, and which contains the data on the installed power capacities, the relationships of power from renewable and non-renewable sources, intermittent RES plants, efficiencies, among others.

This phase takes the input information and converts it to arrays that include the parameters of the first period, a balance of capacity conservation is made, to calculate the investments in new capacity jump by jump of time. Equation (1) is a representation of the classical formulation of the capacity conservation constraint, as recognized in most long-term bottom-up models, such as OSeMOSYS [40], TIMES [41] and Temoa [42].

$$C_{t,k} = C_{t,k}^{new} + C_{t,k}^{res} + \sum_{t'=t-n_k}^{t} C_{t',k}^{new} \qquad (1)$$

The total installed capacity *C* referring to technology *k* in time step *t* is the sum of the new capacity $C_{t,k}^{new}$, installed in that time step, residual capacity $C_{t,k}^{res}$, which represents the capacity available at the beginning of the time horizon and which continues to operate in the time step *t*, is an exogenous parameter. The new capacity installed in the previous steps that continues to operate in the time step *t*, that is, whose life cycle *n* is greater than the difference between *t* and its installation period *t'*.

Running EnergyPLAN calculates the annual operation and maintenance (O&M) costs and CO₂ with the modified baseline scenario according to the input data related to the current period. In addition, the investment costs are calculated in relation to the current period in order to later show the installed power and electricity generation capacities. Equation (2) evaluates the costs of the period under analysis.

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

Where;

$INV_{t,k}$ are the investment costs for the new capacity of technology *k* added in *t*. $O\&M_t$ are the operation and maintenance costs (variable and fixed) of the entire power system in the time step *t*, Annual costs of $O\&M_t$ of the entire energy system are provided at any step by EnergyPLAN. To multiply the anual costs by the number of years *Y* in the time step, the following equation is applied, where *y* is the generic year in the time step and *r* is the discount rate:

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

The equation (4) shows how the insvestment costs $INV_{t,k}$ for technology *k* in time step *t* are calculated as the product of the new capacity $C_{t,k}^{new}$, by the costs of specific investment given as model input. As far as investment costs are concerned, these are considered balloon payments: the full cost of the investment is paid in the first year of the installation period.

$$INV_{t,k} = inv_{t,k} * C_{t,k}^{new} \tag{4}$$

The drawback of using investment costs at a high rate consists of an intrinsic penalty for facilities close to the end of the time horizon. In this case, to avoid such a penalty, a salvage value has been introduced. To determine said value, a linear depreciation of any asset *k* has been assumed. The residual value of *k* decreasing at a constant rate over time, starting from an initial value equal to the investment cost $INV_{t,k}$ at the beginning of the life cycle and a residual value equal to a *R* parameter at the end the cycle of life. The *R* parameter includes the parts of the investment that do not replace the end-of-life replacement. To simplify the application of the model to Ecuador, a value of *R = 0* has been assumed. The concept is presented through the eq (5):

$$Salvage_{t,k} = INV_{t,k} * \left[1 - \frac{T - t}{n_k}\right] \tag{5}$$

The recovery value obtained is referred to the time step t in the sense that it is related to the capacity of the technology k installed in said time step. To evaluate the new installed capacity that is in accordance with the decarbonization process linked to the CO₂ emissions of the period, EnergyPLAN multiplies by the number of years of period Y, as observed in eq. (6):

$$CO_{2t} = CO_{2y} * Y \tag{6}$$

Then, all the costs and emissions of the period are integrated to calculate their accumulated values, taking into account the entire time horizon. The accumulated costs are equal to the sum of all the costs of the period, duly discounted, less the recovery value at the end of the simulation, discounted at the end of the last time step, as shown in equations (7) and (8). Equation 9 shows that cumulative CO_2 emissions can be calculated simply by adding the emissions in all time steps.

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

$$Salvage_{k} = \sum_{t=T+1-n_{k}}^{T} Salvage_{t,k} \tag{8}$$

$$CO_{2cum} = \sum_{t=1}^{T} CO_{2t} \tag{9}$$

Subsequently, the power capacity needed to be installed in the long term and achieve zero emissions can be determined. The tool in this case takes up equation 1 and evaluates in the specified time step.

5. Evaluation of the base year (2021) of the Ecuadorian electrical system

By 2021, the generation capacity at the national level was registered at 8,734.41 MW of nominal power and 8,100.68 MW of effective power, as shown in Table 2.

Table 1. Detailed installed power by source.

	Installed Power in Generation				Production and Imports			
					Total		Only SIN	
Electric Power	**Nominal Power MW**	**%**	**Effective Power MW**	**%**	**GWh 32,558.72**	**% 100.00%**	**GWh 28,525.34**	**% 100.00%**
National (Renewable + Non Renewable)	**8,734.41**	**100.00%**	**8,100.68**	**100.00%**	**32,206.88**	**98.88%**	**28,173.50**	**98.73%**
Renovable	**5,308.27**	**60,77%**	**5,263.78**	**64.98%**	**26,088.42**	**80.10%**	**26,063.96**	**91.34%**
Hydraulic	5,106.85	58.47%	5,072.26	62.62%	25,574.61	78.52%	25,555.53	89.56%
Wind	21.15	0.24%	21.15	0.26%	62.01	0.19%	60.06	0.21%
Photovoltaic	27.65	0.32%	26.76	0.33%	36.87	0.11%	33.44	0.12%
Biomass	144.3	1.65%	136.4	1.68%	372.80	1.14%	372.80	1.31%
Biogas	8.32	0.10%	7.2	0.09%	42.13	0.13%	42.13	0.15%
Non Renewable	**3,426.14**	**39.23%**	**2,836.90**	**35.02%**	**6,118.46**	**18.78%**	**2,109.54**	**7.39%**
MCI	2,020.67	23.13%	1,614.85	19.93%	4,335.56	13.31%	671.95	2.35%
Turbogas	943.85	10.81%	790.55	9.76%	911.82	2.80%	594.53	2.08%
Turbosteam	461.63	5.29%	431.5	5.33%	871.07	2.67%	843.06	2.95%
Import	**650.00**	**100.00%**	**635.00**	**100.00%**	**363.80**	**1.12%**	**363.80**	**1.27%**
Colombia	540.00	83.08%	525.00	82.68%	363.80	1.12%	363.80	1.27%
Peru	110.00	16.92%	110.00	17.32%	0.00	0.00%	0.00	0.00%

In relation to the national nominal power, 5,308.27 MW (60.77%) correspond to plants with renewable energy sources and 3,426.14 MW (39.23%) to plants with non-renewable energy sources [32], see Fig 6.

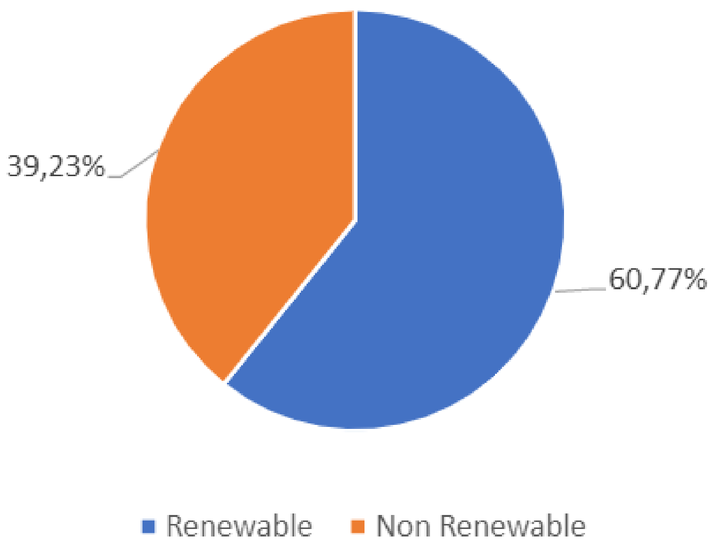


Fig 6. Percentage relationship between renewable and non-renewable energy of the Ecuadorian electrical system.

The national nominal power is divided into plants with renewable energy sources that correspond to 60.77% and plants with non-renewable energy sources that correspond to 39.23%, which will be analyzed in more depth below.

5.1. Renewable Energy Sources in the base year

The renewable energy sources used by the country to generate electricity were: hydraulic, biomass, photovoltaic, wind and biogas. Among these renewable sources, the most prevalent are hydroelectric plants with 5,106.85 MW (96.21%) [33].

Table 2. Installed capacity of generation plants with renewable energy sources in 2021 (MW)

Central	Province	Nominal Power (MW)	Effective Power (MW)
Biomass	Cañar	29.80	27.60
	Guayas	114.50	108.80
Total Biomass		**144.30**	**136.40**
Wind	Galapagos	4.65	4.65
	Loja	16.50	16.50
Total Wind		**21.15**	**21.15**
Hydraulic	Azuay	2,042.49	2,067.39
	Bolivar	8.00	8.00
	Cañar	32.33	32.33
	Carchi	5.82	5.14
	Chimborazo	16.33	16.04
	Cotopaxi	47.39	45.27
	Guayas	213.00	213.00
	Imbabura	75.45	76.61
	Los Rios	57.57	56.20

	Morona Santiago	138.01	137.52
	Napo	1,565.60	1,540.75
	Pichincha	152.85	150.55
	Sucumbios	64.30	64.30
	Tungurahua	505.30	476.76
	Zamora Chinchipe	182.40	182.40
Total Hydraulic		**5,106.84**	**5,072.26**
Solar Photovoltaic	Cotopaxi	2.00	2.00
	El Oro	5.99	5.99
	Galapagos	2.62	2.62
	Guayas	3.98	3.98
	Imbabura	4.00	3.99
	Loja	5.99	5.12
	Manabi	1.50	1.49
	Morona Santiago	0.37	0.37
	Pastaza	0.20	0.20
	Pichincha	1.00	1.00
Total Solar Photovoltaic		**27.65**	**26.76**
Biogas	Azuay	2.12	1.70
	Pichincha	6.20	5.50
Total Biogas		**8.32**	**7.20**

5.2. Non Renewable Energy Sources in the base year

These plants use fossil fuels (derived from oil and natural gas) as an energy source to generate electricity; By 2021, 3,426.14 MW of nominal power were registered nationwide. By 2021, the thermal power plants that use internal combustion engines (ICE) had a nominal power of 2,020.67 MW; followed by turbogas plants with 943.85 MW and turbosteam plants with 461.63 MW [33].

Tabla 3. Power of generation plants with non-renewable energy sources (MW)

Central	Province	Nominal Power (MW)	Effective Power (MW)
ICE	Cañar	19.20	17.20
	Esmeraldas	112.42	94.22
	Galapagos	24.29	21.14
	Guayas	40.37	36.43
	Imbabura	29.28	24.30
	Loja	19.74	17.17
	Los Rios	47.60	40.50
	Manabi	201.62	170.52
	Morona Santiago	4.50	4.00
	Napo	77.08	54.01
	Orellana	651.86	498.75
	Pastaza	61.10	50.97
	Pichincha	110.94	102.72
	Santa Elena	131.80	105.03
	Sucumbios	483.88	374.31
	Tungurahua	5.00	3.60

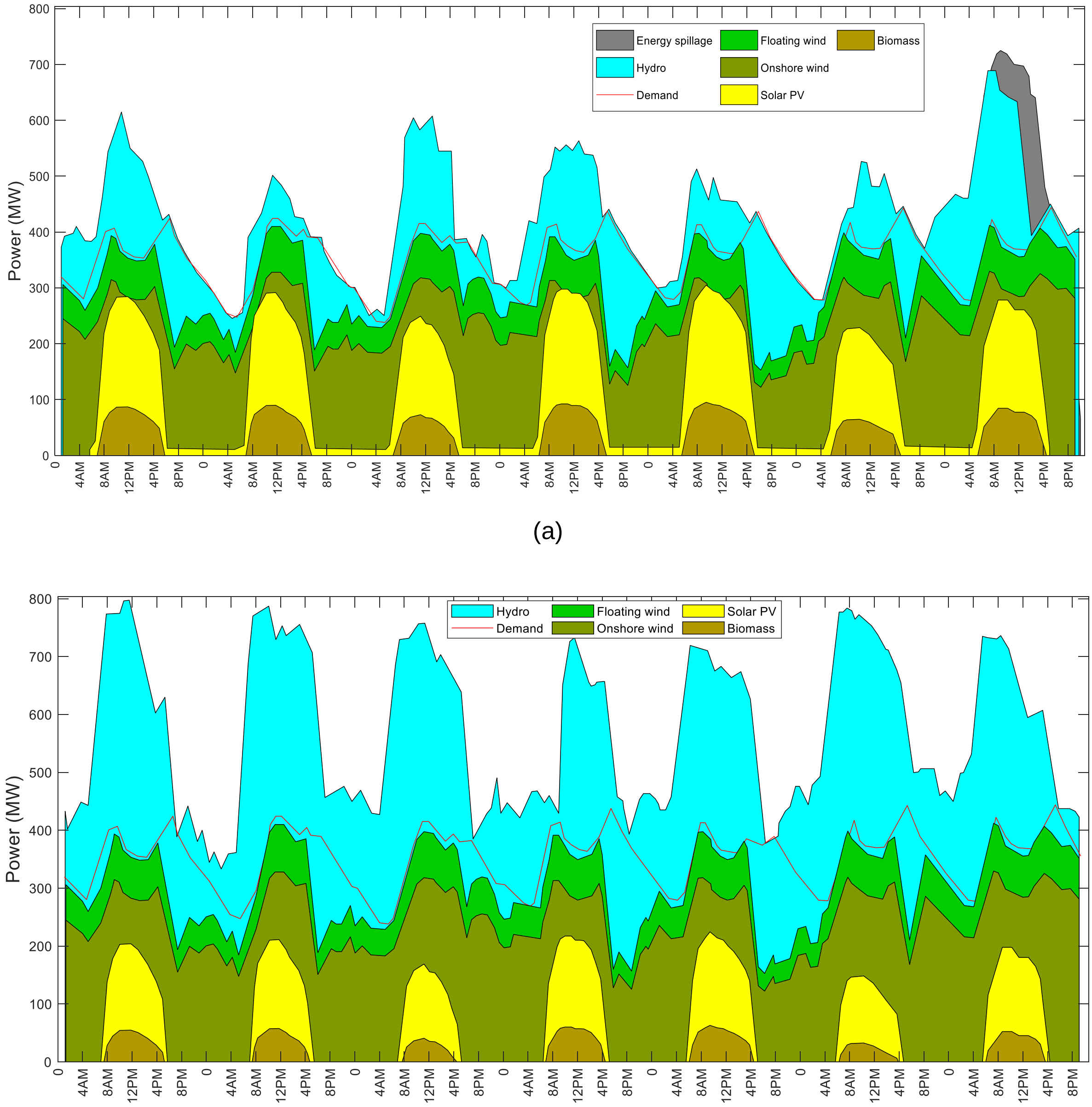
Total ICE		**2,020.68**	**1,614.87**
Turbogas	El Oro	275.36	249.6
	Guayas	451.34	379.00
	Manabi	22.00	19.00
	Orellana	77.00	57.2
	Pichincha	71.10	51.00
	Sucumbios	47.05	34.75
Total Turbogas		**943.85**	**790.55**
Turbosteam	Cañar	3.63	2.50
	Esmeraldas	132.50	125.00
	Guayas	313.50	293
	Orellana	12.00	11.00
Total Turbosteam		**461.63**	**431.50**
Total General		**3,426.16**	**2,836.92**

5.3. Scenario modeling and case study

Fig 7 shows the simulation in EnergyPLAN up to 2050. The typical behavior by month and year accumulated in hours of the electrical system is represented, referring to the generation of wind energy.

The simulation guarantees the balance between production and demand, in Fig 8 the general balance of the Ecuadorian electrical system is made, which includes projected floating wind energy based on the starting scenario with data from Table 3 and Table 4.

By using EnergyPLAN, the operation of the energy systems under investigation is simulated hour by hour. The behavior of the energy mix on the generation side can be seen in interaction with the demand of the geographically defined sectors. For a better understanding, Figure 7 can be seen where, thanks to the MATLAB Toolbox for EnergyPLAN [43], it was possible to simulate the energy mix for 2050 in the months of January and July, which obey two periods marked in Ecuador as summer (Figure 7a) and winter (Figure 7b). The temperature changes in these two periods are analyzed according to the Köppen-Geiger climate classification and detailed according to reference [44]. Global geographic mapping and techno-economic performance optimization of grid-connected and stand-alone hybrid renewable systems in all Köppen-Geiger climates are available [45]. It is due to two seasons in Ecuador, one is classified as Ecuadorian summer dry (Aw) in summer and a high level of solar radiation prevails but reduced water flows, while in Ecuadorian winter dry (As) the flows for generation hydroelectric rise to a large extent and cloudiness increases at these times, so solar radiation drops significantly. Wind power generation maintains relatively similar levels in these two times of the year. Considering these aspects, the behavior of the system in EnergyPLAN is analyzed hour by hour and the demand can include the sectors of electricity, heating, refrigeration, industry and transport. This analysis model is used by many researchers, consultants and policy makers around the world. The use of the software is open access, easy to use, flexible. There is also a user guide for the software to carry out the simulations on the official EnergyPLAN site [46], there are also case studies developed and can serve as a reference for other new developments [47], the Ecuadorian case can be identified among all of them [48]. This is possible due to the key focus on sharing the model and its most current versions.



(a)

(b)

Fig 7. Mix of electricity generation for one week (a) January, (b) July.

6. Results

Within the results it can be seen in Fig 10 and Table 5 that it is possible to include renewable energy rates progressively and limiting the incidence of electrical energy from fossil fuels as the years go by and in 2050 a 100% renewable scenario is established. The wind power component includes floating and onshore wind power.

In order to use closer data, the data available in [39] referring to 2021 were taken and a first time jump of 9 years is determined. Typically, the same jumps are defined until 2050, but this would imply taking data prior to 2020. In this case study, after 2030 the jumps are 10 years with a view to 2050 to finally discuss the results. In all time jumps, the energy of polluting origin would be progressively reduced, while renewable energies would increase. In 2050, the electricity supply will be completely integrated by renewable energy sources, hydropower being the most important, followed by solar photovoltaic and wind. Particularly in this study, the hydroelectric projects proposed as detailed in [49] are included, for this reason a moderate but important growth of hydraulics is identified in the following years, both in installed capacity and in electricity generation in Fig. 8 and Fig. 9, respectively. The results are also detailed in each time jump in Table 5 and Table 6. If this portfolio of hydroelectric projects has not been compromised, it is advisable to consider diversifying renewable energy sources from the beginning to achieve a more balanced scenario in their percentages. of electricity generation, maintaining the same generation levels of the most preponderant source. However, accepting this reality, it is identified that the sources that have achieved greater maturity in the international context such as wind and solar PV are called to play a notable role in the Ecuadorian energy mix. Other small contributions are not neglected and make up the energy matrix for Ecuador. Fig. 9 shows the scenario from 2021 to 2050 regarding energy production.

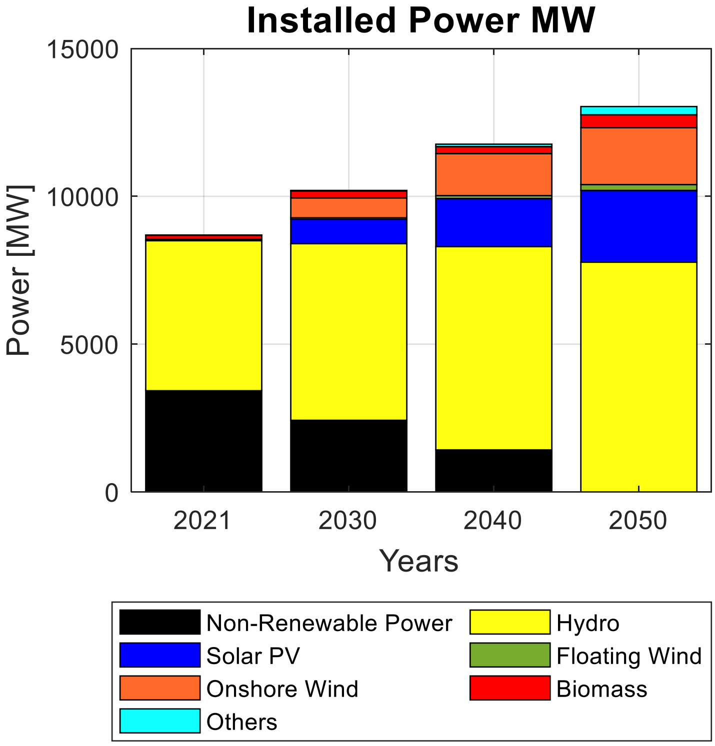


Fig 8. Installed Power in 2021 until 2050.

Table 4. Detailed installed power by source up to 2050 in MW.

Source	**2021**	**2030**	**2040**	**2050**
Non-Renowable Power	3,426.14	2426	1,426	0
Hydro	5,072.26	5,972.26	6,872.26	7,772.26
Solar PV	26.76	826.76	1,626.76	2,426.76
Floating wind	0	50	100	203
Onshore wind	21.15	671.15	1,321.15	1,918.15
Biomass	136.4	236.4	336.4	436.4
Others	7	18	82	280
TOTAL	**8,689.71**	**10,200.57**	**11,764.57**	**13,036.57**

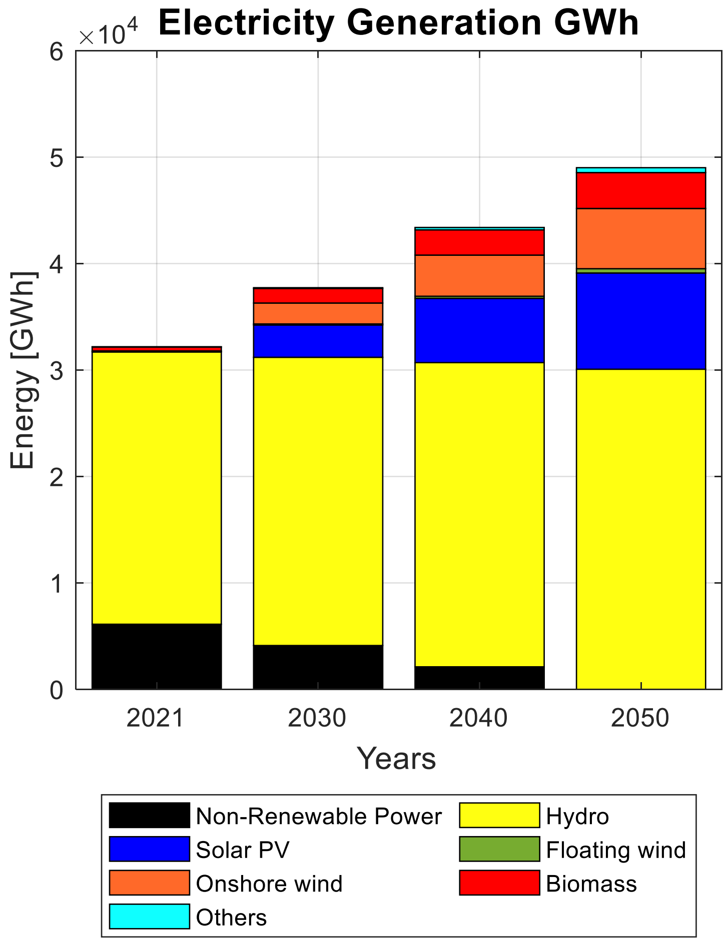


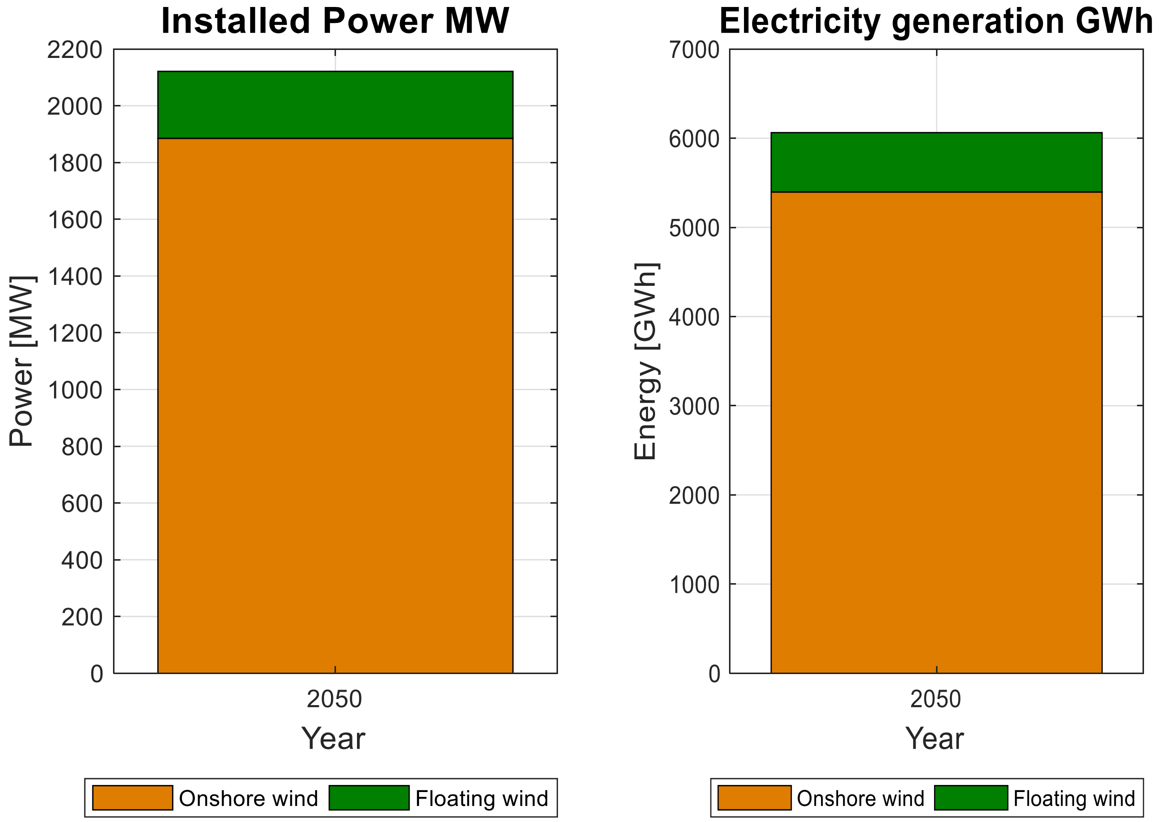
Fig 9. Electricity generation in 2021 until 2050

Table 5. Electrical energy by source in GWh until 2050.

Source	2021	2030	2040	2050
Non-Renewable Power	6118.46	4118.46	2118.46	0
Hydro	25574.61	27074.61	28574.61	30074.61
Solar PV	36.87	3036.87	6036.87	9036.87
Floating wind	0	100	200	407
Onshore wind	62.01	1962.01	3862.01	5655.01
Biomass	372.8	1372.8	2372.8	3372.8
Others	20	68	225.5	456.8
TOTAL	**32184.75**	**37732.75**	**43390.25**	**49003.09**

Once the scenario for 2050 has been determined, the impact that floating wind energy would have on the total energy component in 2050 is evaluated, disaggregated according to the simulations previously carried out in EnergyPLAN.

Below is Fig. 10a where the installed wind power is specified with its two components for the year 2050, onshore wind and floating wind with 1918.15 MW and 203 MW, respectively. In this same sense, in relation to the power generation presented in Fig 10b, the result is 5655.01 GWh in onshore wind and 407 GWh in floating wind. Although floating wind power does not have a direct impact on the Ecuadorian energy mix, its contribution levels are not negligible either and rather it can be very useful in the energy transition process with a view to 2050.



(a) **(b)**

Fig 10. Analysis of the wind component, both onshore and floating wind. (a) Installed Power. (b) Electricity generation.

Below is presented in Figure 11 the cost scenarios regarding the capacity variations of the floating wind system. The two technologies that would be adding more energy capacity until 2050 are solar PV (2,426.76 MW) and wind (2,121.15 MW). The hydroelectric plant will grow moderately in relation to the base year (7,772.26 MW). It is also observed the behavior of fossil fuels with respect to 2020, in this case the optimum is reached with 0 MW. The results reflects the decrease in the cost of renewables and the optimum is determined until 2050.

FWT may have an installed capacity of 202MW and a cost of 203 million dollars. This cost implies around 50 million dollars per floating wind farm, compared to the one in Minas de Huscachaca that cost 90 million dollars for the 50MW [50]. It is important to indicate that transportation costs are included, and there is also an advantage that costs tend to drop each time. Also, the costs for acquiring lots of floating wind turbines are more convenient because it allows optimizing costs, especially installation and transportation. More details can be seen in Fig 11.

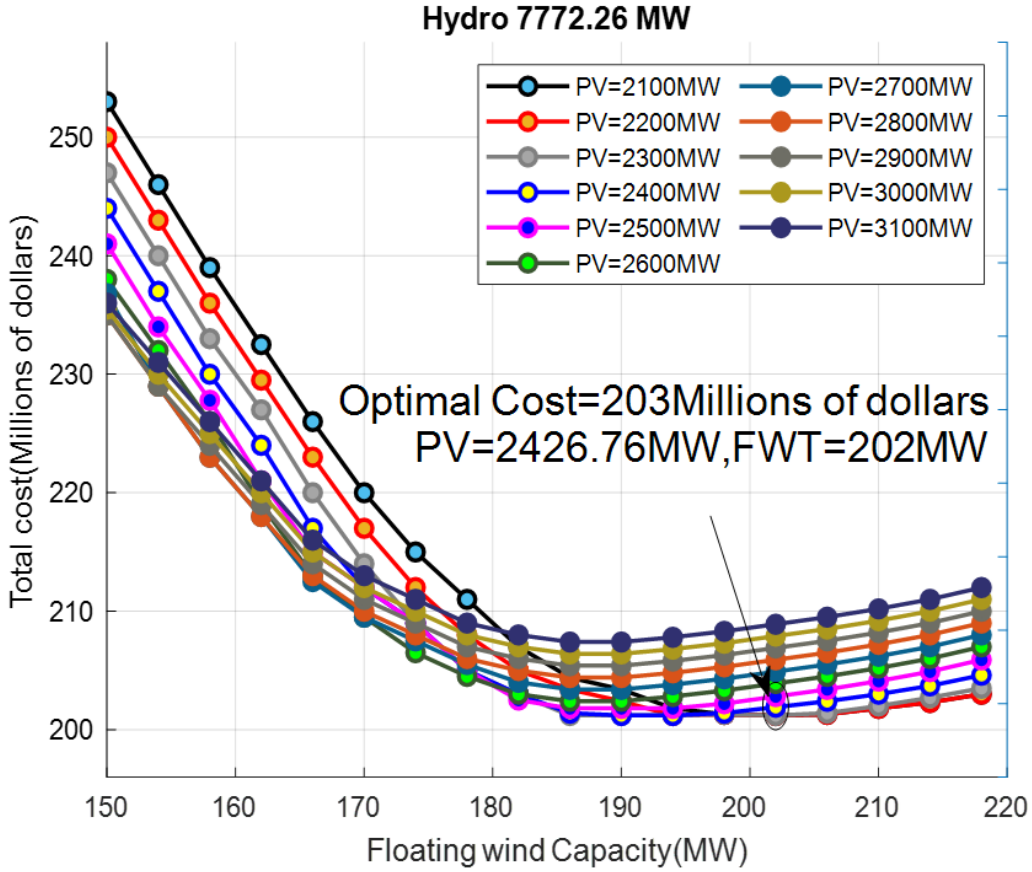


Fig. 11. Analysis of scenarios for 2050 based on marginal costs

7. Case analysis and discussion

After making the projections of the Ecuadorian electrical system with 100% renewable energy by 2050 based on its available energy potential in the territory, it can be identified that the wind component is an important base for the energy transition that has been stipulated by the Ecuador and that among other state policies is the latest decree 059. The production of wind energy taking advantage of the reservoirs is a novel development path in Ecuador and in South America, however it is possible to take advantage of the wind tunnels that are formed between mountains and achieve an energy production component through floating wind power and make better use of the physical space of hydroelectric dams to achieve an environmentally friendly energy transition. The results presented with the support of the energyPLAN design tool allow us to identify the levels of production necessary by source to fulfill the purpose of having a 100% renewable system and leaving behind the use of energy from fossil fuels. Floating wind technology can become much more interesting despite not being essential in the country's energy production, it can be considered as a complementary component of energy and development and innovation. These developments can also be considered as an opportunity to carry out new research by universities and strengthen these internal experiences, including studies to develop floating wind farms, for example, for Galapagos or on the coast of Ecuador. Renewable energies are an important option for many countries and with their implementation it would be possible to change the energy matrix and achieve a healthier world, avoiding the increase in temperature on the planet and its dire consequences that would occur. In relation to the results obtained as a whole considering the execution of the projects proposed at the country level, the hegemony of hydroelectric energy would be maintained with an installed capacity of 7,772.26 MW, which represents 59.62%, followed by photovoltaic solar 2,426.76 MW, representing 18.61%, wind with 2,121.15 MW represents

16.27%, biomass with 436.4 MW represents 3.35% and other small contributions with 280 MW represents 2.14%.

These results also represent a much more diversified energy mix in 2050 in relation to the year 2021 that basically depends on hydroelectric and fossil fuels, in this way it can be considered as a much friendlier roadmap with environment and achievable. Regarding floating wind power, its inclusion would represent 11.13% of the total wind component, which is not negligible either and can be considered a contribution that would diversify the energy mix at the country level.

At the level of the reservoirs, speeds between 6 to 6.5m/s are achieved, although they are not ideal speeds for the generation of wind energy, these speeds will allow important production levels. An average annual gross production of 100 GWh is estimated in each reservoir, which is equivalent to powering 360,000 homes. The purpose of these projects as stated in this manuscript is not to obtain profitability, in itself they are quite expensive and not economically viable with respect to other technologies, even within the renewables themselves. The background is to diversify the Ecuadorian energy mix with this new floating wind technology, taking advantage of 10 km^2 in each reservoir, an adequate space in the long tail formed by the water mirror. Because there are summer times and the flows are drastically reduced, the platforms must be installed at least 500 meters from the banks of the river that leads to the reservoir to maintain the safety strip and the wind platforms do not hit the mounds of land.

8. Conclusions and future work

The modeling approach developed in this work with the support of the EnergyPLAN tool fulfills the objective of improving long-term energy planning of systems with high penetration of renewable energy sources. In this particular case, the evaluation was carried out including all the data provided by the national energy system and was projected to 2050. In the simulations, the floating energy component was considered as a result of the use of the reservoirs of the 4 hydroelectric dams and with data from data provided publicly by the MEER regarding the wind potential at these sites. Although there are sites in Ecuador with greater wind potential, especially onshore, the system analyzed is not negligible either and can contribute very well to the diversification of the Ecuadorian energy matrix to progressively leave in history the fossil fuels that unfortunately are exported and very expensive. A high resolution temporal representation has been introduced for the evaluations in each time jump up to 2050 referring to the evolution of the energy system, analyzing the behavior of the system on an hourly basis as very well presented by EnergyPLAN and analyzing the impact in terms of installed capacity. and power generation.

The analysis of smart energy systems, such as the present case study in Ecuador, requires tools and models that can provide similar and parallel analyzes of electrical, thermal, and gas networks. The advanced energy system analysis model, EnergyPLAN, has been developed to fulfill this purpose on an hourly basis (www.EnergyPLAN.eu), so that very reliable solutions can be identified and are being demonstrated in various investigations provided by the same authors. at the level of Ecuador and in other parts of the world.

It is very probable that some researchers question projecting floating wind energy and instead opt for photovoltaic solar energy, the results presented here have shown that it is possible to take advantage of this technology. Additionally, it is important to indicate that the present study is a part of the analysis, as future work we will present the analysis case with the unique inclusion of floating photovoltaic solar energy in these same reservoirs, which is another of the purposes of the Public Company Corporación Eléctrica del Ecuador (CELEC EP) and the authors in analyzing these other impacts that would have on energy production for Ecuador. In the end, the decision makers will accept one or the other study to commit economic resources with a view to carrying out an orderly energy transition.

As another part of future work, it is suggested that the researchers carry out an experimental modeling and analysis of the efforts to which the floating wind turbines are subjected at the level of the reservoir.

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