Article:

Pupo-Roncallo, O., Campillo, J., Ingham, D. et al. (2 more authors) (2021) The role of energy storage and cross-border interconnections for increasing the flexibility of future power systems: the case of Colombia. Smart Energy, 2. 100016. ISSN 2666-9552

https://doi.org/10.1016/j.segy.2021.100016

Smart Energy 2 (2021) 100016

Contents lists available at ScienceDirect

Smart Energy

journal homepage: www.journals.elsevier.com/smart-energy

The role of energy storage and cross-border interconnections for increasing the flexibility of future power systems: The case of Colombia

O. Pupo-Roncallo [a], [*], J. Campillo [b], D. Ingham [a], L. Ma [a], M. Pourkashanian [a]

[a] Energy 2050, University of Sheffield. 40 Leavygreave Road, Ella Armitage Building, Sheffield, S3 7RD, UK
[b] Department of Electrical Engineering, Universidad Tecnológica de Bolívar. Parque Industrial y Tecnológico, Carlos Vélez Pombo, Km 1 Vía Turbaco, Cartagena, 130012, Colombia

ARTICLE INFO

Article history:
Received 7 November 2020
Received in revised form
26 March 2021
Accepted 10 April 2021
Available online 20 April 2021

Keywords:
Electricity energy storage
Interconnections
RES
EnergyPLAN
Colombia
Optimisation

ABSTRACT

The rapid expansion of renewable energy technologies in the electricity sector introduces new significant challenges for power systems due to their high intermittency. Therefore, more flexibility is needed to ensure that the system can operate reliably and cost-effectively with large shares of variable renewable energy sources (RES). Electricity energy storage and cross-border interconnections are considered two key components for allowing further integration of these sources. Therefore, the aim of this study is to analyse the techno-economic effects of grid-scale electricity storage and interconnections in the integration of variable RES by using the power system of Colombia as a case study. The EnergyPLAN tool was used for building the reference system model and future scenarios. Initially, the technical impacts of electricity storage and interconnections in the power system were examined. Successively, a multi-objective evolutionary algorithm (MOEA) was applied to perform a techno-economic optimisation and identify a set of optimal configurations. The results evidenced that increasing levels of storage and interconnections could allow further penetration of variable RES, achieving total annual electricity production levels of approximately 96.8%. Further, significant reductions in both the fuel consumption and CO_2 emissions might permit an emission factor of the power sector of approximately 26.5 gCO_{2e}/kWh.

1. Introduction

Increasing the flexibility of power systems is a key component in the global efforts oriented to meet the climate change mitigation goals defined at the 21st Conference of Parties (COP21) in Paris in 2015. The integration of large amounts of variable renewable energy sources (RES) into the power grid poses important techno-economic challenges due to their highly intermittent energy generation [1]. This is one of the main focus of the Smart Grid approach, and thus, a flexible power system is required in order to reach renewable integration targets without affecting the reliability and efficiency of the grid. Several options have been proposed in order to increase the flexibility of the system, and these include demand-side management (DSM), energy curtailment, sector coupling, expansion of the transmission grid and energy storage systems [2,3]. In addition, the recent technological developments in power electronics and modern distribution equipment have also contributed to the stability of the grid [4]. Lund et al. [5,6] introduced the concept of Smart Energy System and stated that the smart electricity, thermal and gas grids should synergise in order to achieve optimal solutions for the complete energy system. This study focuses its attention on the smart electricity grid and considers utility-scale electricity storage (ES) and grid capacity expansion as two of the main technologies suited to assist in the successful integration of high share of RES, especially in those countries with poor infrastructure [7]. Therefore, when the term “energy storage” is used in this study, it refers to electricity energy storage as proposed by the smart energy system approach [5,8].

The energy storage potential is specific to each country and it mainly depends on the availability of the resources, regulations, transmission infrastructure and energy consumption patterns. Latin America is reported as one of the most interesting emerging markets for storage projects development due to its current

---

[*] Corresponding author.
E-mail addresses: orpuporoncallo1@sheffield.ac.uk (O. Pupo-Roncallo), jcampillo@utb.edu.co (J. Campillo), d.ingham@sheffield.ac.uk (D. Ingham), lin.ma@sheffield.ac.uk (L. Ma), m.pourkashanian@sheffield.ac.uk (M. Pourkashanian).

https://doi.org/10.1016/j.segy.2021.100016

progress in renewable energy production, fast increasing population and unbalanced grid conditions [9]. Further, the power market integration through a strong interconnection in the region could improve the security of supply, reduce emissions and exploit the complementarities of resources available in each country [10]. However, a complete understanding of the effects of ES and electricity interconnections in the electricity system requires the development of energy models that allow the assessment of its performance. Previous studies have focused its attention on this issue [7], but these are mainly focused on small-scale applications [11], island energy systems [12,13] and specific markets with highly developed economies, such as the case of European countries and the United States [14–16]. For instance, Cebulla et al. [2] analysed different energy storage and RES expansion investigations pertinent to the US and Europe. Bussar et al. [17] used the GENESYS model to analyse the long-term impact of energy storage in the future interconnected European power system.

Other studies have focused their attention on the national level, for instance, Edmunds et al. [14] developed four future scenarios including energy storage and interconnections in the Great Britain power system. Andersen at al [18]. Explored the effects of large-scale storage in Denmark. Limpens et al. [19] studied the different trade-offs between RES shares, storage and curtailment for Belgium, and Conolly et al. [20] investigated the benefits of pumped hydroelectric energy storage (PHES) and wind power in the Irish power sector.

In the case of countries characterised by a high share of hydropower in their electricity mix, such as many Latin American countries, very few studies [21] have investigated the effect of grid-scale ES and international electricity interconnections for increasing the flexibility of the power system. Regarding this latter, the main focus of these works has been on the market behaviour rather than the impact of RES penetration [22]. Thus, the aim of this paper is to analyse the techno-economic impact of large-scale electricity energy storage and interconnections in the integration of intermittent renewable energy by using the electricity system of Colombia as a case study. Two approaches are followed in this study: a parametric analysis for finding the effect of energy storage and interconnections on the integration of wind and solar PV in the power system; and a multi-objective optimisation oriented to minimise energy-related GHG emissions and costs. The EnergyPLAN modelling tool has been used to develop the model and simulate the scenarios. Further, a new optimisation model, named MOEA Eplan and developed by the authors in MATLAB, is introduced and used for the analysis. Technical details of these tools are further explained in Section 3.

In the literature, some studies have already introduced some optimisation tools linked to the EnergyPLAN simulation software [23]. For instance, Bjelic et al. [24] used the optimisation tool GenOpt linked to EnergyPLAN for the planning of national energy systems under EU framework. Eurac Research [25] developed the EPLANopt model that couples EnergyPLAN with Python, and applied it to optimise energy efficiency scenarios in buildings. Manhub et al. [26] also built an optimisation model written in Java in order to design future scenarios, and applied it to the city of Aalborg in Denmark. Cabrera et al. [23] developed the MATLAB Toolbox MaT4EnergyPLAN to run EnergyPLAN from MATLAB. However, all these tools require a certain level of experience in the coding language they were designed for its use and configuration. MOEA Eplan offers a user-friendly interface in a widely used software between the scientific community (MATLAB) in order to run the optimisations and no previous knowledge of coding is required for its execution.

The findings of this work can greatly assist energy system planners and policymakers to understand the positive effect of flexibility options such as energy storage and interconnections when modelling and analysing future energy systems in countries with a high share of hydropower in their electricity mix.

This paper is composed of five sections. Section 2 presents an overview of the current Colombian power system and its cross-border interconnection capacity. Section 3 introduces the methodology used to build the scenarios and perform the techno-economic optimisation. Section 4 presents the results from the simulated scenarios and the Pareto front obtained. Finally, the conclusions provide a final discussion of the main findings and further research areas are identified.

2. Electricity sector in Colombia

The Colombian electricity sector comprises 17% of the entire energy demand in the country. It has been historically dominated by hydropower generation with an average annual electricity production of about 71% of the total, followed by conventional thermal generation (28% of the total) and other renewables (i.e. wind, solar and bioenergy) that account for only 1% of the total production [27]. The total installed capacity in 2017 (14.4 GW) consisted of 69.9% hydropower, 29.2% conventional thermal power generation (mainly natural gas, coal and diesel fuelled-plants), 0.8% bioenergy and 0.1% wind [28]. There is not currently any large-scale electricity storage system installed in the country, and although the hydropower dam reservoirs store large amounts of energy, it can only be used for long-term purposes because its short-term operation is constrained because of the system configuration. The high reliance on hydro resources makes the system vulnerable to cyclical weather anomalies caused by El Niño and La Niña southern oscillation (ENSO) [29]. During these periods, the electricity production by hydropower plants can fluctuate between 45% and 95% due to the changes in the natural water inflows to the dams [30]. Conventional fossil fuel energy production is used to preserve the stability of the grid due to constraints in the power transmission system. Further, during dry seasons, when hydropower generation is reduced, they are used to meet the electricity demand.

In terms of cross-border interconnection, the first agreement was reached between Colombia and Venezuela in 1992 with two main projects (Cuatricentenario and Corozo) as shown in Table 1. These projects were developed by governmental companies due to the lack of international regulation [31], however, they are not currently in operation and were replaced by a new line with lower capacity (Cadafe). Later in 2003 and following the Decision 536 of the Andean Community (CAN), the interconnection between Colombia and Ecuador was developed. This line is part of an ambitious plan, proposed by the CAN, that is expected to include Peru, Bolivia and Panama [22]. These countries have historically shared a similar organisational structure of the electricity market, promoting competition through the participation of the private sector. They have abundant resources for hydropower production and use the merit order dispatch mechanism [10]. As illustrated in Table 1, Colombia and Ecuador share four transmission lines with a maximum export capacity of 535 MW [32]. The interconnection between Colombia and Panama is expected to start operations by the end of 2020 with a maximum capacity of 300 MW [33]. Colombia, Ecuador, Panama and Peru are highly dependent on hydroelectricity and thus they are affected by seasonal variations caused by ENSO that limits their generation ability to match the demand during dry periods. However, the effect of this weather anomaly on each country is different, while there are droughts in Ecuador and Peru, high level of precipitations occurs in Colombia and Panama, and vice versa. Therefore, increasing the interconnection capacity between these countries could also contribute to the reliability of the power supply taking advantage of their

Table 1
Cross-border interconnection capacity in Colombia [32,34].

	Import capacity [MW]	Export capacity [MW]
Interconnection Colombia-Ecuador		
Ecuador 230	360	500
Ecuador 138	35	35
Interconnection Colombia-Venezuela		
Corozo 1 (not operative)	55	150
Cadafe	0	36
Cuatricentenario 1 (not operative)	150	150

hydrological complementarity patterns [22].

3. Methodology

This section describes the methods used in order to build the scenarios and analyse the techno-economic impacts of electricity energy storage and cross-border interconnections in the future Colombian electricity system.

3.1. Colombian model in EnergyPLAN

Analysing the effects of energy storage at the national level requires the development of a model that is able to represent in detail the Colombian power system. In this study, the EnergyPLAN tool was selected after considering a wide range of modelling tools currently available in the literature [35]. This tool was developed as open-source by Aalborg University in Denmark [36,37] and its main objective is to assist in the design of local, regional or national long-term energy planning strategies based on the technical and economic analysis of different alternatives defined by policymakers. EnergyPLAN generates a deterministic model using analytical programming instead of iterations, and thus is able to compute the calculations in a smaller amount of time than similar models that use iterative solvers. It runs a high-temporal resolution simulation over a one-year period and produces hourly outputs. Therefore, the effects of intermittent renewable sources production, large-scale energy storage and cross-border interconnections can be examined in detail. The process diagram of the EnergyPLAN inputs/outputs are shown in Fig. 1. More details about the modelling tool features and applications can be found in Refs. [36,37].

The development of an energy system model in EnergyPLAN that accurately represent the Colombian power system requires a group of inputs and assumptions that need to be validated against actual data [27,32]. The detailed methodology applied for the validation process is provided by Conolly in Ref. [38], and this involves a comparison between the reference model outputs and actual figures reported by different agencies. In this study, the relative difference between the modelled and actual production from the different power sources was found to be less than 4%, as reported in previous works developed by the authors and available in Refs. [27,39]. Therefore, the reference model represents the Colombian power system accurately and thus can be used to build future energy scenarios. This model was built from inputs based on the country's statistics from 2014. Data from 2015 to 2016 were available at the time the model was developed, but these years were affected by a strong ENSO and thus they do not exemplify the usual behaviour of the power system. The total electricity demand for the reference year was approximately 64.3 TWh, and the hourly power supply and demand were supplied by XM (National grid) [34]. Conventional power plant capacities and efficiencies were provided by the Colombian Electrical Information System (SIEL) [28]. The total variable RES installed capacity connected to the national grid in the reference year was only 19.5 MW, and this corresponds to the Jepirachi wind farm. In order to include further integration of RES in the future scenarios, wind and solar datasets were built following the approach adopted by the authors in previous studies [27,32]. The CO_2 emissions were estimated based on the fuel consumption following the guidelines for stationary combustion provided by the Intergovernmental Panel on Climate Change (IPPC) in Refs. [38,40].

3.2. Future scenarios

Following the validation of the reference model, a complete system analysis can be performed. Thus, a baseline scenario and two alternatives were built for the Colombian power system in 2030 (see Table 2). These scenarios were developed based on the inputs from previous studies [22,27,41–43] and different specialised governmental and private organisations [44,45] as follows:

1. Scenario 1 (baseline): This scenario is commonly known as the business as usual (BaU) scenario and it is based on the outlook defined by the Colombian government in order to define the intended Nationally Determined Contributions (iNDC) presented in the COP21 [46]. It assumes that the current trends in energy demand and supply will remain unaffected.
2. Scenario 2 (COL 2030 + ES): This scenario was developed from the results of Section 4.1, and it suggests further penetration of wind and solar PV in the power mix with storage levels that could be technically achievable by 2030.
3. Scenario 3 (COL 2030 + ES and interconnections): This scenario was built according to the results from Section 4.1. This alternative includes the same inputs as scenario 2 and assumes an increase in the capacity of cross-border interconnection with neighbouring countries based on the government projections for 2030 [45].

3.2.1. Energy storage and cross-border interconnections

In order to quantify the technical impacts of grid-scale energy storage and interconnections in electricity systems with increasing capacities of intermittent renewable sources, it is necessary to vary the levels of penetration of these variables.

For the case of energy storage, different amounts of installed charge/discharge power were simulated for increasing levels of wind, solar PV and a combination of both. It should be noted that charging and discharging capacities are assumed to be the same for these simulations and the energy storage capacity is fixed at 10 GWh based on the results reported by IRENA in Ref. [43]. During the optimisation process, different levels of power and energy storage capacities were explored in order to find the best system configurations (see Section 4.3).

Pumped hydro energy storage (PHES) was selected as the technology to be modelled in the power system due to its current level of development [47], suitability for assisting in the integration of large-scale RES [21,43] and the great potential reported

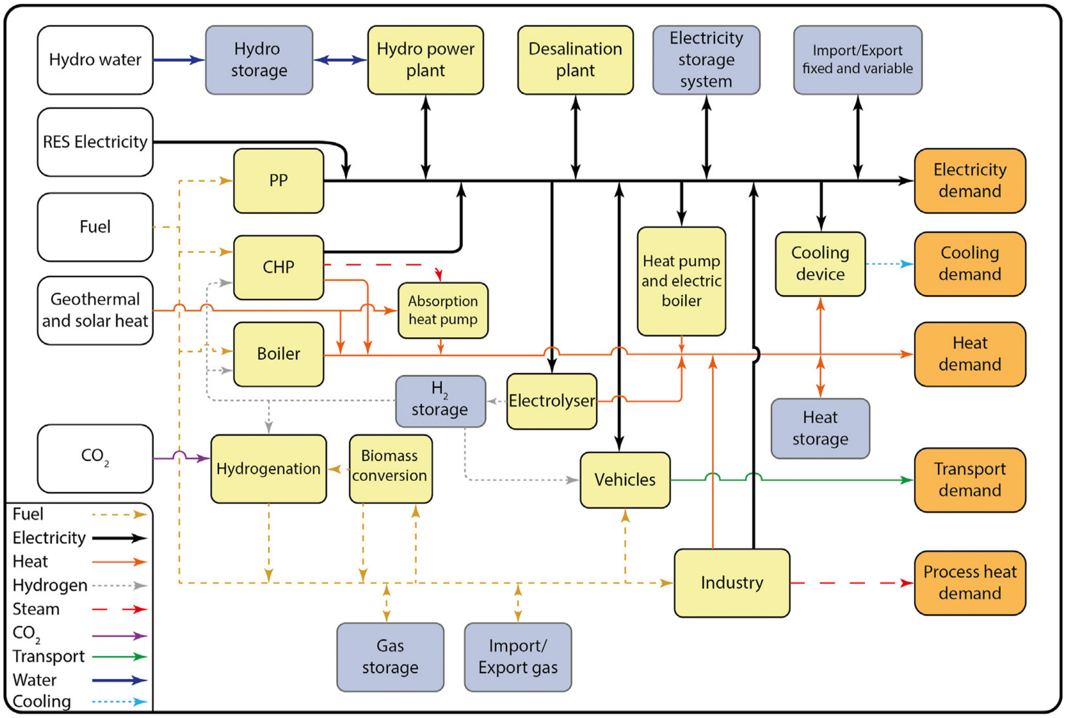

Fig. 1. Overall sketch of the EnergyPLAN modelling tool [37].

Table 2
Input data for the reference and future scenarios.

	Ref. 2014	BaU 2030	COL 2030 + ES	COL 2030 + ES and Interconnection
Electricity Demand				
Total electricity demand (TWh/year)	64.37	100.53	100.53	100.53
Electricity Supply				
Dammed hydro power (MW)	10920	14895	14895	14895
Thermal power (MW)	4735	6149.8	6149.8	6149.8
Biomass (MW)	72	108	108	108
Wind power (MW)	19.5	594	4000	4240
Solar PV power (MW)	0	0	7000	7420
Electricity storage				
Storage power (MW)	0	0	2000	2000
Storage capacity (GWh)	0	0	10	10
Cross-border interconnection				
Transmission line capacity [MW]	571	571	0	1000

[39,43,47] for application in countries with similar topographies to Colombia.

Regarding the interconnections, the current capacity was discussed in Section 2. The interconnection level in Colombia could increase in the coming years, however, the ability to rely on external energy supply will depend on the market agreements and electricity mix within the linked countries [48]. Some studies [49] have analysed the feasibility of an inter-regional grid for the Americas, and for the case of Colombia, Ochoa et al. [43] suggested that by 2030 an interconnection capacity of 3 GW could be achieved. Therefore, in this study the total cross-border interconnection capacities were varied from 0 to 3 GW in order to assess its impact on the national electricity system.

3.3. Energy storage modelling

The simulation of energy storage in EnergyPLAN is performed by defining power and energy capacity, charging and discharging efficiency and the operation strategy. The power capacity represents the charging/discharging rate of the device (usually in MW for large-scale applications), the energy capacity represents the amount of energy stored in the device (typically measured in GWh for utility-scale applications) [50,51]. The tool can simulate different storage technologies (PHES, CAES, battery or hydrogen storage) and they are mainly used to avoid critical excess of electricity (CEEP) [52]. Therefore, the primary objective is to integrate the maximum feasible levels of variable renewable penetration [20].

A comprehensive description of the equations and simulation strategies applied in this study and available in the EnergyPLAN tool can be found in Ref. [37]. The storage system is charged when there is an excess of electricity that leads to energy curtailment (i.e., if $e_{CEEP} > 0$). In this case, the electricity transferred to the charging device is estimated using equation (1). In addition, the energy stored after the charging process is estimated applying equation (2).

$$e_C = \min\left[e_{CEEP}, \frac{C_S - S_S}{\eta_C}, Cc\right] \tag{1}$$

$$S_S = S_S + (e_c \cdot \eta_c) \tag{2}$$

where C_S is the maximum energy capacity, S_S is the amount of energy being stored, Cc is the charging device capacity, and η_C is the charging efficiency.

The energy discharge process is performed, firstly by replacing electricity imports, and then by substituting thermal power plant production (i.e. if $e_{PP} > 0$). Therefore, the electricity supplied by the storage system is estimated using equation (3). Subsequently, the energy remaining in the system after discharging is calculated using equation (4) as follows:

$$e_T = \min[e_{PP}, (S_S \eta_G), C_T] \tag{3}$$

$$S_S = S_S - \frac{e_T}{\eta_G} \tag{4}$$

where S_S is the amount of energy sent to the grid, C_T is the discharging device capacity, and η_C is the discharging efficiency. The PHES round-trip efficiency used in this study was 76%, according to the values reported in relevant literature [53] for this technology.

In general, the simulation strategy seeks to use RES production directly when is available to match the electricity demand. However, in the case of energy surplus the energy excess will be stored and used when needed.

3.4. Cost structure

The economic assessment is an important part of every renewable integration analysis. In this study, the cost associated with the power system were calculated as a differential cost [13]. Thus, only the investment costs associated with new capacity added to the reference system model (2014) were considered, and these represent the total transition cost from the reference system to the future proposed in the defined scenarios. The total costs were annualised, and these include capital investment, fixed and variable operation and maintenance (O&M), integration and CO_2 costs. All the future technology efficiencies and technology and fuel costs are based on 2030 projections by IRENA [54], the EnergyPLAN cost database [37] and the energy technology reference indicator projections (ETRI) from the European Commission [55]. A discount rate of 8%, which has been used when evaluating other similar projects in Colombia [56], and a CO_2 price of 40 €/tCO_{2e} [57] were defined into the model. Table 3 shows the list of costs in 2030 for all the technologies considered in this research.

3.5. Optimisation with MOEA Eplan

After defining multiple scenarios for assessing the impact of large-scale energy storage and cross-border interconnection on the power system through the parametric analysis, a techno-economic optimisation was performed in order to find the best configurations for the Colombian system. For this purpose, the authors developed a MATLAB app, called MOEA Eplan, that can be accessed freely from the open access repository Zenodo in Ref. [58]. This app integrates the EnergyPLAN modelling tool with the Multi-objective evolutionary algorithm (MOEA) used by the MATLAB optimisation toolbox [59] in order to provide a framework for energy scenario analysis and design. The app was built using the script developed by Cabrera et al. [23] to call EnergyPLAN from MATLAB and link them with the optimisation toolbox through a user-friendly interface. The MOEA is a meta-heuristic optimisation algorithm that was inspired by the natural selection principle. This kind of algorithm is especially suited for complicated problems where finding the optimal solution is computationally impractical [26]. MOEA Eplan uses an elitist and controlled variant of the Non-Dominated Sorting Genetic Algorithm (NSGA-II) described by Deb in Ref. [60]. Fig. 2 illustrates the steps followed by the algorithm. Firstly, all the hourly distributions and relevant costs are defined and fixed into each EnergyPLAN model. These parameters are fixed and do not change during the optimisation process. Then, an initial population is generated, and the objective function of each individual is evaluated by the modelling tool. These values are sent back to the main script that rank them according to its fitness. After the ranking process of all the individuals, the algorithm generates the next generation (new group of individuals) by applying the defined operator of the genetic algorithm: parent selection, crossover and mutation. The loop continues until the convergence criteria are matched and a Pareto-optimal front is generated by the MOEA [25].

In this case study, the objective functions are the total annual costs and GHG emissions of the power system and both are to be minimised. The optimisation decision variables are the following: (i) solar PV installed power, (ii) wind power capacity, (iii) pump capacity (ES charging power), (iv) turbine capacity (ES discharging power) and (v) energy storage capacity. The input range (upper and lower bounds) for each decision variable are shown in Table 4. The cross-border transmission capacity is considered a constraint rather than an input in this study because its expansion usually depends on international agreements.

4. Results and discussions

In this section, the results of the simulated scenarios and the optimisation process are introduced. Section 4.1 summarises the results of adding energy storage and interconnection capacity into a power system with increasing RES penetration. Section 4.2 presents the most important findings from the scenario simulations, and

Table 3
Projected capital investment and O&M costs for 2030 [37,54,55].

Production type	Capital investments [M€/unit]	Lifetime [Years]	O&M [% of invest.]
Large power plants [MW]	0.83	25	3.35
PHES Pump [MW]	0.3	50	0.75
PHES Turbine [MW]	0.3	50	0.75
PHES storage [GWh]	7.5	50	1.5
Interconnection (International) [MW]	0.66	60	1
Wind [MW]	1.14	25	2.2
Solar PV [MW]	0.64	25	1.7
Hydropower [MW]	2.55	60	1.25

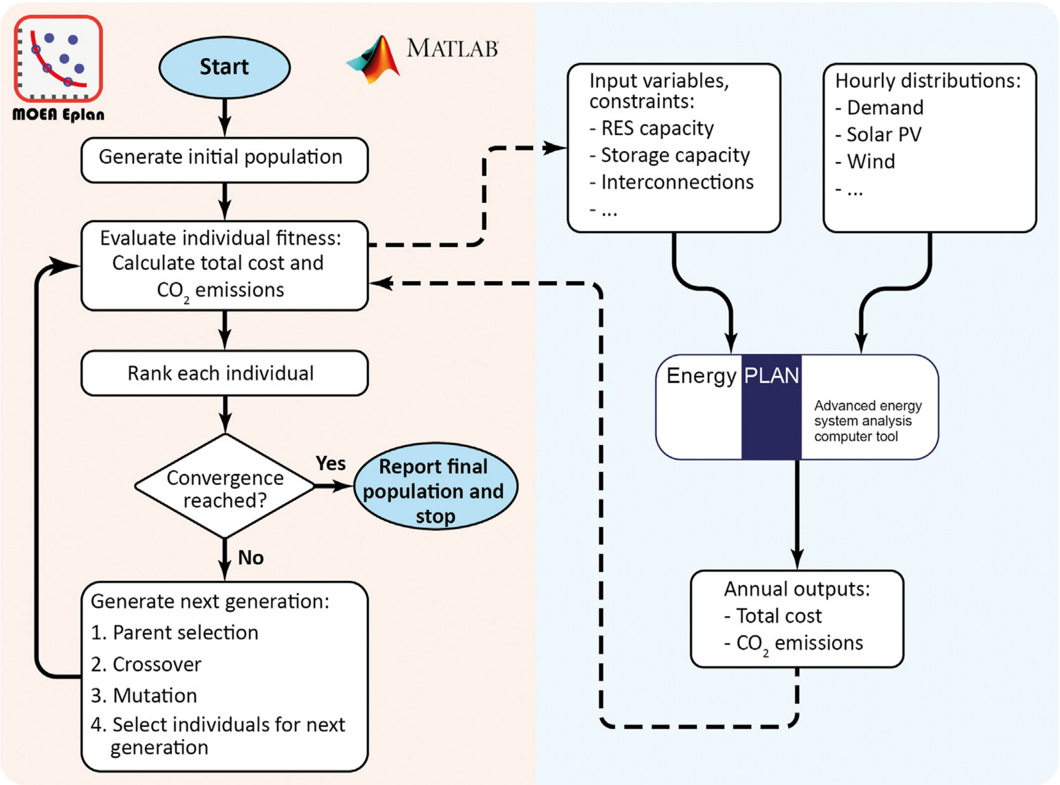

Fig. 2. Diagram of the algorithm followed by the MOEA Eplan tool.

Table 4
Decision variables range for each unit.

Production unit	Lower bound	Upper bound
Wind [MW]	0	10,000
Solar PV [MW]	0	10,000
Pump power [MW]	0	6000
Turbine power [MW]	0	6000
Storage energy capacity [GWh]	0	60

finally, in Section 4.3 the techno-economic optimisation outputs using the MOEA Eplan are discussed.

4.1. Energy storage and interconnections

Rising levels of intermittent renewables generation create new challenges for the operation of the electricity system. However, flexible options such as energy storage and international interconnection could assist in addressing some of these challenges. In this work, the impacts of increasing renewable penetration, electricity storage and interconnections capacities over the power system are evaluated by recording the changes in the CEEP or electricity curtailed, the primary energy supply (PES) or total fuel consumption and the GHG emissions. One of the main objectives of adding flexibility to the national grid is to reduce the CEEP and use it to replace fossil fuel-based plants power production.

4.1.1. Energy storage

In this section, the baseline scenario is used in order to simulate the effects of energy storage with increasing levels of wind, solar PV and a combination of both over the power system. The behaviour of both CEEP and PES when wind penetration increases is shown in Fig. 3. Considering no energy storage, the penetration wind levels below 12% of the total production does not generate any CEEP. As additional capacity is added to the system, wind production needs to be curtailed and no longer displaces fossil-fuel generation, reducing its environmental value to the system [51]. This leads to a technical penetration limit to the technology that is estimated following the procedure described in Ref. [27]. For this case, this limit is around 22% and is equivalent to a wind capacity of about 7.84 GW. It should be noted that as the storage power capacity increases (from 500 MW to 2 GW), the difference in CEEP and PES is reduced, thus establishing a technical limit to the useable storage capacity. In this case, energy storage power levels above 1.5 GW (10 GWh storage capacity) does not have a significant impact on the wind penetration limit. Compared to the scenario without energy storage, a further increase of approximately 2% of wind power

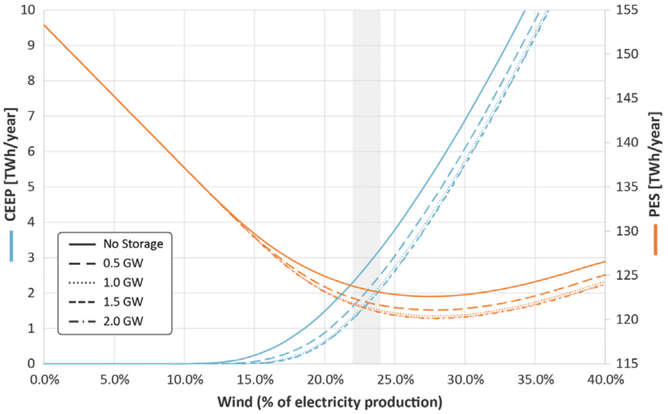

Fig. 3. Changes in CEEP and PES with increasing wind and energy storage power capacities.

capacity (shaded region in Fig. 3) could be accommodated in the system without wasting energy and this represent a reduction of 14.7% and 8.4% in the CO_2 emissions and energy curtailed, respectively.

Energy storage plays a more significant role in power systems with high solar PV power. This is mainly due to the nature of solar energy, which is only available during daylight periods and cannot generate energy continuously throughout the day as other types of renewables, such as the case of wind. Fig. 4 shows that the ES power capacity has a significant impact on the technically feasible penetration limit of Solar PV until about 2 GW. Above this level, the changes in CEEP, PES and CO_2 emission are not significant. An increase from approximately 11%–16% (5.82–6.12 GW) in the technical solar PV penetration limit is evidenced, and the major impact is on the reduction of the amount of energy curtailed (about 26% compared to the baseline scenario). Further, a reduction of approximately 17% and 4% in CO_2 emissions and PES, respectively, is evidenced.

An increase in both wind and solar PV installed capacity is a more realistic scenario and combine the benefits of the two technologies [27]. The results illustrated in Fig. 5 also show that rising levels of energy storage can reduce the amount of electricity curtailed and fuel consumption, and therefore support the integration of higher shares of RES. Similar to the previous case, ES power capacities over 2 GW does not result in important changes to the system and the combined (wind and solar) technical feasible RES penetration increases from approximately 19%–25% of the total electricity production. This latter represents installed wind and solar capacities of approximately 4 GW and 7 GW, respectively. Also, CO_2 emissions and PES are further reduced by 34% and 6.3%, respectively.

4.1.2. Cross-border interconnections

As described in Section 2, the interconnection capacity with neighbouring countries could expand in Colombia over the coming decades. However, this will depend on several uncertain factors such as the economic situation, politics, market arrangements, demand profiles and the future power mix of the countries involved. Fig. 6 shows the impact of increasing transmission capacity on the baseline scenario (from 500 MW to 3 GW) with different levels of RES penetration and without adding energy storage. The main effect is on the CEEP because this energy excess could be ideally used by neighbour systems in order to satisfy their demand. Regional interconnections could also expand significantly the maximum technical RES penetration in the system, and in this case, it climbs from about 19% to 24% of the total energy production. Further, a drop of approximately 17.7% in CO_2 emissions is evidenced with the PES levels remaining unchanged.

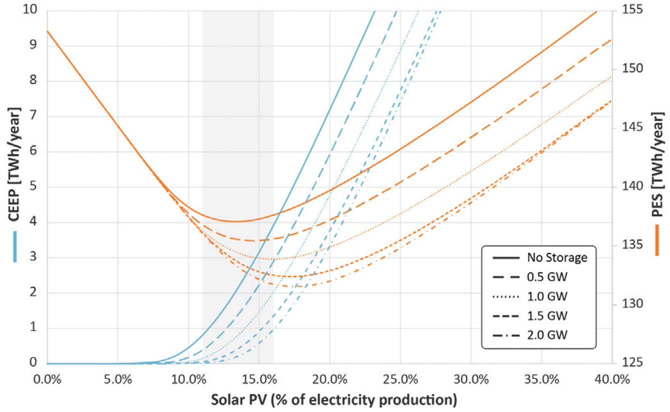

Fig. 4. Changes in CEEP and PES with increasing Solar PV and energy storage power capacities.

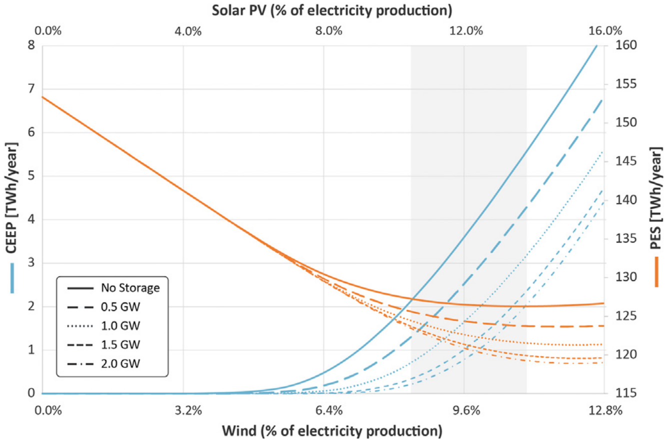

Fig. 5. Changes in CEEP and PES with increasing combined RES and storage power capacities.

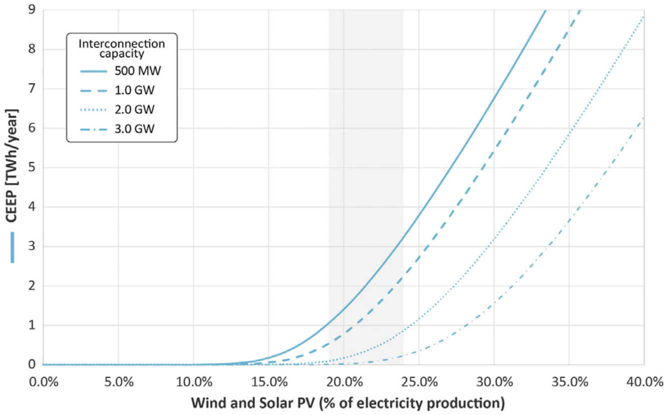

Fig. 6. Change in CEEP with increasing cross-border interconnection capacity.

4.2. Scenario results

This section presents the results obtained from simulating the

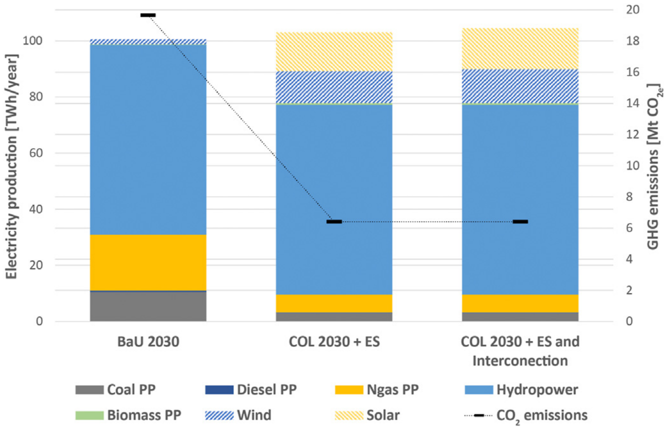

Fig. 7. Electricity production and GHG emissions for all the scenarios.

three scenarios described in Section 3.2. The results have been analysed comparing key energy indicators such as annual GHG emissions, fuel consumption, energy curtailed and RES share. Fig. 7 shows the total electricity generation by source and estimated CO_2 emissions in 2030 for the three scenarios simulated. It is evident that hydro generation will continue to be the main source of energy for the country and this is a clear advantage for increasing the flexibility of the system and its capacity to absorb more variable renewable capacity. The results of the scenario 2 show the benefits of adding variable RES with ES into the electricity system represented in a reduction of approximately 67% in the GHG emissions of the sector and an increase in the RES share to be about 89.4% of the total electricity production. The results of scenario 3 show that adding cross-border interconnection capacity allows additional penetration of variable RES into the system and the total RES production reaches about 91.6% of the total. Further, the annual CEEP is reduced by 47% compared to scenario 2. The annual CO_2 emissions remain constant, however, the emission intensity of the sector could also be further reduced to approximately 61.2 gCO_{2e}/kWh, which is about 69% less than the value estimated in the BaU scenario (195.3 gCO_{2e}/kWh).

4.3. Techno-economic optimisation

In this section, the results from the techno-economic optimisation are presented. As discussed in Section 3.5, a MOEA optimisation was performed using the MOEA Eplan app for the selected five decision variables with respect to the two objectives (GHG emissions and total cost). The rest of the inputs remain the same as the used for scenario 3. The optimisation was run 5 times and the following parameters used to set into the model: Population size: 100 individuals; Number of generations: 100; Crossover fraction: 0.9; and Pareto fraction: 0.5. These parameters have been applied in similar studies [26] in order to provide enough convergence time for the optimisation and guarantee a Pareto-optimal front that does not stay trapped in local optimums. Fig. 8 shows the resulting Pareto front and the two objective variables, the GHG emissions ($MtCO_{2e}$) and the annual cost of the power system (M€), are both represented on the horizontal and vertical axis, respectively. The scenarios with lower emissions but the higher annual cost can be seen on the left side of the Pareto front. On the contrary, scenarios with higher emissions and lower cost are shown on the right side of the figure. The Pareto front is formed by points where different configurations of the decision variables represent an optimal scenario with respect to the objective variables [26]. This allows policymakers and energy planners to identify a range of different options between optimal scenarios when designing future national strategies.

It should be noted that for emission values lower than 3 $MtCO_{2e}$, the annual cost of the system increases exponentially. Whereas for higher emission levels, the cost decreases on linear trends. An optimal reference configuration at this point, identified with an orange square in the figure, was selected in order to compare the optimisation results with the baseline scenario. This is just a reference between the multiple possible optimal configurations found. The green point in Fig. 8 corresponds to scenario 3 described in the previous section. Note that this scenario was built using the results from the parametric analysis and it is close to the Pareto front. Compared with the reference scenario, numerous points on the Pareto front lead to a significant improvement in CO_2 emissions without a major increase in costs. Figs. 9 and 10 show the capacity values of the associated decision variables over the Pareto front as a function of the annual emissions. This objective variable is used to analyse their effect on the final configurations considering that the system cost will increase with higher capacities.

As expected, there is a clear correlation between the increase in total intermittent RES capacity and the reduction in CO_2 emissions. Even though the wind capacity is higher than the solar PV for the configurations with high emissions, solar installations are favoured for the scenarios with low emissions and this is mainly because of the Colombian weather characteristics and the positive impact of adding energy storage to the system.

The energy storage optimal configurations suggest that charging and discharging power levels, represented by pump and turbine power in the case of PHES, should be different. Both power and energy levels evidence a strong correlation with the solar PV. The pump capacity is higher than the turbine capacity in all the cases and the difference is clearer for configurations that result in low emissions. This may be due to the demand and supply profile of the system, where there are periods with elevated levels of energy production and lower demand (see Fig. 11). Regarding the economic aspect of PHES, total installation costs including both reservoirs for the technology were considered for the assessment. These costs could be further reduced if some of the current dams used for hydro generation in the country are adapted for adding PHES systems. However, this analysis requires more detailed infrastructure studies on the feasibility of each individual case, and thus, it is beyond the scope of this research.

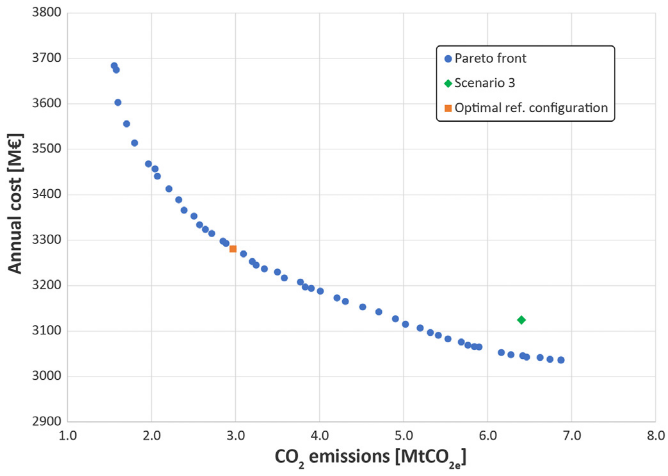

Fig. 8. Pareto front for best system configurations.

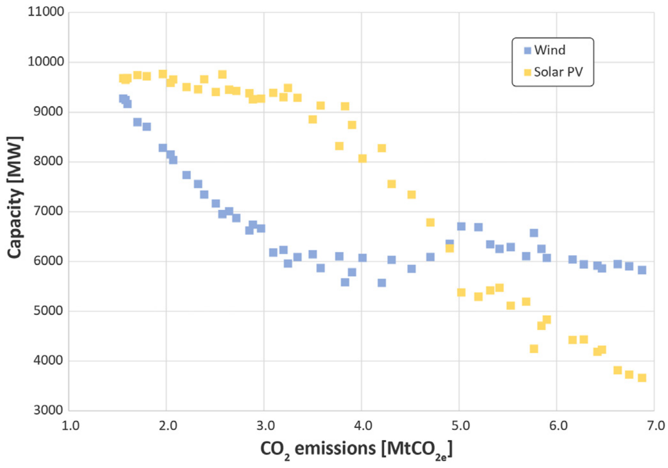

Fig. 9. Wind and solar PV capacities on the Pareto front.

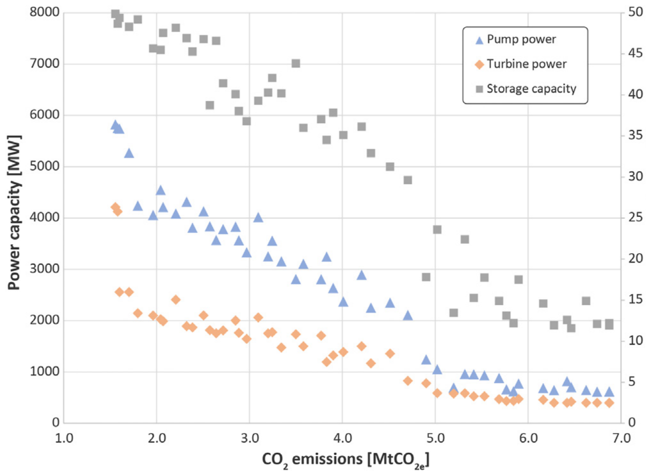

Fig. 10. PHES components capacity on the Pareto front.

Figs. 11 and 12 show the hourly electricity supply and demand profiles for three consecutive days (two working days and a weekend) in two different cases. Fig. 12 illustrates the results of Scenario 2 without ES. The negative values in the figure indicate the amount of electricity curtailed due to the excess of production by the intermittent RES. The annual CEEP is approximately 5.9 TWh and is generated mainly by solar PV during its peak generation hours. The results show that high RES penetration levels in the power sector impact directly the thermal generators ramping demands [27]. During the morning hours, as solar PV production increases, the conventional generators ramp down its supply quickly. In the evening hours, where the system faces its peak demand and solar supply declines, the thermal utilities experience sharp ramp-ups.

The impact of adding flexibility measures, such as ES and interconnections, into the power system is evidenced in Fig. 12, where the hourly distribution of supply and demand for the optimal reference configuration can be seen. Wind and solar PV experience different seasonal and diurnal generation patterns that impact directly in the amount of energy curtailed and the required system storage levels. In this case, they substitute most of the thermal plants' electricity generation. ES plays a key role in reducing sharp ramps for conventional generators during rapid load change hours, and thus, facilitates the operation of these utilities. The electricity surplus in the system, produced mainly during solar peak generation time (middle hours of the day), is used by the PHES pump (ES charging) and the electricity produced by the system turbines is sent back to the grid (ES discharging) when is mostly needed. However, there are days with lower demand and higher intermittent generation where some remaining energy still must be curtailed to ensure the stability of the grid.

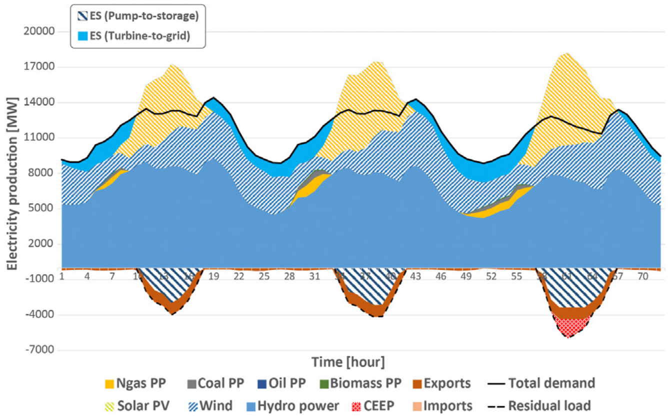

Fig. 12. Hourly distribution of supply and demand for the optimal reference configuration.

The optimal reference configuration has a RES generation share of approximately 96.8% of the total annual electricity production, and the CO$_2$ emissions levels are reduced by approximately 86.4% compared to the baseline scenario, representing an emission factor of the power sector of about 26.5 gCO$_{2e}$/kWh.

As shown previously in Section 4.2, increasing the international transmission capacity in order to increase the energy interchange with neighbouring countries is an effective flexibility option to reduce the excess of generation in the system. Fig. 13 shows the load-duration curve of CEEP for the technical interconnection levels that could be achieved in Colombia by 2030. It is clear that the higher the transmission capacity the less energy is wasted and curtailed. However, achieving these levels of interconnection does not depend exclusively on the internal planning of an individual country and must be discussed at regional level seeking to define clear frameworks that could allow a further integration in the area.

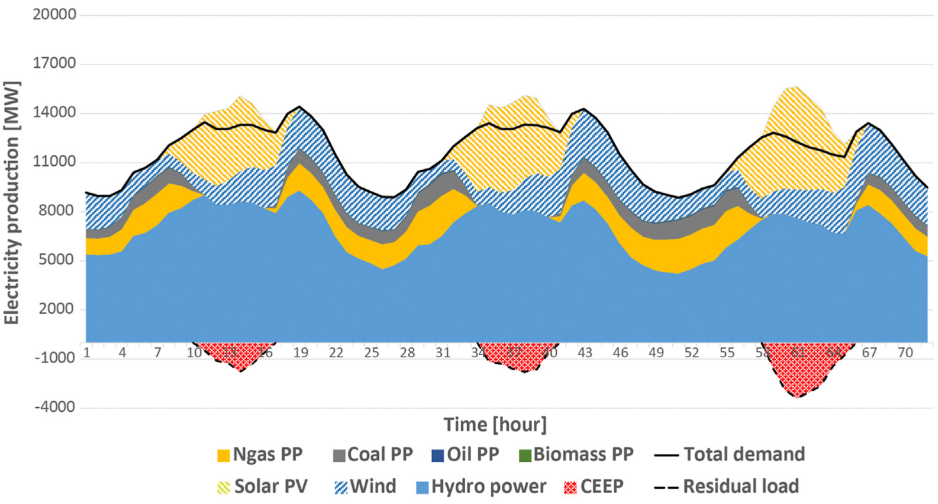

Fig. 11. Hourly distribution of supply and demand for scenario 2 without ES.

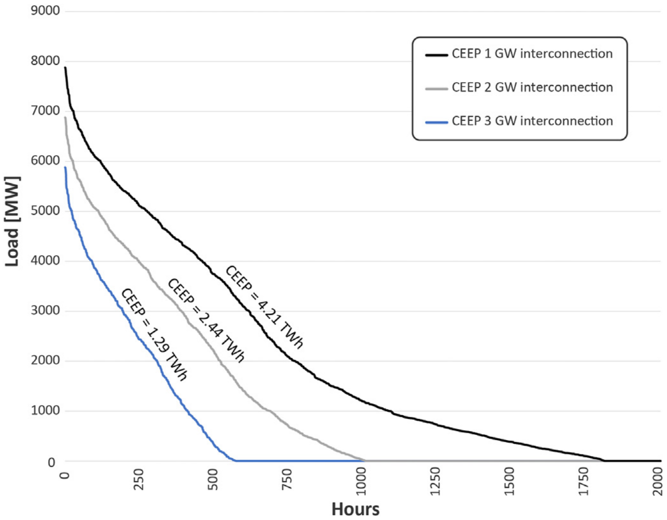

Fig. 13. Load-duration curves of CEEP for different cross-border interconnection capacities at the reference configuration.

This is highly relevant in Latin America mainly due to the persistent public order problems in the vicinity of the borders and the lack of political stability which could impact the international electricity market [22]. A comprehensive understanding of the inter-regional power exchanges in future systems with high intermittent generation will require a complementary Latin American market analysis, however, this is not within the scope of this study.

5. Conclusions

In this paper, the impacts of large-scale electricity energy storage and cross-border interconnections in the future Colombian power system were analysed using the EnergyPLAN modelling tool. Initially, a parametric analysis using diverse scenarios was performed in order to find the effects of these flexibility options on the integration of high shares of wind and solar PV; then, the MOEA Eplan tool was used to run a techno-economic optimisation and analyse the best trade-offs between the annual CO_2 emissions and the total system cost. The results proved that energy storage and cross-border interconnections have a very significant role in enabling larger levels of intermittent RES into the power system, and therefore adding more flexibility and diminishing its carbon intensity. In the case of Colombia, the optimal reference configuration selected from the Pareto front could allow a RES generation share of approximately 96.8% of the total electricity production and assist in the reduction of 86.2% of the sector's emissions compared to the baseline scenario. This could represent an emission factor of the power sector of approximately 26.5 gCO_{2e}/kWh and clearly exceeds the target defined by the country during the COP21 by 2030. Further reductions could be achieved at higher system cost and this represents an advantage for energy planers that can select from a broad range of optimal scenarios depending on the diverse possible trade-offs between cost and emissions.

A more integrated electricity system with higher cross-border interconnection capacity provides benefits in terms of increasing the RES penetration and reducing the amount of energy curtailed. The diversity in resources, load patterns and hydrological complementarities of the different countries in the region could be highly beneficial for achieving a more resilient power sector. In Colombia, this also could assist in overcoming the internal transmission constraints between the different sources of generation and allow better exploitation of its energy potential.

The results of this study can assist policymakers and energy planners to understand the impact of flexibility options on national power systems and the developing of appropriate policies in order to ensure the effective deployment of strategies oriented towards a smooth energy transition. Furthermore, additional scenarios including the other sectors of the energy system should be considered for a more detailed analysis. As proposed by the smart energy system approach, the integration of the electricity, heat and transport sector will be needed in order to achieve an affordable and more sustainable national system.

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.

Acknowledgements

This research was supported by the Fundación CEIBA - Gobernación de Bolívar through the program "Bolivar gana con ciencia". We also thank IDEAM for providing their weather station data.

References

[1] Haas J, Cebulla F, Cao K, Nowak W, Palma-Behnke R, Rahmann C, et al. Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review. Renew Sustain Energy Rev 2017;80:603–19. https://doi.org/10.1016/j.rser.2017.05.201.

[2] Cebulla F, Haas J, Eichman J, Nowak W, Mancarella P. How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany. J Clean Prod 2018;181:449–59. https://doi.org/10.1016/j.jclepro.2018.01.144.

[3] Haas J, Cebulla F, Nowak W, Rahmann C, Palma-Behnke R. A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply. Energy Convers Manag 2018;178:355–68. https://doi.org/10.1016/j.enconman.2018.09.087.

[4] Mathiesen BV, Drysdale D, Chozas J, Ridjan I, Conolly D, Lund H. A review of smart energy projects & smart energy state-of-the-art. Aalborg, Denmark: Department of planning, Aalborg university; 2015.

[5] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14. https://doi.org/10.5278/ijsepm.2016.11.2.

[6] Lund H. Renewable energy systems: a smart energy systems approach to the choice and modeling of 100% renewable solutions. second ed. Amsterdam: Beaverton: Ringgold Inc.; 2014.

[7] Castillo A, Gayme DF. Grid-scale energy storage applications in renewable energy integration: a survey. Energy Convers Manag 2014;87:885–94. https://doi.org/10.1016/j.enconman.2014.07.063.

[8] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/j.apenergy.2015.01.075.

[9] International Finance Corporation (IFC). Energy storage trends and opportunities in emerging markets. 2017. Boulder, USA.

[10] Ochoa C, Dyner I, Franco CJ. Simulating power integration in Latin America to assess challenges, opportunities, and threats. Energy Pol 2013;61:267–73. https://doi.org/10.1016/j.enpol.2013.07.029.

[11] Guezgouz M, Jurasz J, Bekkouche B, Ma T, Javed MS, Kies A. Optimal hybrid pumped hydro-battery storage scheme for off-grid renewable energy systems. Energy Convers Manag 2019;199:112046. https://doi.org/10.1016/j.enconman.2019.112046.

[12] El-Bidairi KS, Nguyen HD, Mahmoud TS, Jayasinghe SDG, Guerrero JM. Optimal sizing of Battery Energy Storage Systems for dynamic frequency control in an islanded microgrid: a case study of Flinders Island, Australia. Energy 2020;195:117059. https://doi.org/10.1016/j.energy.2020.117059.

[13] Alves M, Segurado R, Costa M. Increasing the penetration of renewable energy sources in isolated islands through the interconnection of their power systems. The case of Pico and Faial islands, Azores. Energy 2019;182:502–10. https://doi.org/10.1016/j.energy.2019.06.081.

[14] Edmunds RK, Cockerill TT, Foxon TJ, Ingham DB, Pourkashanian M. Technical benefits of energy storage and electricity interconnections in future British power systems. Energy 2014;70:577–87. https://doi.org/10.1016/j.energy.2014.04.041.

[15] Arciniegas LM, Hittinger E. Tradeoffs between revenue and emissions in energy storage operation. Energy 2018;143:1–11. https://doi.org/10.1016/j.energy.2017.10.123.

[16] Headley AJ, Copp DA. Energy storage sizing for grid compatibility of intermittent renewable resources: a California case study. Energy 2020;198: 117310. https://doi.org/10.1016/j.energy.2020.117310.

[17] Bussar C, Stöcker P, Cai Z, Moraes Jr L, Magnor D, Wiernes P, et al. Large-scale integration of renewable energies and impact on storage demand in a European renewable power system of 2050—sensitivity study. J Energy Storage 2016;6:1—10. https://doi.org/10.1016/j.est.2016.02.004.

[18] Andresen GB, Rodriguez RA, Becker S, Greiner M. The potential for arbitrage of wind and solar surplus power in Denmark. Energy 2014;76:49—58. https://doi.org/10.1016/j.energy.2014.03.033.

[19] Limpens G, Jeanmart H. Electricity storage needs for the energy transition: an EROI based analysis illustrated by the case of Belgium. Energy 2018;152: 960—73. https://doi.org/10.1016/j.energy.2018.03.180.

[20] Connolly D, Lund H, Mathiesen BV, Pican E, Leahy M. The technical and economic implications of integrating fluctuating renewable energy using energy storage. Renew Energy 2012;43:47—60. https://doi.org/10.1016/j.renene.2011.11.003.

[21] Lopez J. Efecto del almacenamiento de energía en el mercado mayorista eléctrico Colombiano. Universidad Nacional de Colombia; 2013.

[22] Ochoa C, van Ackere A. Does size matter? Simulating electricity market coupling between Colombia and Ecuador. Renew Sustain Energy Rev 2015;50: 1108—24. https://doi.org/10.1016/j.rser.2015.05.054.

[23] Cabrera P, Lund H, Thellufsen JZ, Sorknæs P. The MATLAB Toolbox for EnergyPLAN: a tool to extend energy planning studies. Sci Comput Program 2020;191:102405. https://doi.org/10.1016/j.scico.2020.102405.

[24] Batas Bjelić I, Rajaković N. Simulation-based optimization of sustainable national energy systems. Energy 2015;91:1087—98. https://doi.org/10.1016/j.energy.2015.09.006.

[25] Prina MG, Cozzini M, Garegnani G, Manzolini G, Moser D, Filippi Oberegger U, et al. Multi-objective optimization algorithm coupled to EnergyPLAN software: the EPLANopt model. Energy 2018;149:213—21. https://doi.org/10.1016/j.energy.2018.02.050.

[26] Mahbub MS, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164:140—51. https://doi.org/10.1016/j.apenergy.2015.11.042.

[27] Pupo-Roncallo O, Campillo J, Ingham D, Hughes K, Pourkashanian M. Large scale integration of renewable energy sources (RES) in the future Colombian energy system. Energy 2019;186:115805. https://doi.org/10.1016/j.energy.2019.07.135.

[28] Colombian electrical information system (SIEL). http://www.siel.gov.co/. [Accessed 24 July 2018].

[29] Garcia-Freites S, Welfle A, Lea-Langton A, Gilbert P, Thornley P. The potential of coffee stems gasification to provide bioenergy for coffee farms: a case study in the Colombian coffee sector. Biomass Convers Biorefinery 2019. https://doi.org/10.1007/s13399-019-00480-8.

[30] Gómez-Navarro T, Ribó-Pérez D. Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia. Renew Sustain Energy Rev 2018;90:131—41. https://doi.org/10.1016/J.RSER.2018.03.015.

[31] Lambertini G. Los Convenios bilaterales que soportan las interconexiones energéticas en América del Sur. ENERLAC Rev Energía Latinoamérica y El Caribe 2018;1:126—45.

[32] Pupo-Roncallo O, Campillo J, Ingham D, Hughes K, Pourkashanian M. Renewable energy production and demand dataset for the energy system of Colombia. Data Br 2020:105084. https://doi.org/10.1016/j.dib.2019.105084.

[33] CAF, (CIER) C de IER. Nuevas oportunidades de interconexión eléctrica en América Latina. Bogotá D.C., Colombia: CAF; 2012.

[34] XM. Portal BI - gestión información inteligente. http://informacioninteligente10.xm.com.co/pages/default.aspx. [Accessed 30 March 2020].

[35] Ringkjøb H-K, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev 2018;96:440—59. https://doi.org/10.1016/j.rser.2018.08.002.

[36] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN — advanced analysis of smart energy systems. Smart Energy 2021;1:100007. https://doi.org/10.1016/j.segy.2021.100007.

[37] Lund H, Thellufsen JZ. EnergyPLAN - advanced energy systems analysis computer model (version 15.1). https://doi.org/10.5281/zenodo.4017214; 2020.

[38] Connolly D. Finding and inputting data into the EnergyPLAN tool. Aalborg; 2015.

[39] Pupo-Roncallo O, Ingham D, Pourkashanian M. Techno-economic benefits of grid-scale energy storage in future energy systems. Energy Rep 2020;6: 242—8. https://doi.org/10.1016/j.egyr.2020.03.030.

[40] IPCC. IPCC guidelines for national greenhouse gas inventories, Intergovernmental Panel on Climate Change (IPCC). Task Force on National Greenhouse Gas Inventories (TFI); 2018. n.d, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. [Accessed 28 September 2018].

[41] Gonzalez-Salazar M, Venturini M, Poganietz W-R, Finkenrath M, Acevedo H, Kirsten T. Bioenergy technology roadmap for Colombia. 2014. https://doi.org/10.15160/unife/eprintsunife/774.

[42] Calderón S, Alvarez A, Loboguerrero A, Arango S, Calvin K, Kober T, et al. Achieving CO2 reductions in Colombia: effects of carbon taxes and abatement targets. Energy Econ 2016;56:575—86. https://doi.org/10.1016/j.eneco.2015.05.010.

[43] International Renewable Energy Agency (IRENA). Colombia power system flexibility assessment. Abu Dhabi: IRENA; 2018.

[44] Mining and Energy Planning Unit (UPME). Actualización y Revisión de los Balances Energéticos Nacionales de Colombia 1975—2009. Tomo I - balances Energéticos Nacionales. Bogota: UPME; 2011.

[45] Mining and energy planning unit (UPME). Plan de Expansión de Referencia generación transmisión 2017-2031. 2017. Bogota.

[46] Environment and Sustainable Development Ministry MADS. Upstream analytical work to support development of policy options for mid- and long-term mitigation objectives in Colombia. 2016. Bogota.

[47] Balza L, Gischler C, Janson N, Miller S, Servetti G. Potential for energy storage in combination with renewable energy in Latin America and the caribbean. 2014. Washington, D.C., USA.

[48] Wilson IAG, McGregor PG, Hall PJ. Energy storage in the UK electrical network: estimation of the scale and review of technology options. Energy Pol 2010;38:4099—106. https://doi.org/10.1016/j.enpol.2010.03.036.

[49] Aghahosseini A, Bogdanov D, Barbosa LSNS, Breyer C. Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030. Renew Sustain Energy Rev 2019;105:187—205. https://doi.org/10.1016/j.rser.2019.01.046.

[50] Belderbos A, Virag A, D'haeseleer W, Delarue E. Considerations on the need for electricity storage requirements: power versus energy. Energy Convers Manag 2017;143:137—49. https://doi.org/10.1016/j.enconman.2017.03.074.

[51] Denholm P, Mai T. Timescales of energy storage needed for reducing renewable energy curtailment. Renew Energy 2019;130:388—99. https://doi.org/10.1016/j.renene.2018.06.079.

[52] Lund H, Salgi G. The role of compressed air energy storage (CAES) in future sustainable energy systems. Energy Convers Manag 2009;50:1172—9. https://doi.org/10.1016/j.enconman.2009.01.032.

[53] Victoria M, Zhu K, Brown T, Andresen GB, Greiner M. The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. Energy Convers Manag 2019;201:111977. https://doi.org/10.1016/j.enconman.2019.111977.

[54] IRENA. Electricity storage and renewables: costs and markets to 2030. Abu Dhabi: IRENA; 2017. 978-92-9260-038-9 (PDF).

[55] Joint Research Centre. Energy technology reference indicator projections for 2010-2050. 2014. https://doi.org/10.2790/057687. Petten, the Netherlands.

[56] Mining and Energy Planning Unit (UPME). Integración de las energías renovables no convencionales en Colombia. 2015. Bogota.

[57] Thomson Reuters Point Carbon. The MSR: impact on market balance and prices. 2014. Oslo, Norway.

[58] Pupo-Roncallo O, Ingham D, Pourkashanian M. MOEA Eplan (Multi-objective evolutionary algorithm optimisation for EnergyPLAN). 2020. https://doi.org/10.5281/ZENODO.3770479.

[59] The MathWorks Inc. MATLAB. 2017. version 9.2 2017.

[60] Deb K, Kalyanmoy D. Multi-objective optimization using evolutionary algorithms. USA: John Wiley & Sons, Inc.; 2001.

List of Acronyms and Abbreviations

BaU: Business as Usual
CAES: Compressed air energy storage
CAN: Andean Community
CEEP: Critical Excess of Electricity Production
COP: Conference of the parties
DSM: Demand-side management
ENSO: El Niño and La Niña southern oscillation
ES: Electricity storage
ETRI: Energy technology reference indicator
GHG: Greenhouse gases
IDEAM: Hydrology, meteorology and environmental institute
iNDC: Intended Nationally Determined Contributions
IPCC: Intergovernmental Panel for Climate Change
IRENA: International Renewable Energy Agency
MOEA: Multi-objective evolutionary algorithm
MOEA Eplan: Multi-objective evolutionary algorithm optimisation for EnergyPLAN
NGSA: Non-dominated sorted algorithm
O&M: Operation and maintenance
PES: Primary Energy Supply
PHES: Pump hydroelectric energy storage
PV: Photovoltaics
RES: Renewable Energy Sources
SIEL: Colombian Electrical Information System
tCO_{2e}: ton of CO_2 equivalent
UPME: Unidad de Planeación Minero Energética (Mining and Energy Planning Unit)
XM: Compañía de Expertos en Mercados (Market experts company)