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Large-scale integration of renewable energies by 2050 through demand prediction with ANFIS, Ecuador case study

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ABSTRACT

The growing reliance on hydroelectric power and the risk of future droughts pose significant challenges for power systems, especially in developing countries. To address these challenges, comprehensive long-term energy planning is essential. This paper proposes an optimized electrical system for 2050, using Ecuador as a case study. For forecasting electricity demand, a Neuro-Fuzzy Adaptive Inference System is employed, utilizing real historical data. Subsequently, the EnergyPlan software constructs a long-term energy consumption model, exploring three scenarios based on Ecuador's energy potential. The first scenario represents a 'business as usual' approach, mirroring the current trend in the Ecuadorian electricity system. In contrast to the second scenario, it encompasses a broader range of renewable sources, including offshore wind, pumped storage, biomass, and geothermal energy. The third scenario extends the second one by incorporating demand response systems, such as vehicle-to-grid and hydrogen-to-grid technologies. In terms of novelty, this study highlights the innovative use of the Neuro-Fuzzy Adaptive Inference System for demand forecasting, along with a comprehensive exploration of multiple scenarios to optimize the electrical system. Research findings indicate that the integration of these new renewable energy sources not only reduces electricity import costs but also ensures surplus electricity production. Consequently, it is anticipated that the 2050 electricity system will reduce its dependence on hydroelectric energy while adopting photovoltaic and wind energy with penetration rates of 65 %, 11.2 %, and 9 %, respectively. This transition will be facilitated by a pumped storage system with a 28 % penetration rate and enhanced connectivity with neighboring countries, enabling the seamless integration of electric and hydrogen vehicles.

1. Introduction

The rising global temperatures and increased pollutant emissions underscore the importance of electricity generation from renewable energy sources (RES) [1]. Integrating these RES into the electrical power system (EPS) would decrease reliance on hydrocarbons [2]. Nonetheless, the inherent intermittency of RES presents significant stability challenges when extensively integrated into the grid [3]. Heavy dependence on hydroelectric power (Hydro), although it mitigates intermittency issues for some RES at a large scale, introduces the risk of electricity shortages during future droughts [4]. This concern is particularly pronounced in developing countries with abundant hydroelectric potential [5], like Colombia [6], Chile [6], Brazil [7,8] and notably Ecuador, where hydroelectric production has surged by 32.19 % in the last decade, constituting 92 % of the electricity generation in 2022, as illustrated in Fig. A1 (a) of supplementary material. According to Ecuador's governmental electrification master plan, this dependency is anticipated to further escalate in the upcoming years, heightening the potential for electricity shortages [9,10]. This vulnerability underscores the importance of diversifying energy sources and enacting strategic energy planning for the country [11]. This paper focuses on addressing this issue and presents a study focused on optimizing the electrical system for the year 2050, using Ecuador as a case study.

The electrification and decarbonization of electrical systems are critical priorities on the global energy agenda. Scientific literature provides valuable insights, emphasizing the importance of region-specific approaches. For instance, Nigeria has proposed a plan to achieve complete electrification by 2030 [12]. This plan relies on a comprehensive strategy that leverages various energy resources, including natural gas (NG), photovoltaic (PV), and onshore wind (WT). Similarly, Montenegro is actively pursuing a fully renewable energy system [3], with a strong

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Nomenclature

Acronyms

ANFIS	Adaptive neuro fuzzy inference system
ANN	Artificial neural network
BAU	Business as usual scenario
CEEP	Critical excess electricity production
CO_2	Carbon dioxide
COMP	Coefficient of commitment
DR	Demand response
EI	Electricity interconnection
EPS	Electrical power system
EV	Electrical vehicle
Hydro	Hydroelectric power plants
H_2	Hydrogen
H2G	Hydrogen-to-grid
NG	Natural gas
NARX	Nonlinear autoregressive with exogenous
ΔCEEP	Change in critical excess electricity production
ΔPES	Change in primary energy supply
O&M	Operation and maintenance
PH	Pumped hydro
PES	Primary energy supply
PV	Photovoltaic
RES	Renewable energy system
S0	Business as usual scenario
S1	Decarbonization scenario
S2	Demand response integration scenario
TS	Transition scenarios
V2G	Vehicle-to-grid
WT	Wind on-shore
WOFF	Wind off-shore

emphasis on integrating variable RES like PV and WT, along with energy efficiency measures and storage systems.

At the European level, the transition toward a decarbonized electricity grid places significant emphasis on the roles of WT and PV [13]. This transition necessitates the expansion of energy storage capabilities and the establishment of international transmission line connections and electricity interconection (EI).

China serves as an exemplary case, demonstrating the substantial energy and carbon reduction potential of widespread electric vehicle (EV) adoption [14]. This underscores the importance of holistic solutions that address both energy generation and consumption. Meanwhile, Portugal is working towards covering approximately 75 % of its electricity demand with WT and PV by 2050 [15], showcasing the feasibility of harnessing regional natural resources for a transition to a more sustainable energy mix.

In Colombia, efforts to explore variable renewable sources such as WT, PV, Hydro, and bioenergy aim to reduce CO_2 emissions and decrease fossil fuel dependency by 20 % in 2030 [16]. Hydropower's adaptability is highlighted as a crucial advantage in this context. Denmark is actively evaluating the feasibility of a 100 % renewable energy system, which would cover 75 % of electricity demand [17]. Likewise, Ireland is exploring a 100 % renewable energy system based on biomass, hydrogen (H_2), and electricity [18]. However, both countries recognize the need for further research and meticulous planning to define an efficient transition strategy.

The authors in Ref. [19] present renewable energy-based system designs for Macedonia in 2030 and 2050, contingent on meticulous long-term planning. Hungary is assessing the viability of integrating WT and PV energy resources to meet a significant portion of electricity demand [20]. A developing country like Chile presents transition scenarios (TS) toward a 100 % renewable energy system by 2050, demonstrating both technical feasibility and efficiency in reducing CO_2 emissions [21]. Indonesia examines the interconnection of electricity, transportation, and refrigeration sectors to reduce primary energy consumption and CO_2 emissions [22]. In Chad, the analysis explores the possibilities of achieving 100 % renewable electrification using renewable energy technologies, with a particular emphasis on biomass [23]. Finland explores the introduction of H_2 into the energy system as a decarbonization strategy, despite facing challenges related to electricity demand and H_2 storage [24].

Collectively, these studies endorse the transition to renewable energy sources, energy efficiency measures, and interregional collaboration as key elements in achieving more sustainable energy systems worldwide. They also underscore the importance of tools like EnergyPLAN in planning and assessing these systems. Nevertheless, the complexity of addressing region-specific challenges is acknowledged, necessitating ongoing research for a truly sustainable energy future.

Within the context of increasing global energy demand, countries heavily reliant on Hydro, such as Ecuador, face significant challenges, particularly amid intensifying droughts (Fig. A1 (c)) [9,10]. Solutions explored include incorporating conventional power plants and importing electricity from neighboring Colombia and Peru, as seen in Fig. A1 (b), to address vehicle-to-grid (V2G), hydrogen-to-grid (H2G), and conventional electricity demand [11]. The viability of these solutions largely depends on the electrical infrastructure of neighboring countries, an aspect requiring further detailed analysis in existing literature.

Several energy planning studies applied to Ecuador underscore the need to transform fossil fuel-based energy systems into 100 % renewable systems, utilizing untapped resources within Ecuador, as depicted in Table A1. Research in Ref. [25] suggests that renewable sources such as Hydro, PV, and WT will play a fundamental role in meeting future energy demand in this country. Meanwhile, the authors of Ref. [26] support the transition to 100 % renewable energy systems, utilizing RES. However, they acknowledge the need to improve demand forecasting mechanisms, consider new RES, and integrate EVs into the grid. In the Galápagos Islands and the city of Cuenca in Ecuador, plans are being developed for a transition to 100 % renewable energy systems by 2050. These plans consider unique characteristics and energy analysis tools to calculate the optimal combination of renewable sources like WT and PV [27]. Additionally, the implementation of renewable energy is expected to increase the penetration of clean energy sources in Cuenca [28]. Gradually phasing out fossil fuel-based energy sources is crucial for reducing the carbon footprint and protecting the fragile ecosystem of the Galápagos Islands, as indicated by the authors of Ref. [29]. On the other hand, technical-economic studies demonstrate the feasibility of a 100 % renewable energy system in these areas, as shown in Ref. [30].

Finally, in forecasting Hydro production in Ecuador, artificial neural network (ANN) models are highlighted for their superior performance in time series forecasting, as demonstrated in Ref. [31], playing a fundamental role in sustainable Hydro energy management. Nonetheless, Ref. [32] evaluates the Ecuadorian electricity system for 2040. The study makes several assumptions, such as long-term demand forecasting, and does not consider technical limits of renewable energy sources' penetration and interconnection, which lack the foundations to conclude the optimal long-term configuration.

In summary, these studies support the urgency of transitioning to more sustainable energy systems, with a specific focus on Ecuador. They underscore the complexity of long-term forecasting and the need for real-world scenario analysis, as well as the importance of long-term planning and investment in renewable technologies for a cleaner and more efficient energy future.

The future electrical planning of EPS is currently a widely explored research field, driven largely by the advancement of tools like EnergyPlan. Despite the extensive available literature, this study is motivated by notable deficiencies identified in previous research, summarized in Table 1. Several significant research gaps are highlighted.

Firstly, there is a noticeable lack of attention to demand response (DR). For instance, Ref. [26] focuses on EVs but overlooks strategies for managing electrical demand, such as V2G or H2G. Additionally, studies on transitioning to sustainable energy systems in Ecuador (Ref. [28,30]) often disregard crucial aspects of DR. Another identified gap relates to the lack of a detailed focus on the maximum technically feasible penetration of RES in previous research (Ref. [12,19,27]). These studies do not delve deeply into the maximum technical viability of these resources, leaving a gap in understanding their full potential. Furthermore, a research gap is identified concerning the lack of a comprehensive analysis of electricity interconection possibilities in energy systems. Although studies concentrate on 100 % renewable systems in Ecuador (Ref. [26–30]), they do not explore how to optimize electricity interconection between regions.

Finally, Refs. [29,30], prior works by the authors, lack adequate attention to DR, maximum RES viability, V2G, and H2G. Concerning demand forecasting, Ref. [30] employs a Nonlinear AutoRegressive with eXogenous inputs (NARX) model, while this study improves precision through Adaptive Neuro-Fuzzy Inference System (ANFIS). ANFIS offers advantages over purely neural models as it combines neural networks' learning capacity with the interpretative and reasoning abilities of fuzzy logic. This results in improved demand forecasting accuracy and, consequently, more precise electrical system planning.

In summary, this study addresses gaps in demand response, maximum RES technical penetration, electricity interconection, V2G and H2G technologies, while enhancing demand forecasting accuracy with ANFIS. These advancements represent significant progress in electrical system planning.

To simplify, the key contributions of this study are outlined below:

- This research addresses the identified gap related to the insufficient focus on DR in prior studies. It delves into and proposes demand-side management strategies, providing a detailed examination of V2G and H2G technologies. This fills a void in prior research, which did not thoroughly explore these technologies and their roles in electric DR and renewable energy integration. Collectively, this contributes to a more comprehensive understanding of how DR technologies can play a pivotal role in future electrical planning.
- Investigation into the maximum technically feasible penetration of RES, an identified gap in earlier research. This paper conducts a meticulous analysis of the maximum technical viability of RES, yielding valuable insights into the extent to which renewable energy can be effectively integrated into the EPS without compromising its reliability.
- Exploration of the limited in-depth analysis of electrical interconection in energy systems, with a focus on strategies to optimize cross-border electrical interconection between neighboring countries like Colombia and Peru.
- Advancement in demand forecasting. This paper enhances the precision of demand forecasting by employing the ANFIS model, outperforming the accuracy of the NARX model used in previous studies or relying solely on databases provided by EnergyPlan. This enhancement contributes to more exact electrical system planning, thereby addressing one of the limitations identified in prior research.

This paper is structured as follows: Section 2 describes the proposed methodology, Section 3 examines the electricity demand forecasting model, and Section 4 focuses on the modeling description in EnergyPlan. Section 5 delves into the results and discussions, and, finally, section 6 presents the conclusions of the article.

2. Methodology

The methodology employed in this paper focuses on comprehensive long-term planning of the Ecuadorian electrical system, with a particular emphasis on accurately forecasting demand for the year 2050. This objective is achieved through the ANFIS implementation, which utilizes real historical data as the basis for prediction. The ANFIS model is developed by integrating neural network and fuzzy logic techniques and is implemented using the MATLAB software. It considers essential factors like actual demand growth, population growth, and ambient temperature trends, all of which impact the projected electrical load behavior in 2050.

Once the demand projection for that year is obtained, three different scenarios are explored to meet this future electrical demand. The first scenario, referred to as the "Business as Usual Scenario" (S0), involves maintaining the current trajectory of the EPS, utilizing existing energy sources such as Hydro, WT, PV, conventional sources, and interconnections. The second scenario, known as the "Decarbonization Scenario" (S1), focuses on decarbonizing the EPS by introducing

Table 1
Summary of relevant literature.

Ref.	Solver	Renewable energy sources	DR	Max RES	V2G	H2G	EI	TS	Indices
[2]	EnergyPlan	Hydro, PV, WT	✓	–	✓	–	✓	✓	Tec, Econ, Env
[12]	EnergyPlan	Hydro, NG, PV, WT, wind off-shore (WOFF)	–	–	✓	–	–	✓	Tec, Econ, Env
[13]	LIBEMOD	Hydro, PV, WT, WOFF	–	–	–	–	✓	–	Tec, Econ, Env
[14]	EnergyPlan	NG	✓	–	✓	–	–	–	Tec, Econ, Env
[15]	EnergyPlan	Geothermal, Hydro, PV, WT, WOFF	–	✓	–	–	✓	✓	Tec, Econ
[16]	EnergyPlan	Bioenergy, NG, Hydro, PV, WT	–	✓	–	–	–	–	Tec, Env
[17]	EnergyPlan	NG, biomass, solar thermal	–	–	–	–	✓	✓	Tec, Econ, Env
[18]	EnergyPlan	Biomass, hydrogen	–	–	✓	✓	–	✓	Tec
[19]	EnergyPlan	Biomass, geotermal, PV, WT	–	–	✓	–	–	✓	Tec, Econ, Env
[20]	EnergyPlan	PV, WT	✓	✓	✓	–	–	✓	Tec
[21]	EnergyPLan and Eplan	Biomass, geotermal, PV, WT	–	–	–	–	–	✓	Tec, Econ, Env
[22]	EnergyPlan	Geothermal, hydro, PV, WT	✓	–	✓	–	–	✓	Tec, Econ, Env
[23]	EnergyPlan	Biomass, geotermal, hydro, PV, WT	–	–	✓	–	–	✓	Tec, Env
[24]	EnergyPlan	Biomass, hydro, NG, PV, WT	–	✓	✓	–	–	✓	Tec, Econ, Env
[25]	EnergyPlan	Biomass, geothermal, hydro, NG, PV, WT	–	–	✓	–	✓	✓	Tec, Econ, Env
[26]	EnergyPlan	Biomass, hydro, PV, WT	–	–	✓	–	–	–	Tec
[27]	EnergyPlan	Biomass, geotermal hydro, NG, PV, WT	–	–	–	–	–	–	Tec, Env
[28]	EnergyPlan	PV, WT	–	–	✓	–	–	✓	Tec, Econ, Env
[29]	EnergyPlan	PV, hydro, WT	–	–	✓	–	–	✓	Tec, Econ
[30]	EnergyPlan and NARX	PV, WT	–	–	–	–	–	✓	Tec, Econ, Env
[32]	LEAP model	Biomass, NG, hydro, PV, WT,	–	–	–	–	–	✓	Tec, Econ, Env
Present study	EnergyPlan and ANFIS	Biomass, geotermal, hydro, pumped storage (PH), PV, WT, WOFF, H_2	✓	✓	✓	✓	✓	✓	Tec, Econ, Env

innovative technologies, including PH, WOFF, biomass, and geothermal energy sources. Finally, the “Demand Response Integration Scenario” (S2) explores the incorporation of demand response systems, including technologies like V2G and H2G.

For each of these scenarios, a thorough optimization process is conducted to identify the most suitable combination of energy sources and technologies. This process evaluates crucial factors such as the total cost and the Critical Excess Electricity Production (CEEP), while also considering the need for imported electricity. The ultimate goal is to determine the combination that best aligns with demand projections and meets the expected economic, technical, and environmental criteria for the year 2050. The graphical representation of this methodology is presented in Fig. 1.

2.1. Current Ecuadorian electrical power system

Over the past decade, Ecuador’s electricity sector has made significant strides in expanding its installed capacity. By the year 2022, the total installed capacity had reached 8786.83 MW, with RES contributing 59.23 % of this capacity, while conventional sources accounted for the remaining 40.77 %. This represents a notable shift compared to the situation in 2009. In terms of electricity pricing, the regulatory body responsible for overseeing energy and non-renewable natural resources, through resolution 009/2022 dated April 14, 2022, has mandated that the average national electricity service rate remains fixed at 9.2 ¢USD/kWh [33]. By the conclusion of 2022, the breakdown of Ecuador’s power generation capacity was as follows:

- Hydro capacity: 5155.30 MW
- Steam-turbine power plants capacity: 605.93 MW
- Turbogas power plants capacity: 943.45 MW
- Power plants equipped with internal combustion engines: 2031.96 MW
- RES capacity: WT - 21.15 MW and PV - 28.65 MW.

Table 2 presents actual production and maximum power values recorded for the year 2022 [9], while Fig. 2 illustrates the daily average performance during the same period.

In response to the increasing electricity demand, the Ecuadorian government has initiated several power generation projects. These projects encompass 187 MW of capacity in thermoelectric plants, 50 MW in WT, and 3403.5 MW of Hydro capacity [10]. This planning horizon extends until 2025. However, it’s important to acknowledge the potential sustainability challenges associated with exclusively relying on this model in the long term. These challenges could emerge due to

Table 2
Actual electricity production of the Ecuadorian EPS for 2022 [11].

Component	Generation, Demand & Exchange (TWh/year)	Maximum Value Reached (MW)
Hydro	24.55	3497.96
NG	0.55	84.88
Steam	1.50	346.86
Bunker	1.04	428.66
Diesel	0.42	364.23
RES	0.31	75.76
Imported	0.45	405.34
Exported	−0.19	−246.72
Total (Generation & Exchange)	28.64	4956.98
Total Demand	28.64	3678.46

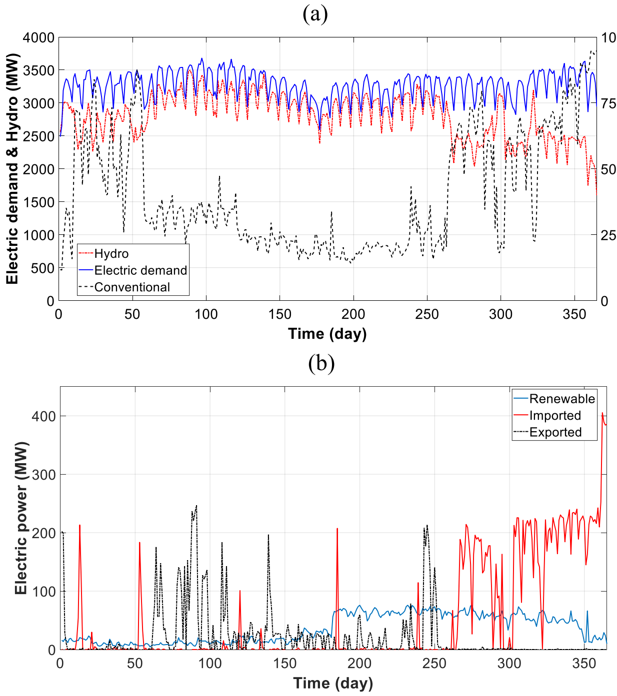
(a)
(b)

Fig. 2. Actual data for the Ecuadorian EPS in 2022.

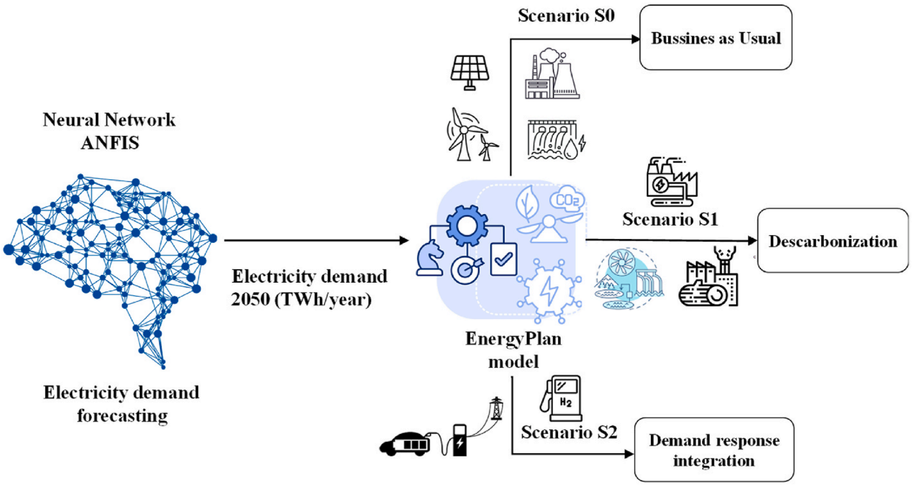

Fig. 1. Overview of the proposed methodology in this paper.

various factors, including droughts, which have the potential to impact not only Ecuador but also its neighboring countries. Consequently, there is a growing need for efficient, long-term electrical planning that takes into account these potential scenarios.

3. Proposed electricity demand forecasting model

The literature provides a wide range of methods for electricity demand forecasting. However, it is crucial to emphasize the significance of addressing the intermittency of renewable energies, uncertainties associated with real-time multi-horizon weather and load forecasts, and the absence of comprehensive control systems [34]. Surprisingly, the importance of accurate predictions is often overlooked in robust electrical system analyses using EnergyPlan. For example, Ref. [35] used an ANN model in MATLAB to predict Turkey's 2050 electricity production for meeting regional energy demands. Challenges in long-term demand forecasting include data complexity, especially in renewable systems with multiple random variables. ANFIS, an integrated approach combining fuzzy logic and ANN, effectively handles imprecise data, improving accuracy [36].

Numerous short-term studies employ ANN models (e.g., Refs. [37,38]) for monthly electricity consumption predictions using ANFIS-based algorithms. While ANFIS has been applied in Ecuador for time series and ANN-based demand forecasts [31,32], its potential for long-term electricity demand prediction in the Ecuadorian EPS remains unexplored. ANN, inspired by biological neural networks, comprise neurons and a weight matrix, typically with input, hidden, and output layers [39,40]. The electricity demand forecasting process involves several stages, as discussed in the cited studies.

3.1. ANFIS model configuration

ANFIS, based on ANNs, optimizes the fuzzy inference system by adjusting fuzzy rules and membership functions to minimize output errors in a complex system improving the structure of a conventional ANN. Its structure (as shown in Fig. 3) includes input variables, a membership layer, fuzzification layer, normalization layer, defuzzification layer, and the output layer [39,40].

In this case, the subtractive grouping method is applied, which ensures that the number of generated rules matches the number of membership functions assigned to each input variable. This method effectively reduces computational complexity. The membership functions are fine-tuned by adjusting the subclustering parameters, and the specific values can be found in Table B1 in the supplementary material.

The selected parameters aim to achieve maximum precision without overfitting the ANFIS model to the training data. To prevent overfitting, the range of influence was constrained to 0.55, as indicated in Table B2. The epoch number was set at 3, as further increases were unnecessary given the achieved root mean square error (RMSE) of 8 × 10ˆ(−5). The development of the ANFIS model was facilitated using a hybrid optimization method.

3.2. Data preprocessing

To ensure precise network training, historical power demand data is effectively preprocessed by employing the cubic spline method within the MATLAB software [41].

3.3. Network training

The input variables for ANFIS include the number of inhabitants [42], minimum temperature, maximum temperature, and average temperature [43]. Subsequently, the number of neurons in the middle layer is heuristically adjusted to optimize the results [41]. A general scheme is illustrated in Fig. 4. The training dataset consists of hourly data spanning 11 years, totaling approximately 95,000 data points.

3.4. Network testing

This performance testing process for ANFIS involves using data from two different time periods to ensure the model's accuracy and effectiveness in various scenarios. These two periods are 2011–2016,

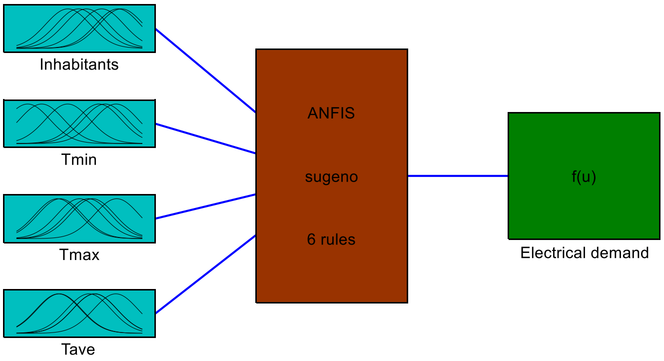

Fig. 4. Overall ANFIS architecture for the Ecuador case study.

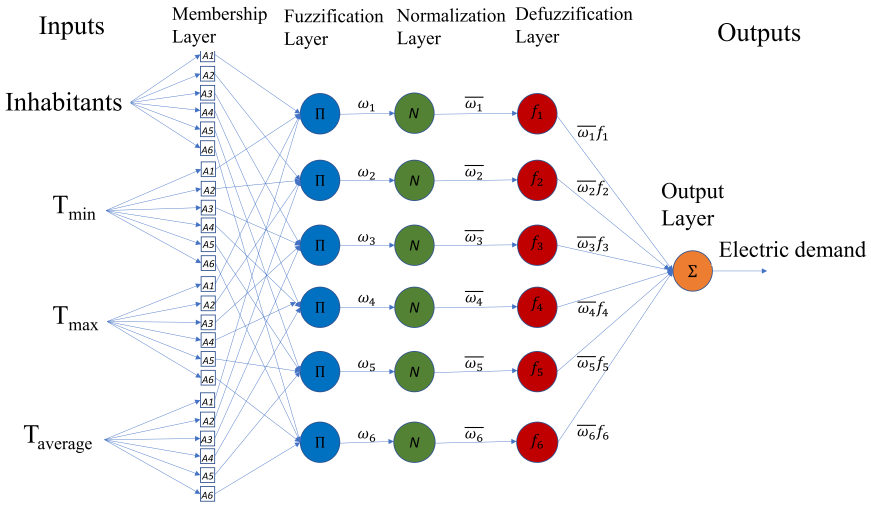

Fig. 3. ANFIS system structure for the proposed case study analysis.

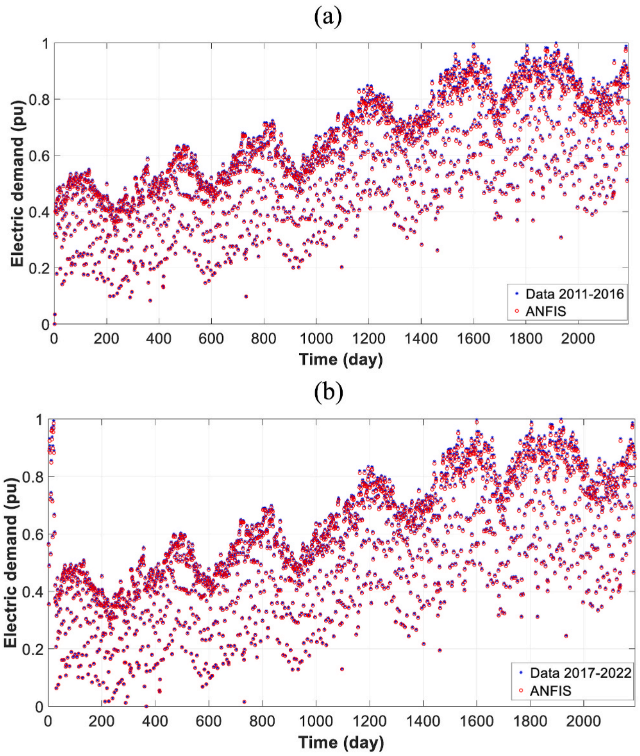

Fig. 5. Comparison between ANFIS predicted values and actual data (Per Unit): (a) Period 2011–2016 and (b) Period 2017–2022.

represented in Fig. 5 (a), and 2027–2022, illustrated in Fig. 5 (b). Each of these periods spans five years. It's important to note that the selection of these time intervals is done randomly from a larger dataset covering a total period of 11 years, from 2011 to 2022. This approach is employed to avoid potential biases or incorrect trends that could arise if a single, very long time interval were used for model training and testing.

In summary, this strategy of dividing the data into shorter intervals within a longer timeframe ensures that the ANFIS model is robust and accurate in predicting electrical demand, regardless of the specific time period under evaluation. As can be observed, the results in Fig. 5 (a) and 5 (b) demonstrate exceptional accuracy in electrical demand prediction.

3.5. Electricity demand forecasting

Once the ANFIS model has been adequately trained and tested, the process of demand forecasting is initiated. To accomplish this, historical data spanning 11 years are employed in a feedback loop for repeated predictions, ultimately forecasting demand up to the year 2050. Following these iterative operations, a clear growth trend in electricity consumption for Ecuador emerges, as depicted in Fig. 6. This figure illustrates the annual electricity demand forecast for Ecuador until the year 2050, generated through the ANFIS proposed model. The forecasted values show a significant increase in electricity demand, highlighting the growth trajectory expected in the coming decades. Specifically, the model forecasts an annual energy consumption of 87.66 TWh for the year 2050. This represents a substantial increase compared to the 28.64 TWh consumed in 2022. This means that, on average, electricity consumption in Ecuador will experience an annual increase of 5.41 % from 2022 to 2050.

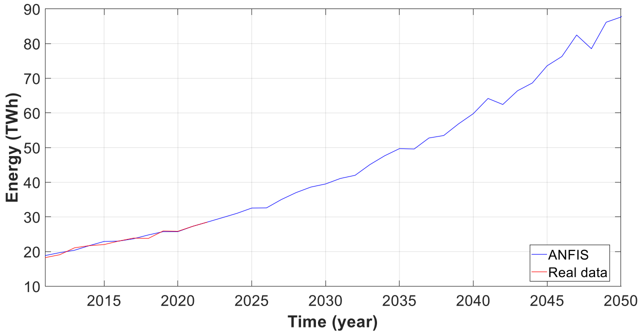

Fig. 6. ANFIS-based annual electricity demand forecast for Ecuador up to 2050.

4. Modeling description in EnergyPlan

In a comprehensive study detailed in Ref. [44], 37 computational tools were assessed for modeling national EPS, with EnergyPlan emerging as the most suitable software for this purpose. Within the scope of this research, EnergyPlan has been utilized to construct a precise model of the Ecuadorian energy system. As depicted in Fig. 7, EnergyPlan encompasses a range of inputs and outputs.

The primary data employed in this analysis include electricity demand, V2G, H2G, renewable RE, indices such as CEEP, and electricity storage, among others. These factors have been explored through various strategic simulations [45]. EnergyPlan excels in facilitating the analysis of energy exchange among significant energy blocks, including cross-border electricity exchange, and conducting technical assessments and feasibility studies related to the integration of RES and decarbonization.

Notably, EnergyPlan presents several advantages over alternative modeling approaches, as described in Ref. [46] and further described below:

- The model analyzes hourly data for a single year, in contrast to models relying on multi-year datasets, allowing for the combination of multiple scenarios within a reasonable computational timeframe.
- Rather than relying on iterations or complex mathematical techniques, this model is rooted in analytical programming, significantly reducing computational overhead.
- EnergyPlan operates as a deterministic model, unlike stochastic models or those employing Monte Carlo methods.

4.1. Validation of the Ecuadorian reference model for accuracy assessment in EnergyPlan

This section validates the Ecuadorian reference model for 2022 using EnergyPlan. Given EnergyPlan's assumptions, accuracy assessment is essential. The validation uses Table 2 data as a basis, considering adjusted capacity factors for energy sources. Monthly average power distribution results are shown in Table 3, including the "Percentage error" column, indicating modeling accuracy by comparing EnergyPlan's output to actual 2022 data [12]. This validation ensures model reliability before long-term 2050 simulations, as direct real-world data comparisons may be impractical.

A detailed comparison of EPS electricity generation data is performed, separating production from each source and comparing it with EnergyPlan. The results are summarized in Table 4, demonstrating a high overall level of accuracy. Minor discrepancies, particularly in thermoelectric (diesel), NG, and Hydro sources, are attributed to seasonal variations, as shown in Fig. A1 (c). These fluctuations result in inaccuracies in EnergyPlan results, leading to increased reliance on conventional sources during specific periods. Importantly, this comparison is based on annual fuel distribution data, ensuring a comprehensive assessment. Despite these variations, the model's accuracy remains highly reliable. After validating the Ecuadorian model in EnergyPlan using real 2022 data, it has been determined to be highly accurate, with a maximum error of 2.33 %. Consequently, this model is

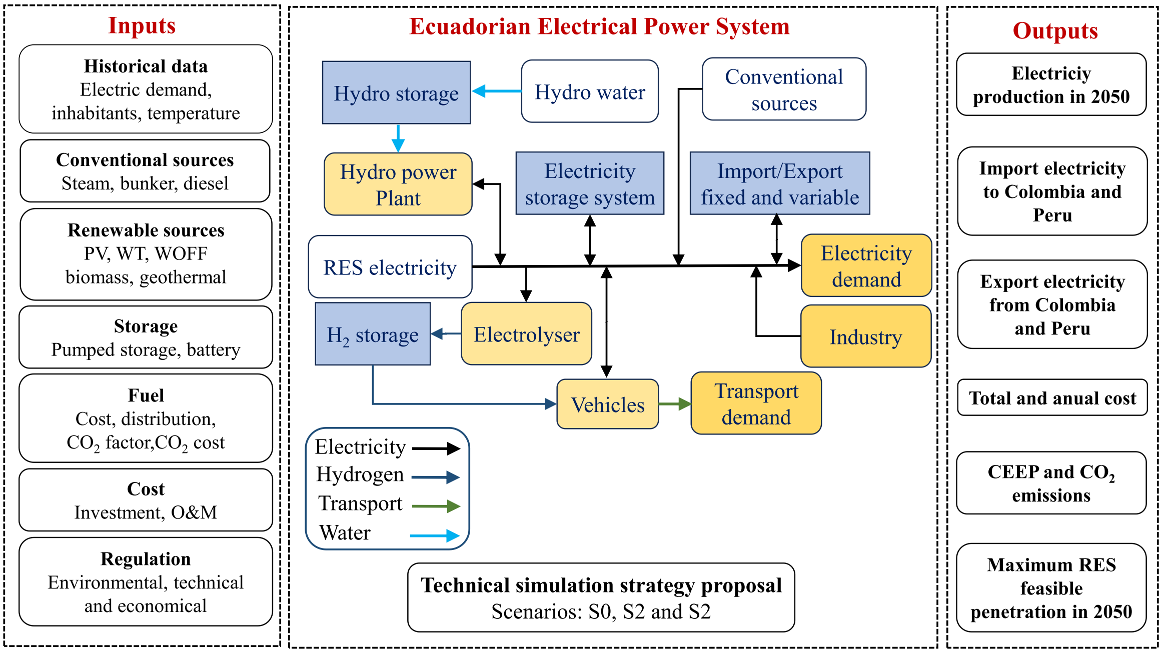

Fig. 7. Schematic representation of the proposed Ecuadorian model in EnergyPlan.

Table 3
Comparison results between EnergyPlan model and actual Ecuadorian EPS data for 2022.

Month	EnergyPlan (MW)	Real data (MW)	Percentage error (%)
January	3038	3060	0.72
February	3163	3183	0.63
March	3190	3197	0.22
April	3188	3196	0.25
May	3033	3039	0.20
June	3014	3021	0.23
July	2992	2999	0.23
August	3047	3054	0.23
September	2995	3002	0.23
October	3149	3156	0.22
November	3138	3146	0.25
December	3173	3180	0.22

Table 4
Comparison of EnergyPlan model and actual Ecuadorian EPS electricity generation by source for 2022.

Energy source	EnergyPlan (TWh)	Real data (MW)	Percentage error (%)
Hydro	24.55	24.80	1.01
NG	0.55	0.56	1.08
Steam	1.50	1.51	0.66
Bunker	1.04	1.05	0.95
Diesel	0.42	0.43	2.33
RES	0.31	0.31	0.32

utilized for the subsequent analysis described in the following sections.

4.2. Proposed scenarios

This section outlines three potential scenarios aimed at fulfilling the electricity demand of the Ecuadorian EPS in 2050, simulated within the EnergyPLAN framework. Each scenario consoders factors such as cost optimization, CEEP, imported electricity, and CO_2 emissions. A comprehensive summary of the input variables for each scenario is provided in Table 5.

4.2.1. Business-as-Usual Scenario for 2050 (S0)

The Business-*as*-Usual (BAU) scenario for 2050 is an extension of the reference scenario, consistent with the goals of the Ecuadorian government's "Plan Maestro de Electrificación 2016–2025" [32]. This scenario considers the integration of projects scheduled beyond 2022, including the addition of 915 MW of Hydro generation and 200 MW of power from RES by 2030. Notably, the introduction of the Santiago project, a major 3600 MW Hydro generation project, is expected in the Ecuadorian EPS by 2030. Throughout this scenario, the capacity of thermoelectric plants remains constant until 2050, with retiring plants being replaced by similarly configured power generation facilities. Additionally, outdated thermoelectric plants are slated to be replaced by NG plants. It is assumed that thermoelectric plants and interconnections with Colombia and Peru will be used to address any shortfalls in Hydro generation and other RES.

4.2.2. Descarbonization scenario (S1)

The main goal of this scenario is to transition towards a more sustainable and environmentally friendly electricity generation system. This scenario aims to eliminate carbon emissions from thermoelectric power plants, making the Ecuadorian EPS 100 % reliant on RES. The electricity demand for 2050 will be met primarily through increased Hydro generation, with a significant contribution from RES like PV and WT energy.

Moreover, this scenario incorporates other RES such as PH, WOFF, biomass, and geothermal energy. To ensure a stable supply of electricity, the interconnections with neighboring countries, Colombia and Peru, are expanded as needed. The specific capacities of these RES and their contributions will be determined based on technical and economic considerations. The goal is to find the optimal combination of these sources to minimize total costs, reliance on imported electricity, and carbon emissions and CEEP, considering the renewable energy potential outlined in Table A1 as a reference.

In summary, scenario S1 envisions a future in which Ecuador's electricity generation is entirely decarbonized and powered by a mix of RES, promoting sustainability and reducing environmental impact.

4.2.3. Demand Response Integration Scenario (S2)

This innovative scenario is specifically designed to address the

Table 5
Input parameters to scenario simulations in EnergyPlan.

Parameter	Capital cost (USD/kW)	O&M cost (USD/kW)	Fuel cost (USD/GJ)	Lifetime (years)	S0	S1	S2	Ref.
WT	650	38	–	25	✓	✓	✓	[47]
WOFF	1400	42	–	25	–	✓	✓	[47]
PV	323	26	–	25	✓	✓	✓	[48]
Hydro	1500	11.2	–	40	✓	✓	✓	[49]
Geothermal	3085	23.3	–	25	–	✓	✓	[49]
NG	920	16.6	24.1	30	✓	–	–	[49]
Conventional	918	5.4	33	30	✓	–	–	[49]
Biomass	2075	11.3	7.59	25	–	✓	✓	[49]
H2G	910	30 USD/MWh	0.65 USD/kg	15	–	–	✓	[50]
V2G	245 USD/unit	–	–	10	–	–	✓	[2]
PH	2780	27	–	40	–	–	✓	[51]
Interconnection	84 USD/kW	10	–	30	✓	✓	✓	[25]

potential significant presence of RES in the Ecuadorian EPS by 2050. It introduces additional criteria compared to scenario 1, specifically involving the integration of V2G and H2G technologies. The aim of incorporating these technologies is to make substantial contributions to the efficiency, sustainability, and stability of the EPS. Additionally, it aims to facilitate the seamless integration of RES and reduce emissions.

Furthermore, this scenario includes an expansion of international interconnections with Colombia and Peru, adding an extra 2000 MW of capacity. This expansion is intended to enhance the system's flexibility and resilience. The scenario's goal is to determine the optimal values for RES while considering the maximum technically feasible penetration of renewables within the Ecuadorian EPS while maintaining system stability.

In terms of EV adoption, this scenario assumes an annual growth rate of 40 %, based on recent trends in Ecuador [52]. Consequently, it projects that Ecuador will have approximately 5.4 million EVs by 2050. The calculation of the aggregate energy capacity, which accounts for charging infrastructure and the number of EVs, is based on the methodology outlined in Ref. [53]. This results in an estimated demand of 10.8 TWh/year for EV transportation, with an average consumption of 616 MW.

Additionally, this scenario introduces a demand of 5 TWh/year for H2G and includes a H_2 storage capacity of 20 GWh, as specified in Ref. [50]. Key technical data for Scenario 2 (S2) are provided in Table 6 [53].

Table 6
Main technical parameters for optimization scenario S2.

Parameters	Value
Demand	87.66 TWh/year
H_2 (produce by electrolizer)	5 TWh/year
EV demand	10.8 TWh/year
Max share EV during peak demand	0.2
Capacity of grid to battery connection	37,800 MW
Share of parked EV grid connected	0.7
Efficiency (grid to battery)	0.9
Battery storage capacity	113 GWh
Capacity o battery to grid connection	1000 MW
Efficiency (battery to grid)	0.9
WT	71.15 MW
PV	176.4 MW
Hydro	8012.96 MW
Electrolizer	712 MW
Hydrogen storage	20 GWh
Total anual cost	34,539 MUSD
V2G demand	9.72 TWh/year
V2G charge	10.8 TWh/year
Trans H2 electr	6.25 TWh/year
Import	47.41 TWh/year

5. Results and discussion

5.1. *Scenario S0*

In this scenario, we assessed the capacities of the main RES within the Ecuadorian EPS and found the following results:

Increasing PV generation capacity to 15,000 MW raises the CEEP to around 24 TWh/year by 2050, as shown in Fig. 8 (a). However, this has minimal impact on electricity imports and CO_2 emissions.

On the other hand, Fig. 8 (b) illustrates that expanding WT capacity results in a substantial increase in CEEP to about 90 TWh/year. This significantly reduces electricity imports and CO_2 emissions when WT capacity reaches 15,000 MW.

Expanding Hydro capacity, as depicted in Fig. 8 (c), virtually eliminates CO_2 emissions. CEEP grows to approximately 17 TWh/year when Hydro capacity reaches 15,000 MW, and there is a significant decrease in electricity imports.

In economic terms, expanding WT capacity reduces the total cost from USD 19 billion to approximately USD 11 billion at 6000 MW, as presented in Fig. 8 (d). The cost of increasing PV capacity remains at around USD 17 billion, while the cost of expanding Hydro capacity starts to rise after reaching 10,000 MW, eventually reaching USD 22 billion.

5.2. *Scenario S1*

5.2.1. *Economic results*

In the S1 scenario, we conducted an economic analysis based on the total annual cost, which includes capital costs and operational and maintenance (O&M) expenses. To ensure a consistent basis for comparison, we assumed that the entire installation of RES was built at once, as outlined in Table 5. During the optimization process, we varied the capacities of the RES installed in 2022 to accommodate the addition of new RES, consider the limits of RES potential indicated in Table A1.

Notably, biogas was excluded due to a lack of available data. Additionally, we factored in an operating reserve of 15 % to ensure EPS stability, following the guidelines set forth in regulation 006/00 (2000) [10]. Of this reserve, 5 % was allocated for primary regulation, while the remaining 10 % was reserved to address significant frequency deviations in the system.

The economic results related to PV(x) capacity are presented in Fig. C1. As observed, increasing the PV capacity leads to a reduction in the total cost compared to the addition of new RES. Even as the capacity of the new RES increases, the total cost remains lower. It reaches a minimum when PV capacity reaches 5000 MW and remains unchanged for larger values. Similar behavior is observed with respect to the new RES, with WOFF contributing to minimum costs when PV capacity increases. Additionally, the cost reduction becomes more gradual as the capacity of the new RES increases.

In the case of WT(x), the economic results exhibit promising behavior, as demonstrated in Fig. C4. The total cost decreases rapidly with increased WT capacity in relation to any new RES. All the results

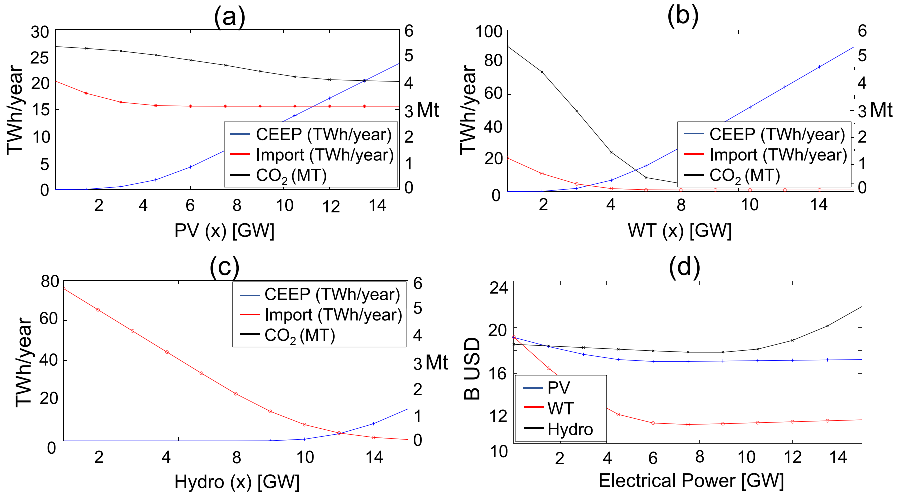

Fig. 8. Scenario S0 results: Impact of RES capacity on CEEP, imported electricity, CO$_2$ emissions, and total cost. (a) PV. (b) WT. (c) Hydro. (d) Total cost.

ultimately converge to similar values, with PH reaching the lowest economic values.

However, the behavior differs for Hydro(x), as shown in Fig. C7. While the total cost is initially low, it begins to rise rapidly beyond 10,000 MW of Hydro capacity, reaching high values. In this case, WOFF emerges as the new RES that minimizes costs. Fig. 9 provides a summary of the economic optimization for each combination of RES studied, with detailed results available in Table C1.

5.2.2. *CEEP analysis in scenario S1*

According to European standards, transmission lines are designed with a 15 % capacity margin [15]. In this analysis, this corresponds to a total transmission capacity of 6750 MW, distributed among exporting countries—Colombia and Peru. This collective capacity can accommodate the transportation of up to 60 TWh/year of electricity.

In the evaluation of CEEP, the study examined its behavior concerning different in scenario S1. When varying PV(x) capacity and other new RES (as illustrated in Fig. C2), it was observed that the maximum CEEP occurs when WOFF capacity reaches 10,000 MW. Conversely, geothermal energy has a relatively minor impact on surplus electricity in this context.

Regarding the WT(x) capacity increase (depicted in Fig. C5), CEEP levels exceeded the maximum allowable limit, reaching up to 140 TWh/year. This situation calls for strategies such as enforced WT stoppages to maintain the electrical system's stability.

Hydro(x) exhibited distinct behavior, as shown in Fig. C8. Beyond a capacity of 10,000 MW, CEEP increased significantly. However, it remained within acceptable ranges. To gain a comprehensive overview, Fig. 10 summarizes CEEP across various combinations of the EPS. Detailed data can be found in Table C1 [15].

5.2.3. *Imported eectricity in scenario S1*

Imported electricity represents the self-consumption of the EPS. Fig. C3 illustrates how imported electricity varies with P(x), with WOFF significantly reducing imports to a minimum when its capacity reaches 10,000 MW (Fig. C6). The impact of Hydro(x) on imported electricity is gradual, decreasing as capacity increases. Fig. 11 provides an overview of electricity imports for each configuration, highlighting PV, WT, and Hydro combinations as the largest annual importers. Nevertheless, the inclusion of PH or WOFF in this mix significantly reduces electricity imports.

Fig. 12 provides valuable insights into the optimal combinations of various energy sources with different capacities. In Fig. 12 (a), the optimal combination of WT(x) + PV + Hydro(x) + PH(x) indicates that expanding WT capacity is the most cost-effective choice compared to PV and Hydro, which tend to incur higher costs. Fig. 12 (b) presents the optimal combination of Hydro + PV(x) + WT + WOFF(x). Here, Hydro plays a crucial role in significantly reducing imported electricity due to its stable base load characteristics, while WT and PV, being intermittent sources, have a lesser impact on import reduction. Fig. 12 (c) illustrates

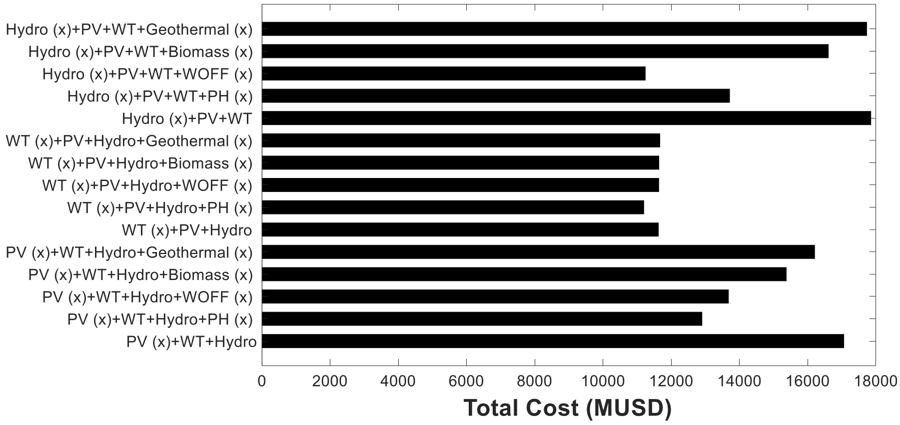

Fig. 9. Economic optimization summary for scenario S1.

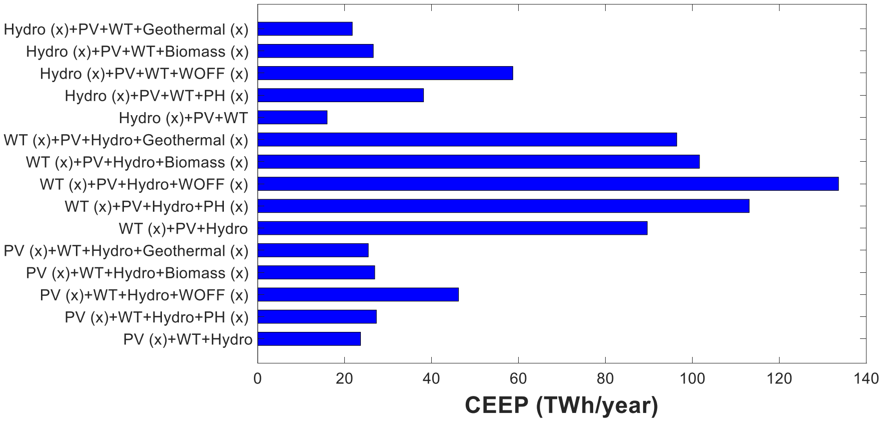

Fig. 10. CEEP outcomes for different RES combinations in scenario S1.

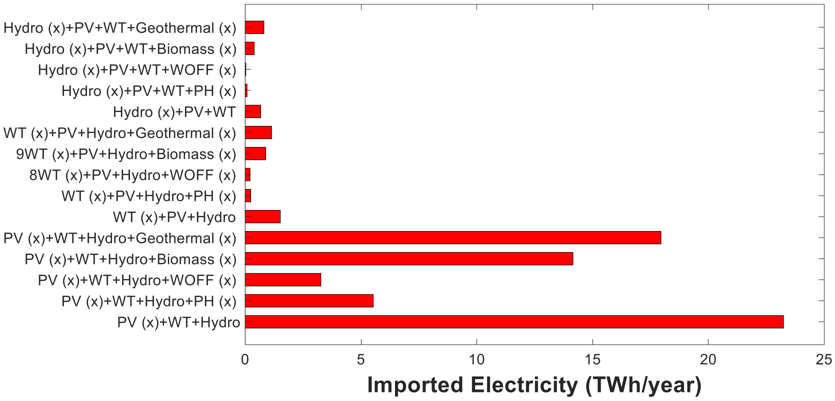

Fig. 11. Summary of the imported electricity in scenario S1.

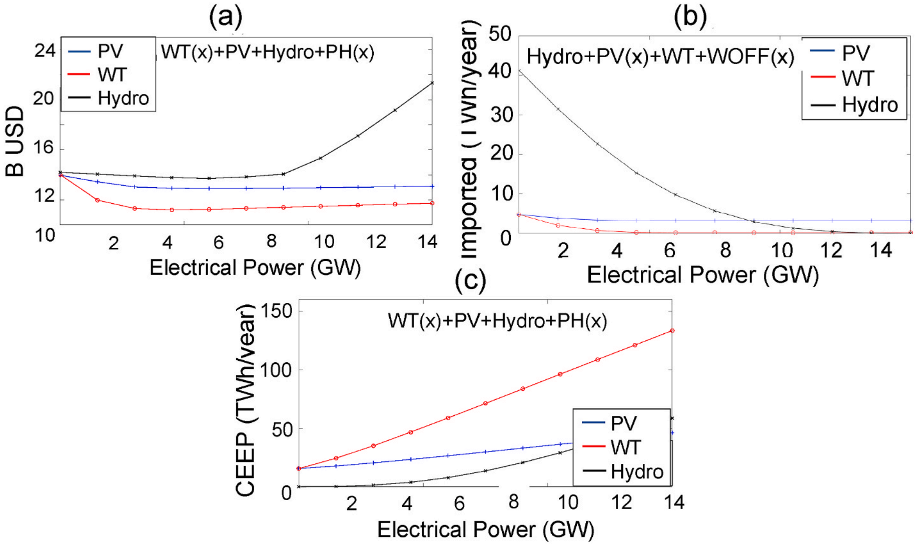

Fig. 12. Scenario S1 optimization: (a) Cost efficiency. (b) Imported electricity. (c) Maximum CEEP.

the optimal combination of WT(x) + PV + Hydro + PH. Concerning increasing WT capacity leads to the highest CEEP values, while Hydro exhibits the lowest increment, and PV remains relatively stable.

In summary, increasing the installed capacity of WT results in minimal total costs and imported electricity, alongside remarkably high CEEP values. Conversely, Hydro maintains relatively high costs, yet the CEEP remains acceptable and close to the maximum allowable limit. Importantly, the imported electricity decreases significantly once Hydro reaches a capacity of 10,000 MW, as demonstrated in Fig. 12.

In essence, optimizing these configurations entails maintaining certain energy sources at fixed capacities while adjusting others to achieve cost-effective and efficient outcomes. For detailed results, please refer to Tables C1–C3.

5.3. Scenario S2

5.3.1. Economic results

The economic results of scenario S2's optimization, as seen in Fig. D1, reveal notable trends. Increasing the capacity of WT(x) leads to a significant rise in CEEP. In contrast, Hydro(x) consistently maintains minimal CEEPs, while PV(x) maintains intermediate values. This CEEP trend inversely affects imported electricity, with WT(x) rapidly reducing this indicator.

Moreover, the total cost exhibits interesting dynamics. Expanding WT capacity substantially lowers the total cost, while increasing Hydro capacity maintains a relatively stable cost. It's essential to note that these results incorporate factors like V2G and H2G but exclude the influence of new RES, which will be discussed separately.

Figures D2, D5, and D8 provide further insights into the relationship between total cost and the capacity increase of PV, WT, and Hydro, respectively. Notably, total costs decrease as new RES capacity increases, with the most cost-effective scenario achieved through WT and WOFF capacity expansion. Detailed results are presented in Fig. 13 and Table D1, providing a comprehensive view of Scenario S2's economic optimization outcomes.

5.3.2. CEEP analysis in scenario S2

In scenario S2, the behavior of the CEEP closely mirrors that observed in scenario S1. Despite increased demand for V2G technology, the CEEP remains consistently high as the WT capacity expands, as depicted in Fig. D6. Conversely, the increase in Hydro capacity does not immediately impact the CEEP. However, once the Hydro capacity reaches 10,000 MW, it experiences a rapid rise, as illustrated in Fig. D9. Additionally, expanding the PV capacity beyond 5000 MW results in some CEEP, although at relatively modest levels. Notably, geothermal energy plays a role in contributing to these lower CEEP levels, as indicated in Fig. D3. For a comprehensive overview of these various combinations, please refer to Fig. 14 and Table D2. According to the data presented in Fig. 14, the combination with the highest CEEP value is WT (x) + PV + Hydro + WOFF + H2+V2G. However, it's important to highlight that removing the WOFF capability from this combination transforms it into the configuration with the lowest CEEP.

5.3.3. Imported electricity in scenario S2

In scenario S2, we explore the impact of RES capacity on electricity imports in the Ecuadorian EPS. Fig. D4, D7, and D10 illustrate how increased capacity in PV, WT, and Hydro affects imports. Expanding capacity in WT significantly reduces imports, highlighting their effectiveness. Higher capacity in Hydro also reduces imports, albeit gradually. PV systems have a milder impact, while WOFF demonstrates effective import reduction.

Table D3 provides a summary of minimum electricity imports for various scenarios in S2. Notably, the configuration of WT(x) + PV + Hydro + WOFF(x) + H2+V2G minimizes costs. WT(x) + PV + Hydro + PH(x) + H2+V2G maximizes CEEP, indicating surplus energy potential. Hydro(x) + PV + WT + WOFF(x) + H2+V2G minimizes imports as shown in Fig. 15. Detailed information about these optimal configurations is available in Fig. 16.

Comparing the results across scenarios S0, S1, and S2, we observe distinct patterns in terms of costs, CEEP, and electricity imports. In S0, the emphasis on conventional energy sources leads to relatively lower costs but limited CEEP and higher electricity imports. In contrast, scenario S1 explores a mix of RES, resulting in higher costs but substantial CEEP and reduced electricity imports. Finally, scenario S2 showcases the importance of optimizing renewable energy configurations. It demonstrates that specific combinations, such as WT(x) + PV + Hydro + WOFF (x) + H2+V2G, can minimize costs, maximize CEEP, and significantly reduce electricity imports, emphasizing the potential of well-designed renewable energy integration in the Ecuadorian EPS. For better understanding, Table 7 displays some advantages and disadvantages of the proposed scenarios.

5.4. Maximum feasible RES penetration in the Ecuadorian EPS

To determine de maximum feasible penetration of RES in the Ecuadorian EPS by 2050, the analysis relies on the CEEP, which depends on transmission line capacities and primary energy supply (PES). Ref. [54] introduces the Coefficient of Commitment (COMP), which signifies the ratio between ΔPES and ΔCEEP as RES penetration escalates. Maximum RES penetration occurs when COMP nears unity, as discussed in Refs. [55,56]. The methodology consistently determines the most feasible penetration levels across all scenarios, with selected COMP values closest to unity presented in Table 8.

The results reveal that the process of decarbonizing the EPS leads to diminished maximum technical RES penetration levels, with S0 demonstrating lower levels compared to S1. The introduction of DR mechanisms, such as V2G and H2G, enhances the potential for renewable integration. In a fully renewable EPS, various energy sources, including PH, biomass, geothermal, and conventional Hydro, play vital roles in preserving EPS stability.

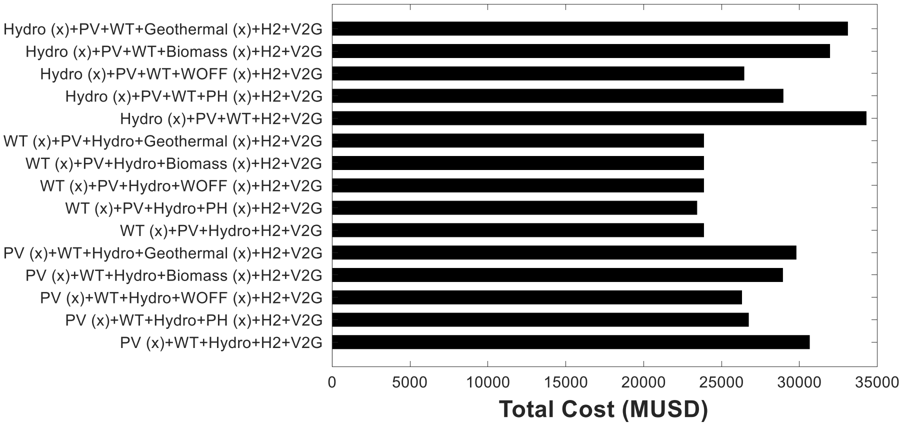

Fig. 13. Summary of the economic optimization of scenario S2.

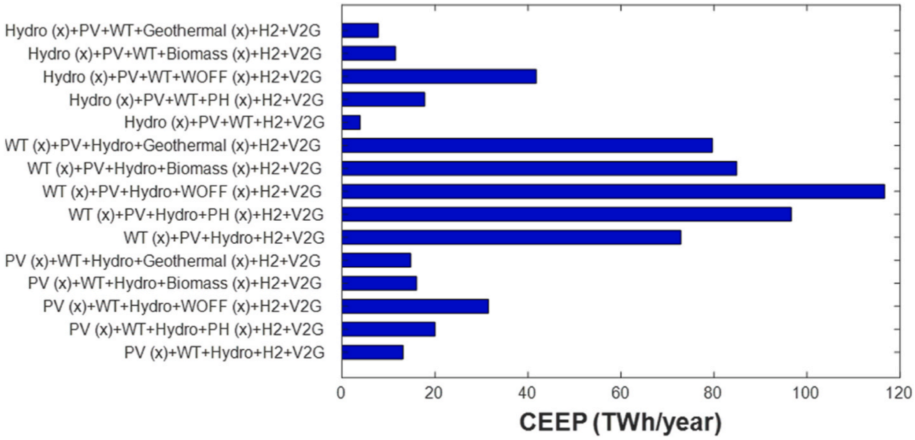

Fig. 14. CEEP outcomes for different RES combinations in scenario S2.

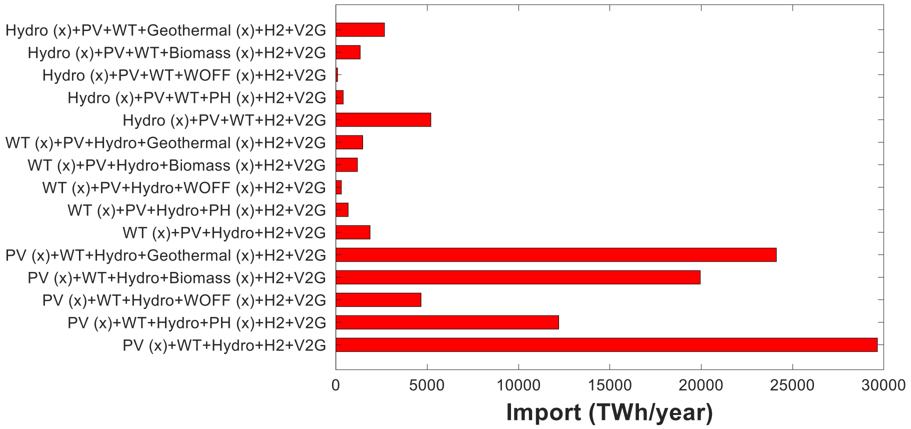

Fig. 15. Imported electricity overview in scenario S2.

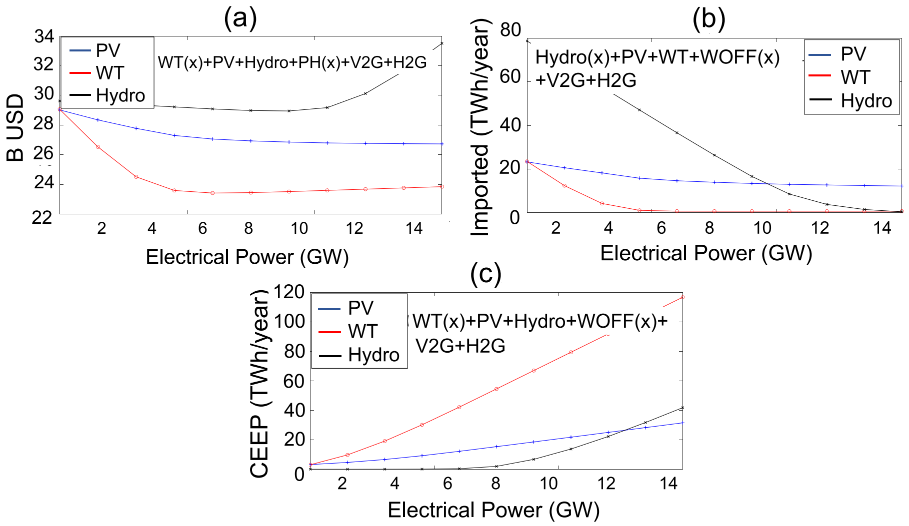

Fig. 16. Scenario S2 optimization: (a) Cost-efficiency. (b) Maximized CEEP. (c) Import reduction.

5.5. *Sensitivity analysis of V2G*

Given the novelty of demand response in the Ecuadorian EPS, this section conducts a sensitivity analysis concerning V2G, specifically within scenario S2. The analysis relies on the maximum technically feasible penetration of RES, as outlined in Table 8. This analysis focuses on the variation in Hydro capacity, a representative RES concerning CEEP, total costs, and imported electricity.

Table 7
Advantages and disadvantages of proposed scenarios.

Criterion	Scenario S0	Scenario S1	Scenario S2
Renewable Energy Penetration	Low renewable energy penetration, high reliance on hydroelectric power.	Higher renewable energy penetration, reduced reliance on hydroelectric power.	High renewable energy penetration, diversification of sources.
Grid Stability	Higher risk of instability due to reliance on a single energy source.	Improved stability due to greater source diversification.	Integration of emerging technologies for enhanced stability.
Environmental Sustainability	Lower contribution to carbon emissions reduction.	Moderate contribution to carbon emissions reduction.	Higher reduction in carbon emissions and greater environmental sustainability.
Energy Independence	Dependence on imported electricity due to lack of source diversification.	Lower dependence on imported electricity due to source diversification.	Higher energy independence due to integration of emerging technologies.
Total System Cost	Lower operating and maintenance costs but higher long-term risks.	Moderate operating costs and lower long-term risks.	Slightly higher operating and maintenance costs but lower long-term risks.

Table 8
Maximum technically feasible RES penetration levels according to COMP index calculations.

Electrical Sources	S0 (%)	S1(%)	S2 (%)
PV	37	36	47
WT	27	25	28
Hydro	86	85	87
PH	–	65	70
WOFF	–	17	23
Biomass	–	18	19
Geothermal	–	10	12

Fig. 17 (a) illustrates the relationship between Hydro(x) and CEEP for various V2G penetration levels. It highlights that the maximum technical level, roughly 87 % of Hydro capacity or around 14,000 MW, results in a CEEP between 40 and 60 TWh/year. Increased V2G penetration corresponds to lower CEEP values.

Fig. 17 (b) demonstrates how the maximum technically feasible Hydro penetration, i.e., 87 %, converges to a total cost of approximately 32,000 million US dollars, and all V2G scenarios converge to this same cost point.

Finally, Fig. 17 (c) depicts the variation of Hydro capacity with respect to imported electricity. In this case, the maximum technical level corresponds to imported electricity close to zero. These analyses elucidate the complex interactions among Hydro capacity, V2G penetration, CEEP, total costs, and imported electricity, offering valuable insights for optimizing the integration of renewable energy sources within the EPS.

5.6. Sensitivity analysis of H2G

This section presents the results of a sensitivity analysis conducted on the relationship between Hydro capacity and H2G, as depicted in Fig. 18. The analysis is aimed at discerning the impact of varying H2G penetration levels on the EPS, particularly with regard to CEEP, total costs and imported electricity.

Fig. 18 exhibits results similar to those observed in the V2G sensitivity analysis (Fig. 17). As H2G penetration increases, there is a noticeable decline in CEEP. However, this reduction is accompanied by an overall convergence in total costs and imported electricity.

To delve into the technical, economic, and environmental implications, Fig. 18 illustrates the intricacies of H2G integration within the EPS. Initially, as H2G penetration increases, costs also rise. However, this cost increase reverses as Hydro capacity expands, leading to a point where total costs converge.

A similar pattern emerges concerning imported electricity; higher H2G penetration leads to increased imported electricity until it stabilizes at the point where Hydro capacity gains dominance. These insights provide valuable guidance for optimizing the integration of H2G within the EPS, considering various technical, economic, and environmental factors.

5.7. Comparative analysis with other research

In this section, Table 9 offers a detailed comparison between the current article and selected references [26,27], and [30]. Key differences and similarities in research focus, methodology, and major findings of these studies are highlighted. Notably, the inclusion of various RES plays a significant role in reducing the heavy reliance on Hydro and conventional sources. For instance, considering the stability of the Ecuadorian EPS, a recommendation is made for a 65 % increase in PV, a

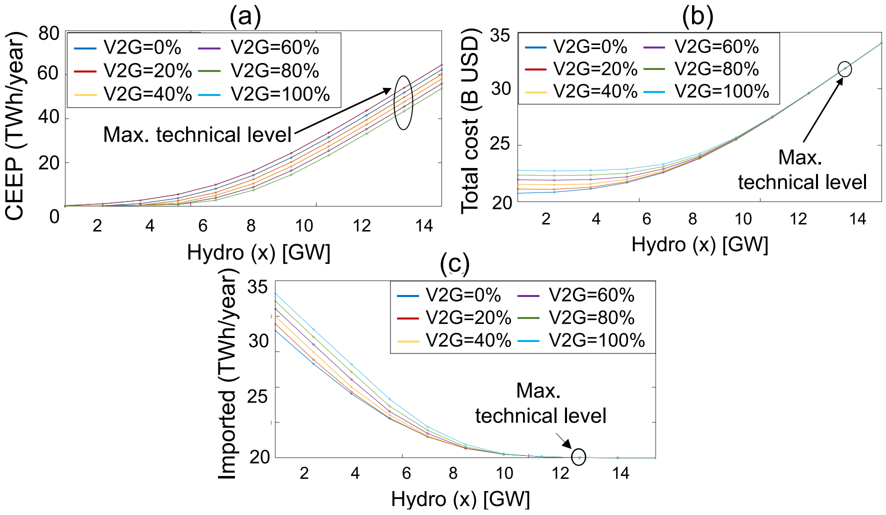

Fig. 17. Sensitivity analysis results of V2G relative to Hydro capacity (x). (a) Critical excess electricity production. (b) Total costs. (c) Imported electricity.

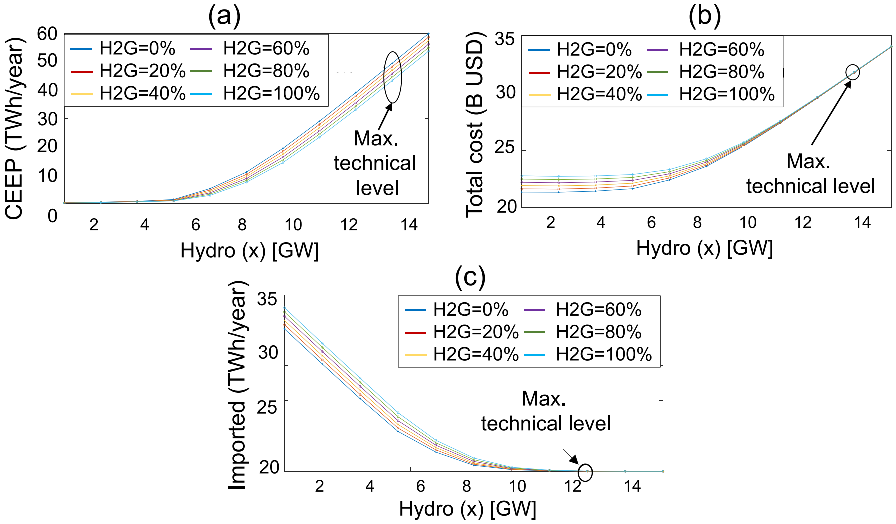

Fig. 18. Sensitivity analysis of H2G in relation to Hydro capacity (x). (a) Critical excess electricity production. (b) Total cost. (c) Imported electricity.

Table 9
Comparative overview of research aspects.

Aspect	Present paper	Ref. [26]	Ref. [27]	Ref. [30]
Research focus	Energy planning for Ecuador in 2050. Focused on demand forecasting accuracy and proposed scenarios.	100 % RES scenario for Ecuador in 2050 with V2G technology. Emphasis on storage impact. Technological based solutions.	100 % RES scenarios for Ecuadorian Sites (Galápagos and Cuenca) in 2050. Optimal energy mix and locations. Emphasis on heritage preservation.	Technical-economic study for 100 % RES in the Galápagos Islands, Ecuador in 2050. Demand forecasting and sensitivity analysis.
Methodology	ANFIS DR mechanisms. Maximum RES feasible penetration EI, V2H and H2G. EnergyPlan.	Hourly data iterations. Analysis with EnergyPLAN. Emphasis on V2G impact on storage.	Scenario planning with EnergyPLAN. Analysis of RES locations. Legal and regulatory considerations	Load curve forecasting with NARX. EnergyPLAN simulations. Sensitivity analysis on renewable and battery capacities.
Key findings	Reduction of hydro dependency Increase in PV, WT, PH, with penetration rates of 65 %, 9 %, and 28 %, Maximum feasible geothermal penetrations of 10 %, and WOFF with 17 %. Increased interconnections with Colombia and Peru.	V2G influences storage needs in energy transition. Importance of diversified energy sources and technological advancements. Significance of political support.	Feasibility of 100 % renewable energy in heritage sites. Optimal energy mix and locations. Need for public awareness.	Cost-effective adoption of RES. Impact of renewable capacities on costs. Carbon reduction through decarbonization. Future developments with EnergyPLAN.

modest 9 % increment in WT, and a substantial 28 % augmentation in PH. Furthermore, the study suggests the need to enhance transmission line capacities with neighboring countries, Colombia and Peru, due to potential limitations associated with new RES such as WOFF or geothermal. Lastly, the seamless integration of V2G and H2G technologies into the EPS is proposed, as they serve as virtual batteries, facilitating effective DR mechanisms.

This comprehensive analysis provides valuable insights into the individual contributions of these research efforts to the fields of energy planning and renewable energy integration.

6. Conclusions

In this paper, a comprehensive long-term electrical system planning model for Ecuador in the year 2050 has been developed and analyzed. The introduction of the Neuro-Fuzzy Adaptive Inference System (ANFIS) for demand forecasting, with a minimum error of 8 × 10ˆ(−5), establishes a robust foundation for precise electrical system planning. Scenario-based optimization (S0, S1, and S2) provides a thorough insight into the implications of various economic and technological options.

By 2050, it is anticipated that the integration of renewable energy sources and energy storage systems, such as photovoltaic, wind, and pumped storage, with penetration rates of 65 %, 9 %, and 28 %, respectively, will significantly reduce the current reliance on conventional and hydroelectric energy sources. Furthermore, it will contribute to ensuring the stability of the electrical system.

Sensitivity analyses of V2G and H2G demonstrate their capability to minimize costs, maximize critical excess electricity production, and reduce electricity imports, highlighting their relevance in sustainable electrical system planning. On the other hand, the determination of maximum technically feasible penetration levels for renewable energy sources reveals that hydroelectricity can achieve the highest levels of penetration, while geothermal, biomass, and offshore wind have the lowest levels of possible penetration in the Ecuadorian electrical system. These findings underscore the importance of cross-border energy collaboration with neighboring countries like Colombia and Peru, improving system stability and maximizing surplus energy utilization.

In summary, this research provides a roadmap for the development of a sustainable, efficient, and resilient electrical system in Ecuador. Future work can focus on the socioeconomic and political implications of the transition to a more sustainable electrical system in developing countries like Ecuador.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.129446.

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