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Large scale integration of Renewable Energy Sources (RES) in the future Colombian energy system

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Abstract

The diversification of the energy matrix, including larger shares of Renewable Energy Sources (RES), is a significant part of the Colombian energy strategy towards a sustainable and more secure energy system. Historically, the country has relied on the intensive use of hydropower and fossil fuels as the main energy sources. Colombia has a huge renewables potential, and therefore the exploration of different pathways for their integration is required. The aim of this study was to build a model for a country with a hydro dominated electric power system and analyse the impacts of integrated variable RES in long-term future scenarios. EnergyPLAN was the modelling tool employed for simulating the reference year and future alternatives. Initially, the reference model was validated, and successively five different scenarios were built. The results show that an increase in the shares of wind, solar and bioenergy could achieve an approximate reduction of 20% in both the CO_2 emissions and the total fuel consumption of the country by 2030. Further, in the electricity sector the best-case scenario could allow an estimated 60% reduction in its emission intensity.

Keywords: Energy system analysis, RES, EnergyPLAN, Colombia.

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1. Introduction

In recent years, governments around the world have been increasing their attention on energy supply policies. These policies are focused towards three main energy goals that define the energy trilemma: security of supply, affordability and environmental sustainability [1]. Nevertheless, these ideas are not necessarily compatible. For instance, some countries could rely on cheap coal to guarantee their supply and this affects the environmental sustainability. Others might prefer the use of clean energy sources at a higher cost. A real balance between these factors is needed when evaluating energy goals and policies in order to achieve a transition towards low-carbon and more efficient energy systems. Further, a change is needed in the way that energy is produced and consumed to observe a real positive impact in terms of environmental protection and economic development [2]. The starting point for this change is an adequate sustainable energy planning. In the last two decades, an increasing trend in the developing of modelling tools for energy planning has been evidenced by the fact that more than 85 tools were available in 2017 [3,4]. The great majority of these models assist in the formulation of strategies for renewable integration in national energy systems [4]. For instance, in Latin America multiple models have been built for this purpose [3,5]. De Moura et al. [6] simulated three long-term future scenarios for the South American power system integration using the Open Source Energy Modelling System (OSeMOSYS). Also, Octaviano et al. [7] used the MIT Economic Projection and Policy Analysis (EPPA) model to evaluate different CO_2 emission reduction alternatives for Brazil and Mexico.

Historically, hydropower has been one of the main sources of energy in Latin America and the Caribbean, assisting these countries to maintain low levels of greenhouse gas (GHG) emissions [5]. These regions are rich in natural resources and hold great potential for variable renewable sources integration. Therefore, the modelling of possible future scenarios has become an essential planning tool, especially in the energy sector [3]. In the case of Colombia, electricity generation has been dominated by hydropower during the last few decades and, in 2017, approximately 53.7 TWh was produced by this source, representing 86% of the total production [8]. This feature makes the Colombian energy mix different from the great majority of countries around the globe. However, this also involves a high risk due to the significant dependence of the resource to weather variations. A clear example is the energy crisis in 1992-93, 2009-10 and 2015-16 due to the El Niño and La Niña southern oscillation (ENSO), and the recent surge in the energy cost. Some models for countries with a similar electricity mix to Colombia have been developed for Brazil [9,10], Norway [11], and New Zealand [12]. The need for research oriented towards the development of a diversified energy matrix has been raised by the Mining and Energy Planning Unit (UPME) [13]. Despite this, little research has been done on assessing the integration of renewable energy in developing countries. For the case of Colombia, there have been limited studies on this issue and none of the current models represents the entire energy system (this includes the heat, gas, electricity, transport, residential and industrial sectors) using a high temporal resolution model. In addition, no previous study has estimated the RES penetration limit into the Colombian electric power system. Vergara et al. [14] investigated the correlation between wind and hydro resources for future energy generation in the country. Gonzalez-Salazar et al. [15] used LEAP (Long-range Energy Alternatives Planning) to evaluate the impact of bioenergy in future scenarios. Paez et al. [16] developed an economic model in LEAP to assess future energy demand scenarios for Colombia. Chavez et al. [17] also used LEAP to model a group of fuel saving strategies for Colombia, Peru and Ecuador aiming to energy security and diversification towards 2030. Calderon et al. [18] examined different alternative CO_2 emission scenarios using GCAM, TIAM-ECN, Phoenix and MEG4C. However, the modelling tools used in these studies used long time-step simulations (yearly simulations). Some previous works [4,19,20] have suggested that a better approach is the use of high temporal resolution tools for studies that evaluate the integration of RES in energy systems due to its intermittency.

The aim of this paper is to model the Colombian energy system and analyse the impacts of integrated renewable sources in future scenarios. An important part of the analysis is focused on the electricity sector by considering the low carbon strategy plans of the country. Furthermore, this study estimates the maximum penetration levels of wind and solar power into the national power system and, for this purpose, the EnergyPLAN modelling tool was used to develop the model and build the scenarios. Technical details about this tool are explained in section 3.

This paper is organised in five sections. The first section presents background information and the scope of this work. Section 2 provides a description of the current Colombian energy system and its renewable energy potential. Section 3 is concerned with the methodology applied, including the modelling tool used, data sources, assumptions and a description of the energy system scenarios. Section 4 presents the findings of the research, focusing on the validation process for the Colombian model in EnergyPLAN and the main results from the simulated scenarios and the sensitivity analysis. The last section provides conclusions and recommendations for future works.

2. Characteristics of the Colombian energy system

This section presents an overview of the Colombian energy system. It includes a description of the current system, the main renewable energy sources and GHG emissions of the sector.

Multiple political and socioeconomic transformations have caused rapid changes in the energy sector in Colombia during the last decades [15]. Between 1975 and 2014, the total primary energy supply (TPES) increased from 197.5 to 472 TWh, representing an average annual growth rate of 2.3% [21,22]. Further. The energy production grew faster than GDP and it is nearly four times greater than the TPES as Colombia exports most of its coal production and three quarters of its oil production [23]. Fossil fuels dominate the total primary energy mix (see Figure 1), with coal, oil and natural gas collectively representing about 93% of the primary demand in 2014 [23]. These are followed by different forms of renewable sources, such as bioenergy that accounts for 4%, hydro energy for 3% and wind energy with less than 1% of the TPES [24].

The energy demand for transport accounted for over 39% of the total final consumption in 2014. This sector is the largest energy consumer, followed by industry (25%) and the residential sector (19%). Oil products and natural gas dominate the transport sector consumption [25].

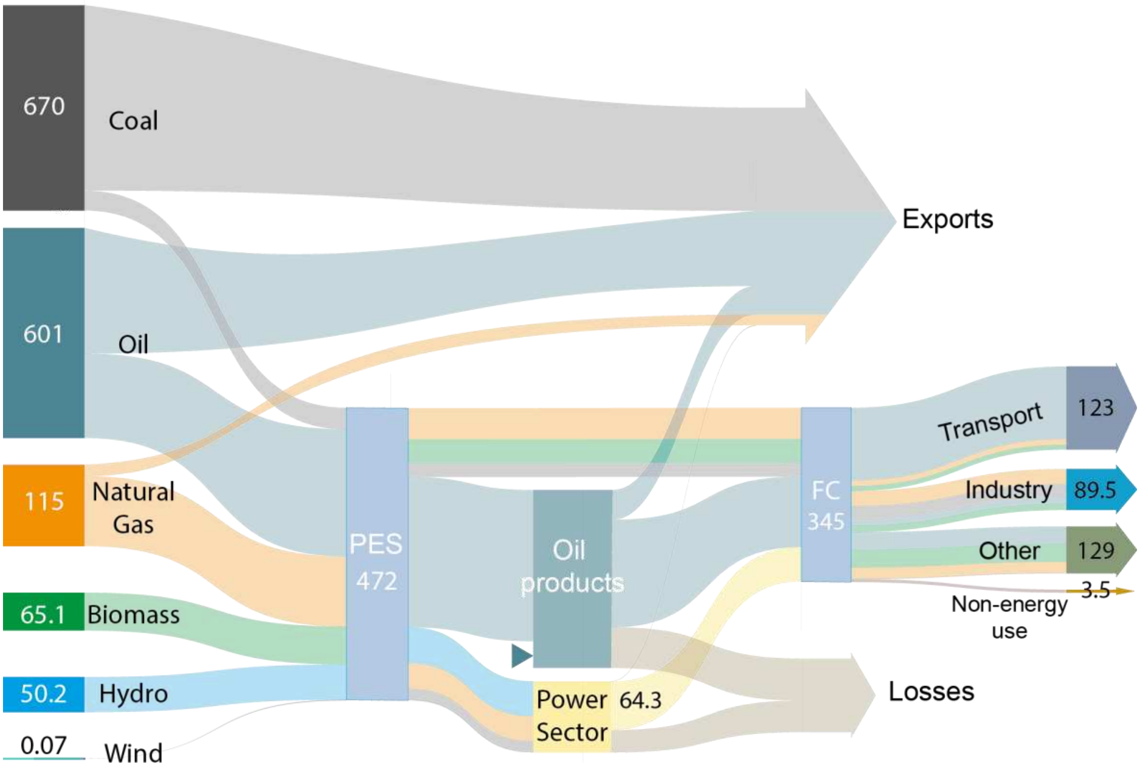

Figure 1. Colombian energy balance in 2014. All units in TWh. Adapted from [26]**.**

2.1 Electricity sector in Colombia

The electricity sector in Colombia accounts for 17% of the total energy consumption of the country [13]. More than 96% of the population has access to electricity through the National Interconnected System (SIN). Nevertheless, about 1 million people still lack access to this service in isolated rural areas that cover about two thirds of the national territory [27,28].

Historically, hydro and thermal generation have dominated the sector with average contributions of 71% and 28%, respectively during the last 20 years [13] and due to the high dependence of hydro resources, the system is highly vulnerable to severe droughts caused by ENSO. In 2015, hydropower electricity production plunged to less than 45% of the total generation due to the reduction of water inflows to the dam reservoirs caused by ENSO [8]. In 2017, the total installed capacity was 14.4 GW and consisted of 69.9% hydropower, 24.8% gas-fired power plants, 4.9% coal-fired power plants, 0.4% cogeneration and 0.1% wind [8].

Because of the availability of resources and the location of the demand, power generators are situated on the northwest and central regions of the country. Further, thermal generation is necessary to maintain the reliability and stability of the national grid due to transmission line constraints. Furthermore, they are used to match the demand during dry seasons when large hydropower plants are not able to produce enough energy [29].

2.2 Renewable energy

Colombia has abundant renewable energy resources that, with the exception of hydropower, remain largely unexploited. In addition to the available hydropower potential, there are extensive wind, solar and biomass resources [13,25,30]. Therefore, the increasing energy demand could be satisfied by these environmentally friendly resources. This section offers a description of their potential for energy generation in the country. Geothermal, tidal and wave power are not included despite their potential due to the lack of interest of investors in these technologies [31].

Hydropower

Hydropower is the main renewable energy source for electricity generation in the world [32]. It offers a clear alternative to fossil fuels for matching the global energy demand, and Colombia has great potential for hydro energy generation due to its topography [28]. There are currently 11,773 MW of installed capacity in the SIN, from which 10,944 MW corresponds to large hydropower plants and 829 MW to small-scale plants [8]. According to ISA [33], the potential hydropower capacity in the country could be up to 93 GW. Nevertheless, this potential cannot be fulfilled completely due to some environmental constraints [28].

Wind power

Wind power currently contributes 0.1% of the electricity demand in Colombia. There is only one wind farm (Jepirachi project) with an installed capacity of 19.5 MW. This project started operation in 2004 as a first step to reduce GHG emissions in the electricity sector. It consists of 15 Nordex wind turbines of 1.3 MW individual capacity [34].

The estimated annual wind energy potential in the country is approximately 81.2 TWh and this could represent an installed capacity of up to 25 GW [31,33]. Most of the resource is located in the northern part of the country, especially in La Guajira region [14,35]. Here, the average wind speed at 80 meters above sea level is about 9 m/s [36].

Previous studies [13,14,35] have shown that the levelized cost of energy (LCOE) from wind cannot currently compete with hydro generation. However, during periods of severe droughts (mainly associated with ENSO in Latin America) wind energy shows a strong complementarity with hydropower [14].

Solar PV

Solar photovoltaic technology in Colombia has been mainly developed in rural areas without access to electricity (ZNI) to meet their basic demands and improve their quality of life [37]. In 2017, the first large-scale PV power plant connected to the SIN started operations. The Celsia Solar Yumbo project has an installed capacity of 9.8 MW, and it is expected to have an average energy generation of 16.5 GWh per year [8]. The total installed capacity of small-scale PV systems (usually of less than 10 kWp) is estimated to be about 5.28 MW (between SIN and ZNI) [37].

The solar atlas of Colombia [38] shows that there is a high potential for the use of this technology. As for the case of wind, the northern region has the highest solar resources with average daily irradiation between 4.5 and 6 kWh/m^2. As opposed to all the countries further from the equator that experience four different seasons throughout the year, tropical countries have minimal seasonality. This allows the irradiation levels to remain relatively stable throughout the year, thus reducing the levels of variability with this type of generation [39].

Bioenergy

After hydro generation, bioenergy is the second largest renewable resource for energy production in Colombia [15]. In 2017, electricity generation using biomass accounted for 804 GWh, representing 1.3% of the total produced [8]. The main use of biomass is as fuel for cooking and heating in rural areas (wood and charcoal), followed by electricity generation in local industries (mainly using sugar cane bagasse) and biofuel production (bioethanol and biodiesel) for the transport sector. Bioethanol is produced using sugar cane as feedstock and biodiesel is produced from palm oil [15]. There are currently two blending regulations designed to reduce GHG emissions in the sector: a 10% bioethanol blending by volume for transport gasoline fuel, and 8-10% biodiesel blending for road transport diesel [22,40].

Also there is a vast biomass energy potential untapped in Colombia [13]. Gonzalez-Salazar et al. [15] estimated a maximum technical potential of approximately 116 TWh per year. A sustainable use of this potential could boost the development of the rural sector, thus driving modernization of agriculture methods, reducing oil dependence and offering a clear option to diversify the energy mix. However, this is not a definite solution and the water-food-energy nexus of biomass production must be further analysed. Deforestation, impacts on food security, dependence on single-crop farming and adequate management of water resources are some of the obstacles to overcome in order to further exploit this potential sustainably.

2.3 GHG emissions

The electricity generation matrix in Colombia is considered very clean because of the high share of hydro generation and low energy consumption levels, which are below the international averages [41]. Electricity generation accounts for only 8.5% of the total emissions, compared to the global average of 42% in the same sector [42]. Historically, the AFOLU (Agriculture, Forestry and Other Land Use) and Energy sectors have presented the highest contribution to the national emissions (see Figure 2). Deforestation appears to be the principal driver in the AFOLU sector, while in the energy sector, transport and energy industries are the main drivers [41,43]. From 1990 to 2014, the energy sector emissions increased by 33 $MtCO_2e$, being transportation (38%), fugitive emissions (28%), and electricity and heat production (20%) the primary causes [44,45]. Currently, road transportation is the largest consumer of energy and the largest source of CO_2 emissions. This is a consequence of the increasing freight activity, rapid urbanisation and rising incomes and motorisation rates [25,44].

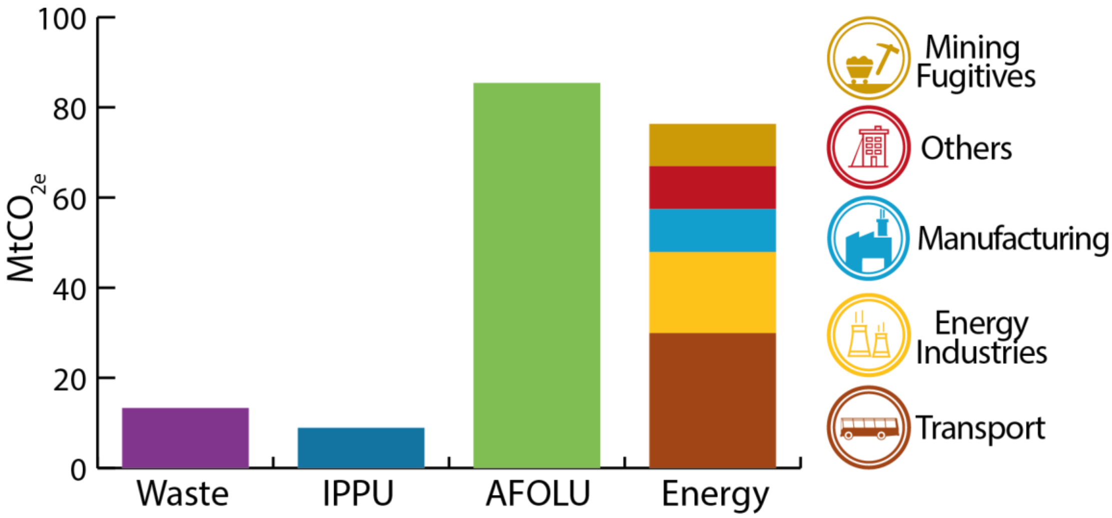

Figure 2. Colombian GHG inventory in 2012. Adapted from [43,46]**.**

In December 2015, Colombia adopted a new legally binding agreement in Paris at the 21st Conference of Parties (COP21) where it committed an unconditional 20% reduction on its GHG emissions by 2030, with reference to the projected Business as Usual (BaU) scenario [41] (see Figure 3). If mitigation measures are not implemented, the government estimates the total GHG emissions to reach 335 $MtCO_2e$ in 2030 (BaU scenario), from which 110 $MtCO_2e$ are expected to be produced in the energy sector only [41].

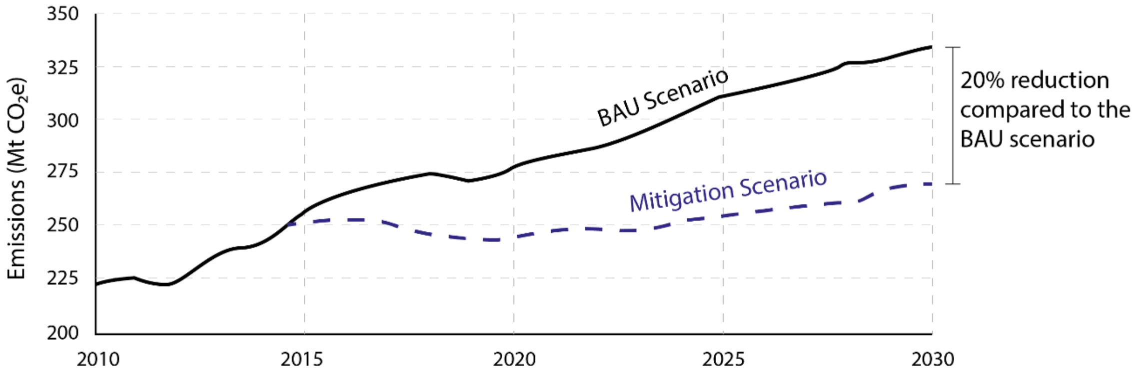

Figure 3. Mitigation target for Colombia [41]**.**

3. Methodology

This section presents a description of the methodology used in order to build the model for the Colombian energy system. The selected modelling tool, data sources, assumptions and defined scenarios are outlined.

3.1 EnergyPLAN modelling tool

Energy systems in emerging economies require adequate planning to face their complexity and challenges. This is only possible through the appropriate selection of modelling tools for each particular case. Each tool has its specific purpose and characteristics that must be assessed by the energy analyst or policy maker. This study adopted a bottom-up approach, integrating detailed engineering interactions between technology activities and energy use [47]. As Deane et al. [48] indicate, no individual tool is capable of addressing the totality of the energy system challenges. However, planners can take advantage of the strengths of different models for developing deeper insights. From the wide range of modelling tools currently available for these analyses [3,4], EnergyPLAN was selected. The main purpose of this tool is to assist in the design of national, regional or local long-term energy planning strategies by simulating the complete energy system [20]. This open source tool was developed at Alborg University in Denmark [49]. EnergyPLAN generates a deterministic model using analytical programming instead of iterations, thus calculating the results in a shorter period of time compared to iterative solvers. It uses a high temporal resolution (hourly) simulation over a period of one year. Therefore, it can examine the effect of intermittent RES on the system and analyse weekly and seasonal differences in power, heat demands and water inputs to large hydropower systems.

The system simulated is defined in terms of energy resources available, a wide range of energy conversion technologies and demands of electricity, heat and fuel for all end-use sectors. It has been designed with the aim to obtain alternative energy systems with high interdependency between sectors, exploring synergies and integrating high proportions of variable renewable sources (VRS). The schematic diagram of the EnergyPLAN tool can be seen in figure 4. Data is provided as annual aggregates combined with its distribution profiles and these profiles include hourly data for a complete year.

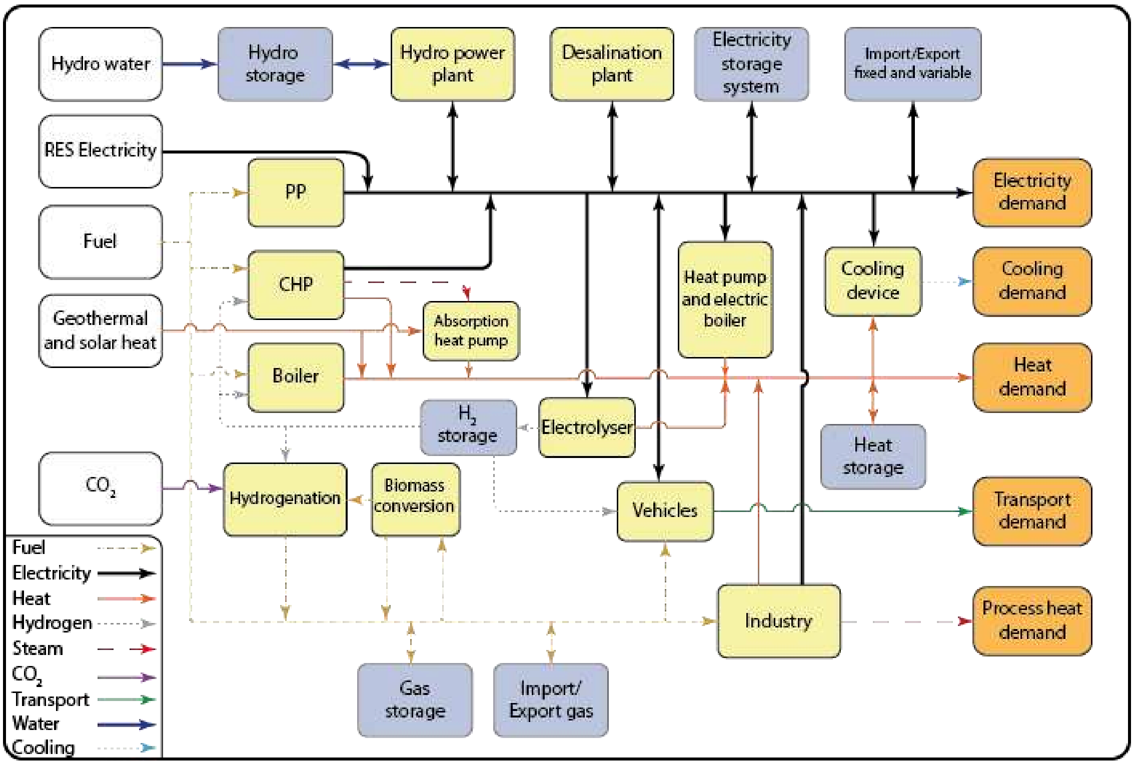

Figure 4. Schematic diagram of the EnergyPLAN tool [49].

The tool calculates the results based on two operation strategies: technical or market-economic regulation strategies. The objective of the technical strategy is to identity the least fuel-consuming alternative and minimise the import of electricity. The market-economic strategy aims to find the least-cost option based on characteristics of each production unit. In this work, the system costs are not included in the analysis and therefore the technical regulation strategy was followed. This strategy uses the defined capacity of each of the components in the energy system in order to balance the difference between supply and demand by minimising fossil fuel consumption. Both approaches allow the estimation of the socio-economic effects of the alternatives built by the system designer. Based on the configuration and regulation selected, the tool estimates the total annual demand and supply of the system and its individual components, CO_2 emissions and costs.

There are three key reasons for choosing EnergyPLAN in this study: Firstly, the modelling tool considers the three primary sectors of any regular energy system, namely power, heat and transport [50]. In Colombia, these sectors are completely segregated. In the future, these three sectors must synergize in order to achieve an efficient penetration of RES [19]. Therefore, a tool that includes these sectors is more useful for assessing future integration scenarios. Secondly, EnergyPLAN has been used in the analysis of energy systems in some emerging economies [19,49], and in some cases where the electricity mix is hydro dominated [11,51]. Finally, the tool has been widely used in the relevant literature considering large-scale integration of RES [52], 100% renewable energy systems [20,53], and in specific studies assessing the effects of different elements of the energy system such as energy storage [54], transport integration [55,56] and demand response technologies [57]. The overall structure of the model for the Colombian system can be seen in Figure 5.

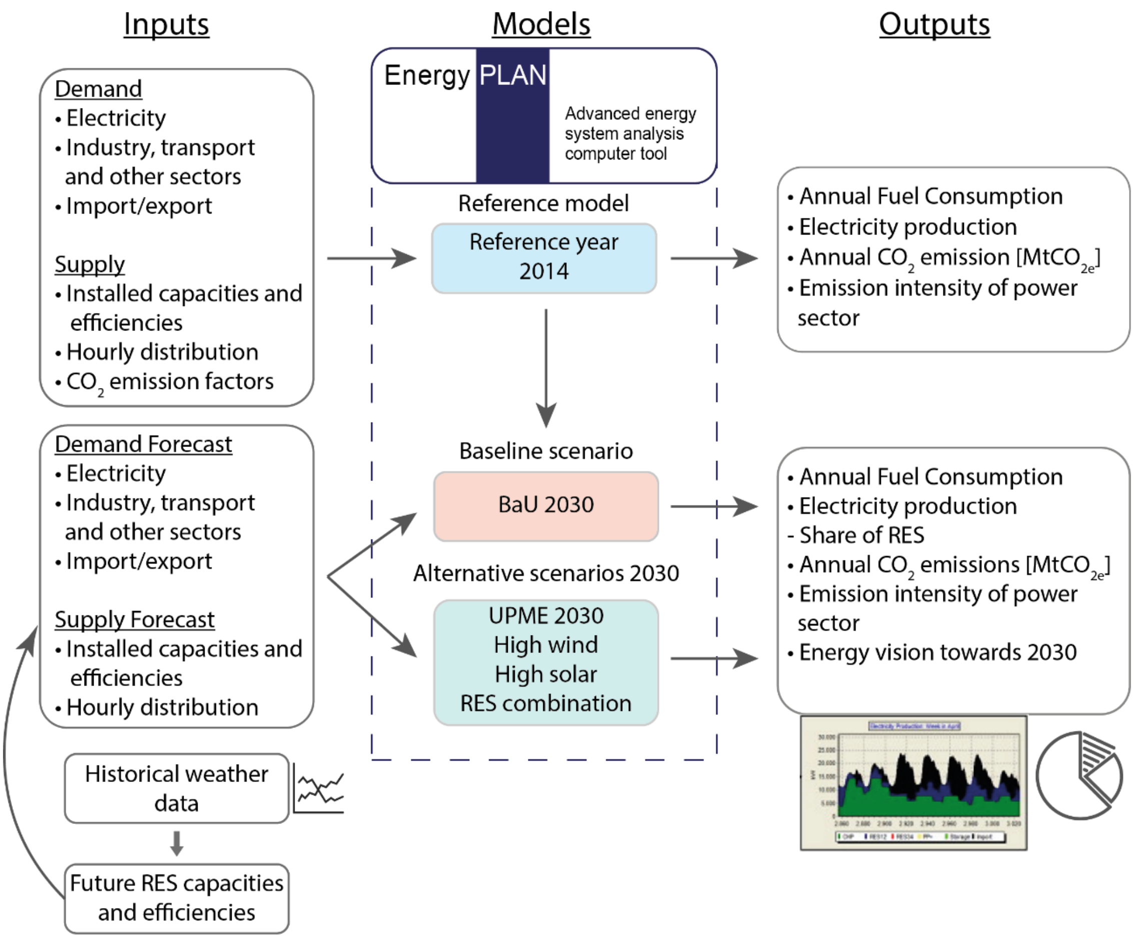

Figure 5. Structure of the Colombian model in EnergyPLAN.

3.2 Reference model data and assumptions

The EnergyPLAN tool requires many inputs and assumptions, and therefore it is important to validate the model against actual data [50]. Connolly [58] provides a complete description of the validation process, and this is described for the Colombian model in Section 4.1. The reference energy system model was built based on 2014 data from Colombian statistics. At the time the model was developed, data from the years 2015 and 2016 was available. But these years were affected by a strong ENSO. Therefore, they do not represent the typical behaviour of the Colombian energy system. Hourly demand and supply historical data were obtained from XM (Market experts company) through its PORTAL BI [59]. This firm manages the SIN and the wholesale energy market in the country. Thus, it offers detailed information about the energy generated by all plants connected to the national grid. The total electricity demand in Colombia for the reference year was 64.3 TWh. To the best knowledge of the authors, there is no existing distribution for electricity cooling demand in the country. However, according to UPME the share of electricity used for cooling is approximately 3.5% of the total generated. Therefore, this value is assumed to be constant throughout the year.

The capacity and efficiency of each power plant is available in the Colombian Electrical Information System (SIEL) [8].

As described previously in Section 2.2, there are currently large and small-scale hydropower plants in operation. Energy production from these plants rely on the water inflow to its reservoirs, and not only on electricity demand patterns. Therefore, modelling the Colombian hydropower system requires the use of natural inflow time series, which are available in the PORTAL BI [59].

Wind power was the only VRS used to generate electricity to the national grid in 2014. According to SIEL [8], the Jepirachi project with an installed capacity of 19.5 MW generated 70.23 GWh that year, and the hourly distribution was obtained in [59]. The RES dataset for wind and solar energy used in the future scenarios was built following the approach suggested by George et al. [60]. The meteorological data for this study was collected considering major current and future renewable energy generation sites. Long period (over 5 years) average hourly wind speed and solar insolation data for each site was supplied by the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM).

The energy consumption from the industry, transport, residential and commercial sectors was acquired from the Colombian energy balance in 2014. This document is completed every year by UPME and available in [21]. The CO_2 emissions were calculated based on fuel consumptions from the energy balance and the Tier 2 approach established in the Intergovernmental Panel on Climate Change (IPPC) guidelines for stationary combustion in [58,61]. Therefore, the GHG emission factors for Colombia reported in [62] were incorporated into the EnergyPLAN model. Following the IPCC guidelines for national GHG inventories in the energy sector [61], only the emissions associated with the direct combustion of fuel nationwide were considered.

3.3 Energy system scenarios

After validating the reference model against actual data, a thorough technical system analysis can be completed. A baseline scenario and four different alternatives were developed for the year 2030 (see Table 1) based on the characteristics of the Colombian system, previous works [15,18] and the inputs from different specialised agencies [22,24,41].

Table 1. EnergyPLAN input data for the reference model and future scenarios.

	Ref. 2014	BaU 2030	UPME 2030	High wind	High solar	RES combination
Electricity Demand						
Total electricity demand (TWh/year)	64.37	100.53	100.53	100.53	100.53	100.53
Electric heating (TWh/year)	1.05	1.64	1.64	1.64	1.64	1.64
Electric cooling (TWh/year)	5.68	8.87	8.87	8.87	8.87	8.87
Fixed Import/Export (TWh/year)	0.84	0.84	0.84	0.84	0.84	0.84
Electricity Supply						
Dammed hydro power (MW)	10920	14895	13729	14895	14895	14895
Thermal power (MW)	4735	6149.8	7061	6149.8	6149.8	6149.8
Biomass (MW)	108	108	272	108	108	600
Wind power (MW)	19.5	594	1250	7845	19.5	5000
Solar PV power (MW)	0	0	1611	0	5824	2000
Transport demand						
Biodiesel (TWh/year)	4.71	4.71	4.71	4.71	4.71	15.05
Bioethanol (TWh/year)	2.35	2.35	2.35	2.35	2.35	15.6
Fossil fuels (TWh/year)	110.6	172.53	172.53	172.53	172.53	152.8
Industry demand (TWh/year)	58.15	101.18	101.18	101.18	101.18	90.52
Other sectors demand (TWh/year)	66.44	115.61	115.61	115.61	115.61	115.61

The baseline scenario is referred to as the business as usual (BaU) scenario. It considers that there will be no changes in energy policies, economics and technology, thus past trends in energy demand and supply can be expected to remain unaffected. Analysing the impacts of the deployment of different renewables alternatives requires the comparison of the four alternatives with the baseline scenario. This scenario and the alternatives were defined as follows:

1. Baseline or business as usual (BaU) 2030: This scenario is based on the BaU outlook presented to the COP21 by the Colombian government [41]. These projections were defined for each of the productive sectors on the basis of macroeconomic assumptions, policy analyses, official information from government agencies and the input of experts. This was the reference level used to define the intended Nationally Determined Contributions (iNDC) for the country.
2. UPME 2030: This scenario is built from the generation and transmission expansion plan (high progression scenario) developed by UPME towards 2030

[24]. It is characterised by a moderate inclusion of additional wind and photovoltaic power plants in the electricity mix.

3. High wind: Built from the BaU 2030, this scenario includes the maximum technically feasible wind capacity estimated by the authors (see Section 4.2.1 for more details).
4. High solar: Built from the BaU 2030, this scenario includes the maximum technically feasible solar photovoltaics capacity estimated by the authors (see Section 4.2.2 for more details).
5. RES combination: this scenario includes inputs developed by Gonzalez-Salazar et al. [15] in the bioenergy technology 2030 roadmap for Colombia and a combination of wind and solar PV for electricity generation based on the authors considerations. It targets a combined deployment of biomethane production, biomass-based powered generation and increasing participation of biofuels in the transport sector. In addition, a combination of wind and solar power proposed by the authors was included in the electricity mix. The list of actions set for this scenario is presented in detail in Table 2.

Table 2. RES combination scenario inputs.

Sector	Plan
Industry	Use 5% of biomass residues and 1% of biogas from animal waste for biomethane production.
Electricity generation	Increase biomass participation in electricity generation to 10%. Wind power capacity: 5000 MW. Solar PV capacity: 2000 MW.
Transport	Biodiesel (palm oil based): increase diesel-biodiesel blend to B20 by 2030. Bioethanol (sugar cane based): increase petrol-bioethanol blend to E20 by 2030.

4. Results and discussions

In this section, the results of the reference and alternative scenarios are presented. Section 4.1 presents the validation process of the reference model (2014). In Section 4.2, a description of the method for estimating the maximum technical levels of RES penetration is described. Finally, the last two sections provide a critical discussion of the main findings from the scenario results and sensitivity analysis.

4.1 Reference model accuracy

The outputs of the reference model must be assessed to confirm its consistency and reliability given that this model is the basis for the future scenarios. The reference model was built using data from the year 2014. The validation process has been described in detail by Connolly [63]. This procedure involves a comparison between the reference model outputs and the actual figures reported by different international and domestic agencies [8,64]. Table 3 shows a comparison between the calculated monthly electricity demand on EnergyPLAN and the actual demand reported by SIEL in 2014 [8]. In this case, the difference is less than 0.5% for all months.

Table 3. Monthly electricity demand validation.

Month	Modelled in EnergyPLAN [MW]	Actual [8] [MW]	Percentage difference
Jan	7150	7138	-0.16%
Feb	7414	7413	-0.01%
Mar	7263	7236	-0.37%
Apr	7217	7235	0.25%
May	7296	7293	-0.04%
Jun	7306	7273	-0.45%
Jul	7437	7433	-0.06%
Aug	7289	7302	0.17%
Sep	7554	7537	-0.22%
Oct	7406	7421	0.20%
Nov	7513	7480	-0.44%
Dec	7214	7201	-0.18%

The modelled production from hydro, conventional power plants, biomass and wind are within the expected margins (less than 4% difference), as shown in table 4. The actual total energy-related emissions for Colombia in 2014 were reported to be 65.96 $MtCO_{2e}$ by the International Energy Agency (IEA) [64]. EnergyPLAN calculated the emissions for the same period as 65.06 $MtCO_{2e}$.

Table 4. Fuel consumption and annual electricity production validation.

	Modelled in EnergyPLAN	Actual data [65]	Difference	Percentage Difference
Electricity production [GWh/year]				
Wind	70	70.23	-0.23	-0.32%
Hydro	44760	44741.96	18.04	0.04%
Conventional Power Plant	19110	19073.95	36.05	0.18%
Biomass	450	441.71	8.29	1.87%
Fuel consumption [TWh/year]				
Natural Gas	79.17	76.90	2.27	2.95%
Coal	34.11	35.17	-1.06	-3.01%
Oil	139.35	138.19	1.16	0.83%
Biomass	34.55	33.54	1.01	3.01%

The results shown in this section allow us to conclude that the reference model accurately simulates the Colombian energy system and can be used with confidence to build future energy scenarios for the country.

4.2 Maximum feasible RES penetration in the Colombian electricity sector

This section describes the method for calculating the maximum technical levels of renewable penetration. The results obtained were used to generate the alternative scenarios 3 and 4 (high wind, high solar).

EnergyPLAN calculates the PES and the critical excess of electricity production (CEEP). This latter is the amount of electricity produced that exceeds the demand and cannot be exported due to transmission line restrictions. This situation will inevitably lead to energy curtailment because an excess of supply could cause a collapse in the transmission system [56]. The presence of an excess of production is a typical characteristic of systems with high levels of RES penetration and its impact can only be reduced using electricity storage systems or increasing transmission line capacity with neighbouring countries [50].

Conolly et al. [63] introduced the compromised coefficient (COMP) in their analysis of the feasible levels of wind penetration for Ireland. The COMP is the ratio between the PES gradient (ΔPES) and the CEEP gradient (ΔCEEP) for each simulation after the RES penetration is increased. This coefficient has been extensively used in similar works [20,50,56,66].

4.2.1 Maximum technical wind penetration

The behaviour of CEEP and PES when wind penetration increases is shown in Figure 6. There is no excess of electricity production below a wind energy penetration of approximately 12%. Then, the CEEP increases gradually until a penetration level of about 40% before it starts rising rapidly.

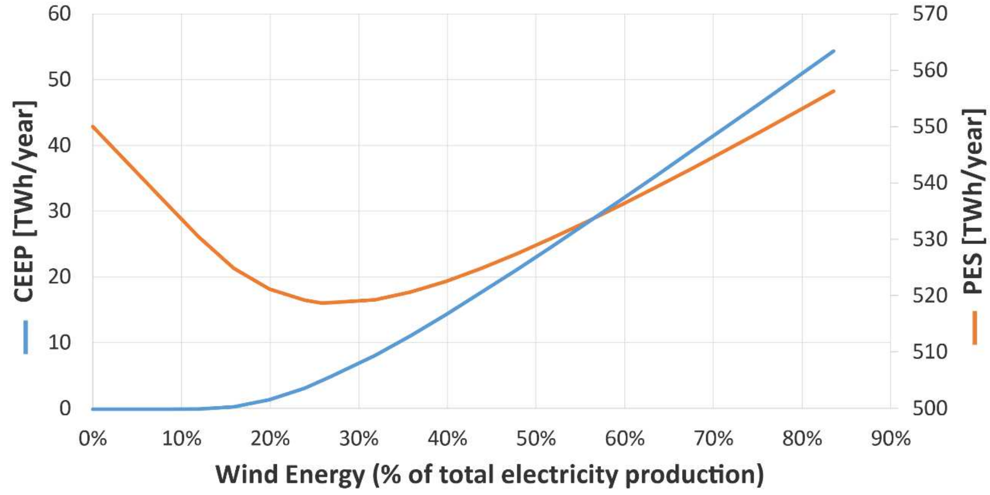

Figure 6. Curtailment and PES change with increasing wind penetration in the electric power system.

The largest technical wind penetration is found when the COMP is close to one. For the baseline scenario, that level is approximately 22%, which represents a wind installed capacity of about 7845 MW.

4.2.2 Maximum technical solar PV penetration

The analysis of the solar PV penetration follows the same procedure as for the case of wind. Figure 7 illustrates the behaviour of CEEP and PES when solar energy penetration increases. It was found that the maximum technical level is approximately 11% of the solar power contribution to the electricity generation (5824 MW installed capacity). Due to the nature of solar energy, which is available only during daylight hours, the penetration level is lower than in the case of wind energy.

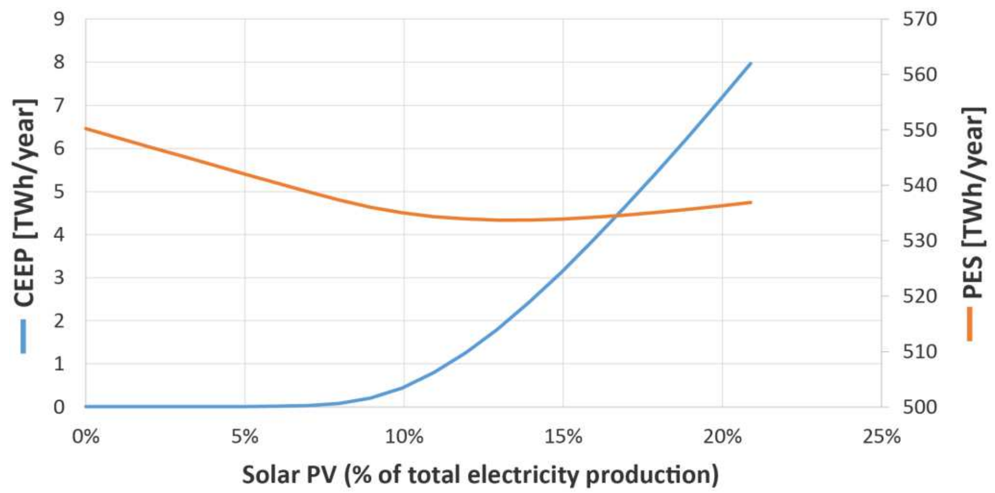

Figure 7. Curtailment and PES change with increasing solar PV penetration in the electric power system.

4.3 Scenario results

In this section, the main outputs of each of the scenarios are discussed. All the scenarios were compared using different indicators: annual GHG emissions, fuel consumption (PES), the share of RES and CEEP. Figure 8 shows an increase of PES from 332 TWh in the reference year (2014) to 547.37 TWh in the base line scenario. This rise of approximately 65% is mainly due to the expected economic growth in the country. Further, the GHG emissions are predicted to grow substantially from 64.46 MtCO$_2$e in 2014 to 108 MtCO$_2$e in 2030. The intensive use of fossil fuels in the industry, transport and electricity sector (oil, natural gas and coal), is the major cause of this upsurge. The figures calculated in this study agree with some of the results found in previous studies. For instance, based on a MARKAL model for Colombia, the Economic Commission for Latin America and the Caribbean (CEPAL) estimate that energy-related emissions might grow between 108 and 168 MtCO$_2$e in 2030 [67]. Similarly, Calderon et al. [18] explored different alternative CO_2 emission scenarios using four models (GCAM, TIAM-ECN, Phoenix and MEG4C) and found that emissions from the energy sector may climb between 115 and 172 MtCO$_{2e}$ by 2030, depending on the model used. In its report to the UNFCC, the national government estimates an increase in overall emissions to 335 MtCO$_{2e}$ by 2030 for their BaU scenario. Energy-related emissions account for approximately 110 MtCO$_{2e}$ in this outlook [41].

The UPME 2030 scenario evidences a reduction of 1.5% in PES compared to the baseline scenario (see Figure 8). This is mainly due to the expansion of the variable RES capacity in the electricity mix with 1250.5 MW in wind power and 1611 MW in solar power. This scenario outlines the current plans of the national government towards 2030. The GHG emission results show a decline of approximately 3% compared to the baseline scenario, thus the emission factor of the electricity system is approximately 172 gCO_{2e}/kWh. It should be noted that only adding wind and solar capacity into the electric power system does not have a significant impact on the emissions reduction in the energy system.

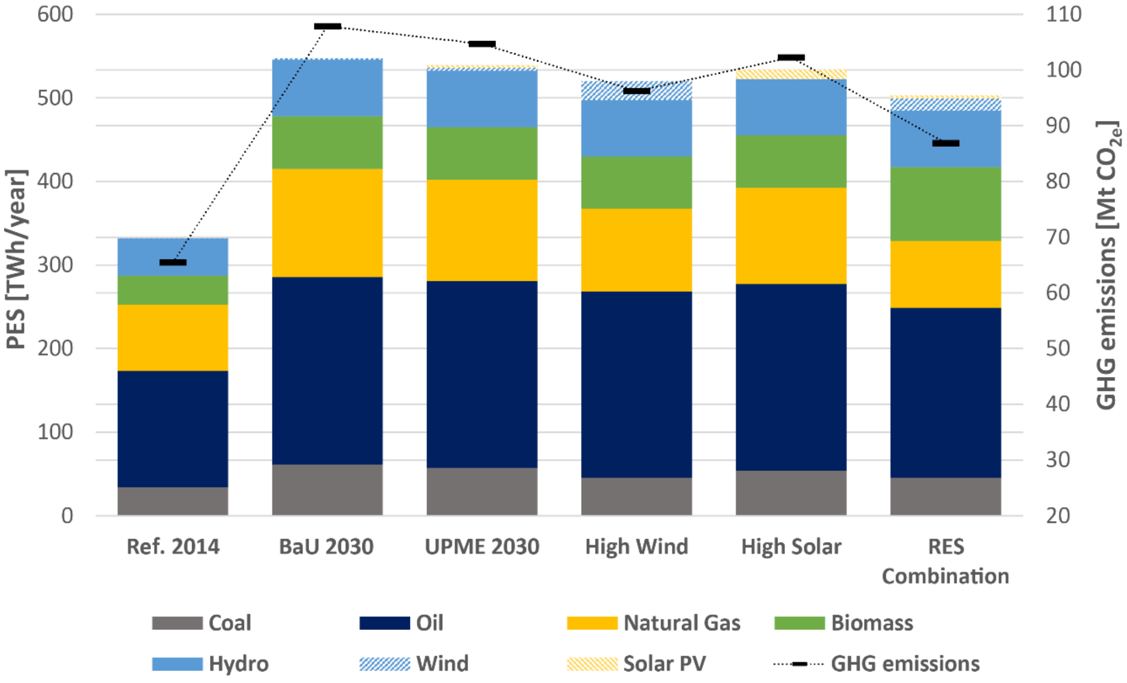

Figure 8. PES and CO_{2e} emissions for all the scenarios.

The alternative scenarios 3 and 4 represent the maximum technical penetration level of wind and solar power as explained in detail in Section 4.2. Both have fuel consumption and GHG emissions lower than the baseline scenario (519.95 TWh and 96.21 $MtCO_2e$, respectively for scenario 3; 534.01 TWh and 102.27 $MtCO_2e$ for scenario 4). However, the high wind scenario leads to higher fuel and GHG depletion due to its continuous supply of energy throughout the day. In the case of solar power, this is only possible during daylight hours.

As expected, the RES combination scenario offers the lowest PES and GHG emissions of all the alternatives with 503.03 TWh and 86.87 MtCO2e, respectively. The mitigation effect is approximately 20% reduction compared to the baseline. This scenario evidences the importance of a more integrated alternative that includes all the different sectors of the energy system. Because of the characteristics of the Colombian system, combined strategies that include the transport sector could have a major impact on the energy sector because this sector is the main driver of GHG emissions. In a country where the road sector is responsible for 88% of the transportation emissions and 95% of the goods are transported by medium or heavy-duty vehicles, increasing biofuel blending regulations could be an effective mitigation strategy. However, in order to reach further decarbonisation of the energy system policy makers in the country should be more ambitious and define comprehensive plans that include energy efficiency in all the sectors, electrification of light-duty vehicles and other sustainable mobility alternatives.

4.3.1 Electricity production results

Figure 9 shows the amount of electricity produced in a year for all the scenarios investigated. The electricity demand was obtained from the UPME transmission and generation expansion plan and this value remains constant for all the scenarios [24]. The excess of production in some of the scenarios is due to the RES over generation during low consumption periods. Further, the hydropower installed capacity will continue to be the main source of energy in the sector, and this might ensure a smooth and efficient system integration. The flexibility of a power system to integrate RES is mainly determined by the type of generation technology used. Hydropower dominated systems are usually more flexible and capable to incorporate variable renewables than thermal plants [11,51].

Figure 9 shows a growth in the electricity generation of about 56% between 2014 and 2030, from 64.39 TWh to 100.55 TWh, respectively. This accounts for an increase in GHG emissions of approximately 69%, thus resulting in an emission factor for the baseline scenario of approximately 204 gCO_2e/kWh.

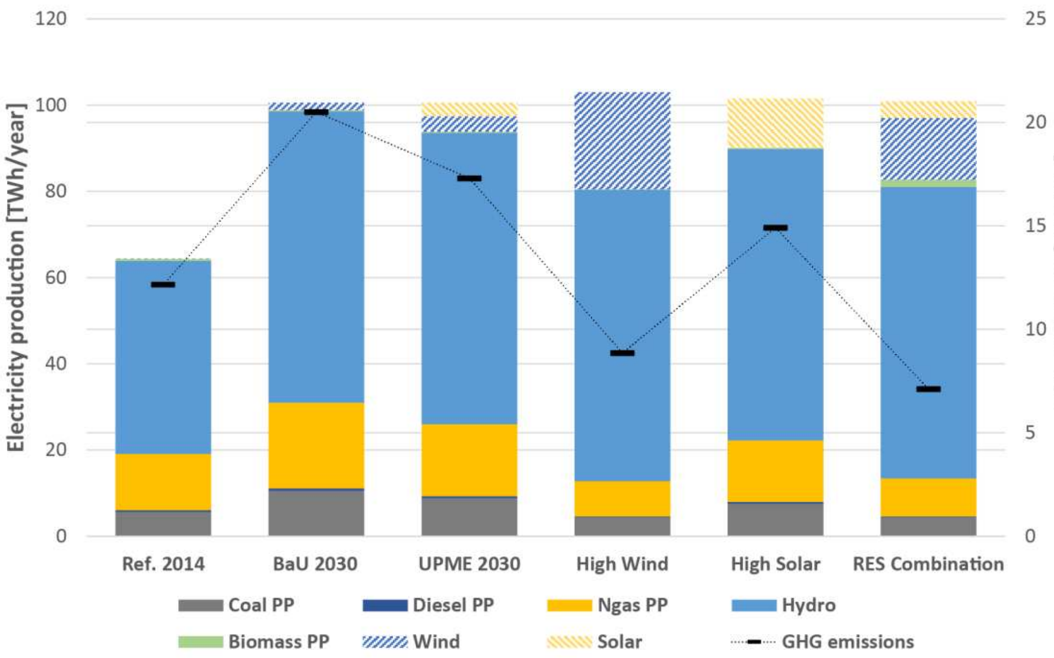

Figure 9. Electricity production and CO_{2e} emissions for all the scenarios.

The high wind and RES combination scenarios evidence the best options in terms of GHG emissions with 8.85 $MtCO_2e$ and 7.11 $MtCO_2e$, respectively. These two scenarios have lower emission than the reference year (2014), even though the electricity production levels are higher. The last scenario results highlight the importance of a diversified electricity mix. In this case, thermal power plants have a role as ancillary services, thus allowing a smooth penetration of alternative sources of energy.

The EnergyPLAN outputs provide an hourly distribution of the total annual electricity production by source. This feature allows a further analysis of the behaviour of the production units with respect to the demand. Figures 10 to 13 illustrate the typical hourly variability of both demand and supply for the different scenarios during three consecutive days (a weekend day and to two working days). As stated in Section 2.2, Colombia is a tropical country and therefore there is minimal seasonality. Consequently, there is no large difference between the patterns of generation throughout the year. Figure 10 shows the hourly distribution of electricity supply and demand for the baseline scenario. As expected, the hydro contribution continues to be the most important source of energy supply (67.2% of the total annual generation), followed by the thermal power generation (31% of the total annual generation). Even though wind power generation plays a more important role than in the current system, its contribution is still less than 2% of the total generation.

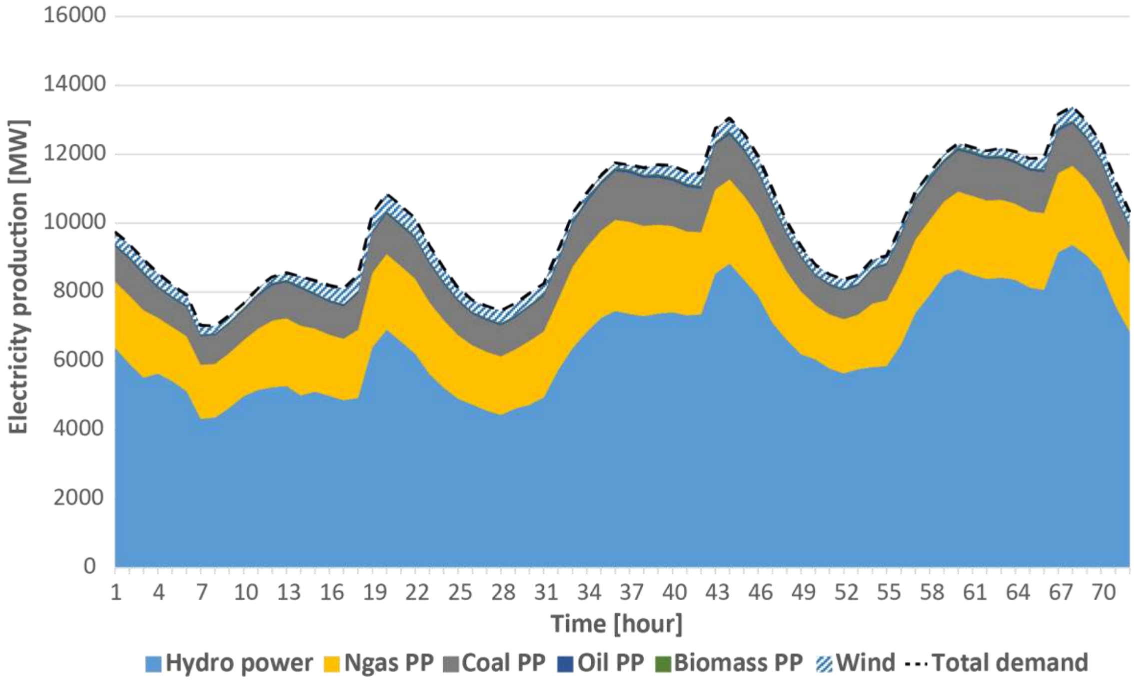

Figure 10. Hourly distribution of energy supply and demand for the baseline scenario (BaU 2030).

Figures 11 and 12 show the hourly distribution for a significant increase in wind and solar power in the electricity mix. In the high wind scenario, the system is able to operate entirely using 100% RES during some periods of time. According to the results, this is equivalent to three months per year using electricity supplied only by RES. However, the amount of energy curtailed is the highest of all the alternatives with approximately 2.46 TWh per year. This energy could be used if large scale storage systems, or greater transmission line capacity with neighbouring countries, are implemented.

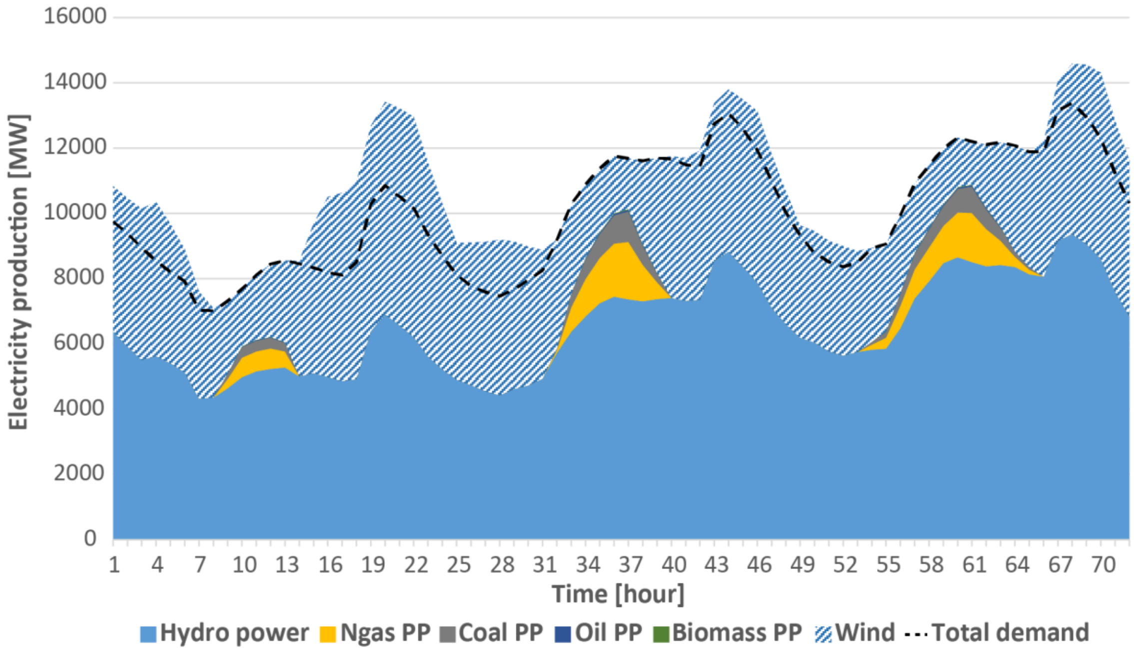

Figure 11. Hourly distribution of supply and demand for the high wind scenario.

Figure 12 illustrates the major challenge for solar power and the possibility of over generation. Two distinct ramp periods develop for thermal power plants. The first one in the downward direction occurs around 7:00 – 10:00 when people start their daily activities and solar PV begins its generation. The second, in the upward direction, arises as the sun sets at around 17:00 and solar generation plunges. This represents a ramp-up for thermal generators of more than 4000 MW in a three hours period. To guarantee the electricity supply under these load conditions, the power system requires the use of highly flexible generation technologies.

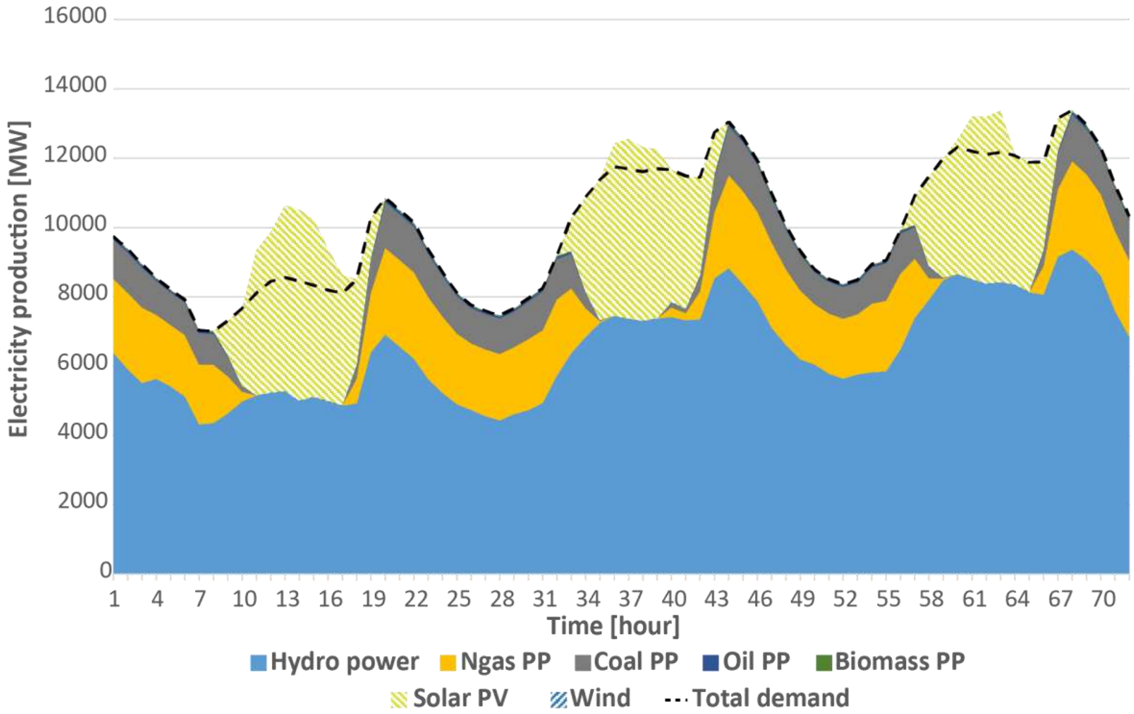

Figure 12. Hourly distribution of supply and demand for the high solar PV scenario.

The RES combination hourly results are shown in Figure 13. This is the most equilibrated of all the alternative scenarios. Although the participation of the thermal power plants is higher than in the previous two scenarios (high wind and high solar), this fact allows better interaction between all the resources. Here, thermal power plants act as ancillary services in the case of scarcity of any of the RES. This is important in order to guarantee the reliability of the electricity system.

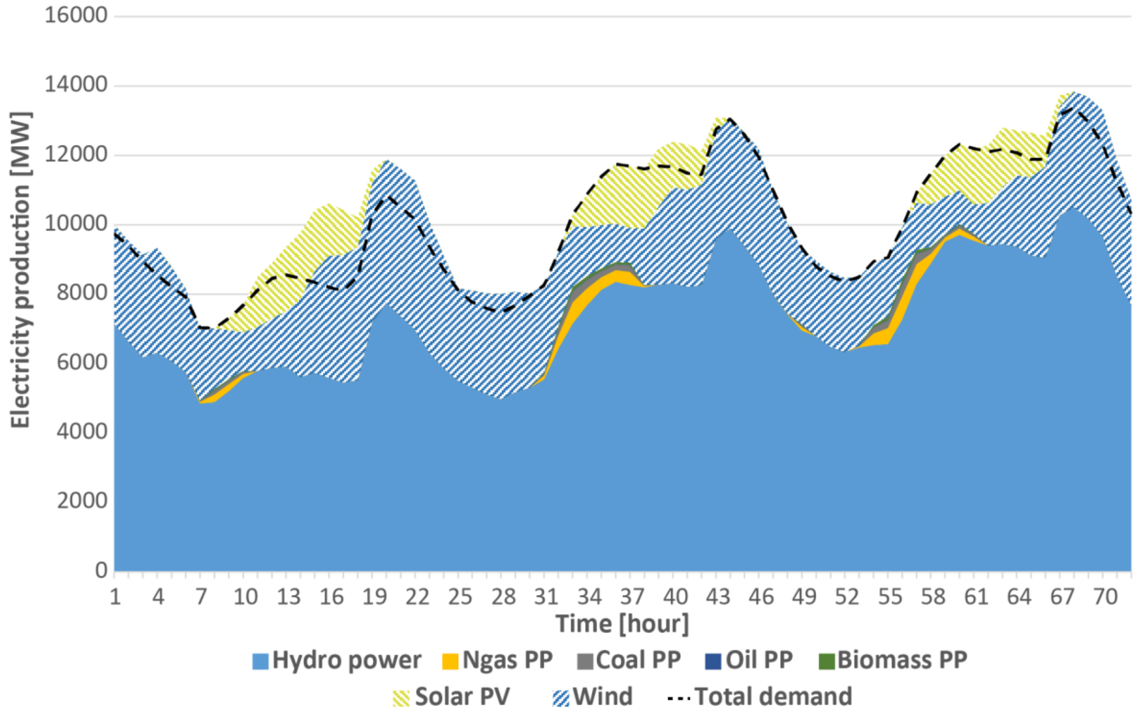

Figure 13. Hourly distribution of supply and demand for the RES Combination scenario.

The effects of large scale RES integration on conventional thermal power plants require special attention. The results shown in Figure 13 evidence that higher RES penetration increase the ramping demands for thermal generators. This case is critical during peak hours when the sun sets in tropical countries and solar production declines.

It is important to note that energy efficiency scenarios were not examined in this paper. Additionally, it was assumed that the future energy demands would remain the same as estimated by the Colombian government. Energy efficiency measures will need to be included in future works when the best cost-efficient renewable energy system for Colombia is estimated.

4.4 Sensitivity analysis

This section presents the sensitivity analysis for the future electricity sector of Colombia. This analysis is important due to the high reliance of the power system on hydro generation, which is affected periodically by extreme weather events. In Section 2.1, the influence of the warm phase of ENSO was described. However, the cold phase of ENSO, also known as La Niña, is characterised by heavy rainfalls that prompt an unusual behaviour on the electricity sector.

The simulations were performed using the scenario 5 as the typical year. Average water inflows data from 2009-10, 2015-16 in the time of ENSO El Niño; and 2007-08, 2010-11 in the time of ENSO La Niña were used as inputs [59]. The aim of this analysis was to examine the electric power system performance in the case of any of these events.

Figure 14 shows the results of the sensitivity analysis. As expected, during dry years (El Niño) hydro generation drops by approximately 19% compared to a typical year. Thermal power plants and renewables production compensate the reduction, and this is a clear evidence of the resilience of the defined power system during periods of low water inflows. The inverse correlation between wind and hydro energy has been reported previously in the literature [14,35], and this is confirmed in the results. Wind production might grow to approximately 15.4% during dry years, and its generation could decrease to about 19.6% during wet years.

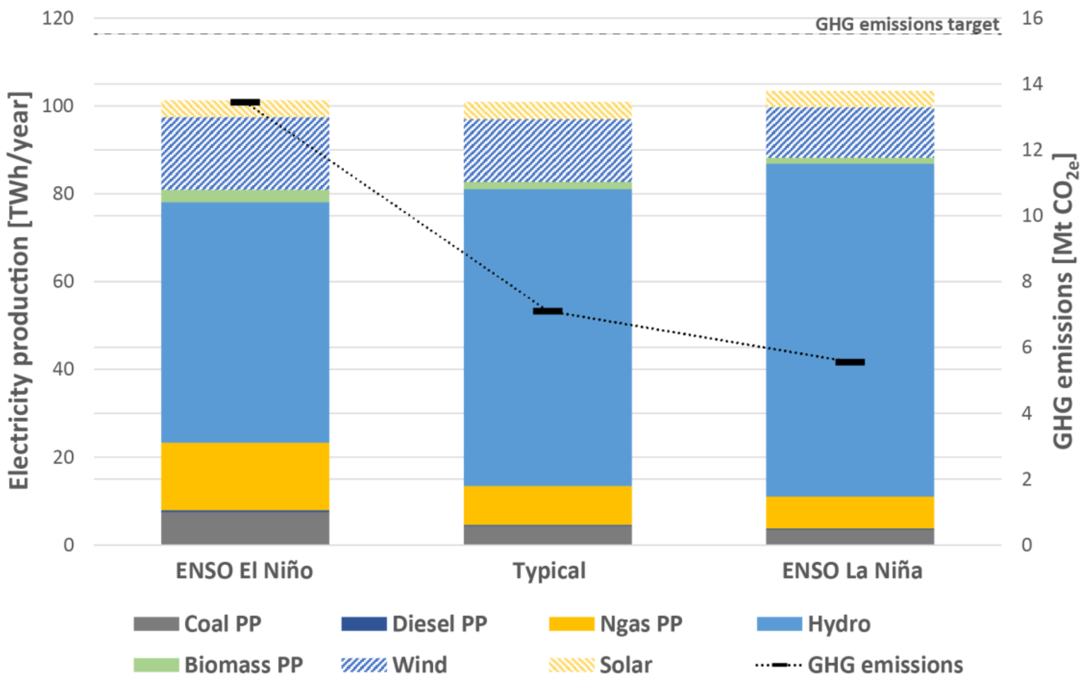

Figure 14. Electricity production and CO2e emissions for the sensitivity analysis.

In terms of GHG emissions, it is expected that during dry years the additional generation from fossil fuel plants could increase the emission intensity of the electricity sector. The results show an upsurge of about 89% compared to a normal year. In contrast, during wet periods, hydro generation might rise and the emission levels could drop to about 21.8% with respect to a typical year.

5. Conclusions

In this paper, a new model for the Colombian energy system has been developed using the EnergyPLAN tool. The purpose of the current study was to analyse the impacts of different integrated renewable sources on possible future energy scenarios. The accuracy of the model was verified considering 2014 as the reference year and then five different scenarios have been built and simulated. Furthermore, the general results of this work agree with those from earlier studies produced for Colombia [15,18,67] and other countries with similar electricity mix [11,51].

The technical analysis of the scenarios evidenced the advantages of including renewable alternatives in a system that has been historically dominated by hydro and fossil fuel resources, such as natural gas and oil. In all the scenarios analysed, hydropower remains as the main source of energy in the electricity sector. Its high flexibility, compared to thermal plants, represents an advantage for the integration of variable renewables. The maximum technical penetration levels of wind and solar power were estimated to be 22% and 11%, respectively. Higher levels of penetration could result in over generation that might limit the feasibility of the electric power system.

Even though the GHG emissions of the electricity sector in Colombia have been generally low compared to international averages, further efforts are required to achieve a significant decarbonisation of the complete energy system. The transport sector remains challenging and the main driver of emissions even in the most optimistic scenario. Therefore, policymakers should focus on long-term planning strategies oriented at reducing its environmental impact through more sustainable mobility alternatives. In the electricity sector, the results from the best-case scenario show an emission intensity of 70.44 gCO_{2e}/kWh that could be achievable by increasing the participation of wind, solar and bioenergy technologies as described in scenario 5.

The findings of this work should be interpreted with caution. The intention of the authors is to suggest a pathway for the future energy system of the country based on the outcomes of several scenario analyses rather than a forecast. The results of this work will be of much assistance to policymakers that are developing a roadmap towards low carbon energy systems in Colombia and other countries with similar potential and characteristics.

Acknowledgements

This research was supported by the Fundación CEIBA - Gobernación de Bolívar through the program “Bolivar gana con ciencia”. We thank our colleague Mauro Gonzalez, from TEBSA, who provided his insights and expertise that greatly assisted this work. We also thank IDEAM for providing their weather station data.

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List of Acronyms and Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
BaU	Business as Usual
CEEP	Critical Excess of Electricity Production
CEPAL	Economic Commission for Latin America and the Caribbean
COMP	Compromised Coefficient
COP	Conference of the parties
ENSO	El Niño and La Niña southern oscillation
EPPA	Economic Projection and Policy Analysis
GDP	Gross Domestic Product
GHG	Greenhouse gases
IDEAM	Hydrology, meteorology and environmental institute
IEA	International Energy Agency
iNDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel for Climate Change
IPPU	Industrial Products and Product Use
ISA	Interconexión eléctrica S.A. (Electric interconnection company)
LEAP	Long-range Energy Alternatives Planning
OSeMOSYS	Open Source Energy Modelling System
PES	Primary Energy Supply
PV	Photovoltaics
RES	Renewable Energy Sources
SIEL	Colombian Electrical Information System
SIN	National Interconnected System
tCO_{2e}	ton of CO_2 equivalent
TPES	Total primary energy supply
UPME	Unidad de Planeación Minero Energética (Mining and Energy Planning Unit)
VRS	Variable Renewable Source
XM	Compañía de Expertos en Mercados (Market experts company)
ZNI	Not-Interconnected Zones