Large-scale integration of renewable energy sources in the future energy system of Colombia

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“We are operating against the laws of mother nature and breaking the natural balance. We need to change our mindset; the little brother has to listen”

Mamo of the Sierra Nevada de Santa Marta, Colombia

Declarations

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

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. In the case of Colombia, the diversification of the energy mix including larger shares of renewable energy sources (RES) is a significant part of the national 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 is to assess the integration of variable renewable technologies and flexibility options into national energy systems by analysing future scenarios (towards 2030 and 2040).

EnergyPLAN was the modelling tool employed for building the country's model and simulate the reference year scenario and future alternatives. The study was divided in three research topics for its analysis: initially, the impacts of increasing shares of variable renewable sources in the energy system towards 2030 were analysed using five alternatives scenarios. Subsequently, a techno-economic optimisation was performed in order to assess the combined effects of large-scale energy storage and cross-border interconnections in the power system. Finally, the impact of road transport electrification in supporting the energy transition in the longer term (2040) was evaluated for the national system.

The results showed that an increase in the shares of wind, solar and bioenergy combined with energy storage, electric vehicles and a strong interconnected market could achieve significant reductions in CO_2 emissions and savings in the total fuel consumption of the country. 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.

Research outputs

List of publications

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

- O. Pupo-Roncallo, J. Campillo, D. Ingham, K. Hughes, M. Pourkashanian, **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

- O. Pupo-Roncallo, D. Ingham, M. Pourkashanian, **Techno-economic benefits of grid-scale energy storage in future energy systems**. *Energy Reports* 2020; vol. 6: pp 242–8. https://doi.org/10.1016/j.egyr.2020.03.030

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Software developed / Dataset published

- O. Pupo-Roncallo, D. Ingham, M. Pourkashanian (2020, April 28). **MOEA Eplan (Multi-objective evolutionary algorithm optimisation for EnergyPLAN) (Version 1.0)**. Zenodo. http://doi.org/10.5281/zenodo.3770479

- Pupo-Roncallo O., Campillo J., Ingham D., Hughes K., Pourkashanian M. **Data on electricity demand and renewable energy production for the Colombian energy system**, 2019. https://doi.org/10.17632/w6cwkn4jm7.2

Posters presented in academic events

- O. Pupo-Roncallo, D. Ingham, L. Ma, M. Pourkashanian. **Renewable energy integration into national energy systems.** *Energy 2050 Research Symposium: Delivering low-carbon energy for all.* July 24th, 2017, Sheffield, UK.

- O. Pupo-Roncallo, D. Ingham, L. Ma, M. Pourkashanian. **Modelling the impacts of RES integration in the Colombian energy system.** *MEC PhD Students Poster Presentations.* May 14th, 2018, Sheffield, UK.

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List of Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
ANDEMOS	Sustainable Mobility National Association
BaU	Business as Usual
BEV	Battery electric vehicle
BRT	Bus rapid transit
CAES	Compressed air energy storage
CAN	Andean community
CCS	Carbon capture and storage
CEEP	Critical Excess of Electricity Production
CEPAL	Economic Commission for Latin America and the Caribbean
CHP	Combined heat and power
CO_2	Carbon dioxide
COMP	Compromised Coefficient
COP	Conference of the parties
CREG	National Electricity and Gas Regulatory Comission
CRF	Capital recovery factor
DEEC	Department of Energy and Climate Change
DIAN	National tax authority
DSM	Demand-side management
ECDBC	Colombian Low-carbon development strategy
EMS	Energy management system
ENSO	El Niño and La Niña southern oscillation
EPPA	Economic Projection and Policy Analysis
ES	Energy storage
ETRI	Energy technology reference indicator
ETS	Emissions trading scheme
ETSAP	Energy Technology Systems Analysis Program
EV	Electric vehicles
GDP	Gross Domestic Product
GHG	Greeenhouse gases
GNI	Gross National Income
HDV	Heavy-duty vehicles
ICT	Information and Communication Technology
IDEAM	Hidrology, meteorology and environmental institute
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IIASA	International Institute for Applied System Analysis
iNDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel for Climate Change
IPPU	Industrial Products and Product Use
IRENA	International renewable energy agency
ISA	Grid interconnection company
LCOE	Levelized cost of electricity
LDC	Load duration curve
LDV	Light-duty vehicles

LEAP	Long-range Energy Alternatives Planning
MARKAL	MARKet Allocation
MOEA	Multi-objective evolutionary algorithm
NDC	Nationally Determined Contributions
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
NTL	Non-technical losses
ORCED	Oak Ridge Competitive Electricity Dispatch
OSeMOSYS	Open Source Energy Modelling System
PES	Primary Energy Supply
PHES	Pumped hydro energy storage
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaics
PVGIS	Photovoltaic Geographical Information System
RES	Renewable Energy Sources
RQ	Research question
RUNT	National Unique Transit Registry
SCADA	Supervisory control and data acquisition
SG	Smart Grids
SIEL	Colombian Electrical Information System
SIN	National Interconnected System
tCO_{2e}	ton of CO_2 equivalent
TEA	Techno-economic assessment
TFEC	Total final energy consumption
toe	ton of oil equivalent
TPES	Total primary energy supply
UNFCCC	United Nations Framework Convention on Climate Change
UPME	Unidad de Planeación Minero Energética (Mining and Energy Planning Unit)
V2G	Vehicle-to-grid
VR	Variable renewable
VRE	Variable renewable energy
VRS	Variable Renewable Source
XM	Compañía de Expertos en Mercados (Market experts company)
ZNI	Not-interconnected zones

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Chapter 1 Introduction

During the last decade, governments around the globe have been increasing their attention on energy supply policies. These policies have focused their attention 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.

The growth in renewables as an energy source has been supported by the political commitments made at the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), at its 21st session in Paris (COP21). The power sector occupies the first place in investment and deployment, led mainly by the development of existing technologies and the reduction of initial costs. Nevertheless, other fields of energy use, such as industry, building and transport, have experienced a slow renewable implementation, mainly due to the lack of supportive policies [2]. Despite the security, environmental and economic benefits that renewables carry, there are numerous challenges that must be tackled. Two of them are their competitiveness with traditional fossil fuels, and the integration into the current energy systems [2]. 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 [3]. 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 [4], [5]. The great majority of these models assist in the formulation of strategies for renewable integration in national energy systems [5]. For instance, in Latin America multiple models have been built for this purpose [4], [6]. De Moura et al. [7] 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. [8]

used the MIT Economic Projection and Policy Analysis (EPPA) model to evaluate different CO_2 emission reduction alternatives for Brazil and Mexico.

There are an extensive number [5], [9], [10] of energy modelling tools and typologies available, such as partial equilibrium, general equilibrium, sectoral demand, single technology, simulation, optimisation, etc. The role of policy analysts is to understand clearly the main characteristics (strengths and weaknesses) of these models to establish which one is best suited to answer the policy questions assessed [11].

1.1 Research aim and questions

The overall aim of this research is to assess the integration of variable renewable technologies and flexibility options into national energy systems, considering scenarios that could allow a successful transition towards a low-carbon and more efficient system. This work intends to focus its attention on the energy system of Colombia, but the findings could be applicable to systems in other countries with similar characteristics. Furthermore, this study substantially contributes to the knowledge and understanding of renewables integration analysis. After a critical review of the relevant literature was completed, some research gaps were identified. Based on these gaps, this study addresses the following three research questions (RQ):

RQ1. *What are the technical and environmental benefits of increasing the shares of variable renewable technology into a national energy system dominated by high hydro generation?*

One of the main concerns reported in the literature is the fact that renewable integration is focused on the deployment of the technology, instead of considering the requirement for system adaptation [12]. Numerous studies have acknowledged the advantages of using these technologies in energy systems [13], [14]. Nevertheless, little research has been performed in evaluating the integration of renewables into the system, especially in developing countries [15].

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 [6]. 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 [4]. 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 electricity production [16]. 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 [17], [18], Norway [19], and New Zealand [20]. The need for research oriented towards the development of a diversified energy matrix has been raised by the Mining and Energy Planning Unit (UPME) [21]. Despite this, little research has been done on assessing the integration of high shares of renewable energy sources into national systems of 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, power, transport, and industrial sectors) using a high temporal resolution model.

For these reasons, the first research question aimed to assess different scenarios that could allow the transition towards a more sustainable and secure energy supply in Colombia. The answer to this question is further discussed in Chapters five and six, and it was the starting point for a more detailed analysis that was addressed in the following chapters.

RQ2. *What are the techno-economic benefits of integrating large-scale energy storage and cross-border interconnections into power systems with increasing intermittent renewable energy penetration?*

As it is described in more detail in Chapter 2, increasing the flexibility of power systems is an important component in the global efforts oriented to meet the climate change mitigation goals by different governments around the world. Two of the main technologies suited to assist in the effective integration of high share of RES are energy storage and international grid expansion [22]. In the case of energy storage, the global debate has changed significantly over the past few years, and the main reason for this is the steady drop in the price of storage devices since 2010 [23]. The debate is now focused on how these technologies could replace part of the power grid system or support the integration of a large share of the variable solar and wind power. Some experts [23]–[25] argue that energy storage is an essential pillar in the large-scale integration of renewable energy.

Each country has a specific potential for energy storage according to its characteristics, such as energy resources available, grid infrastructure, regulatory framework, and electricity demand patterns and trends. Latin America is considered as one of the most attractive emerging markets for storage projects development due to its recent growth in renewable generation, rapidly growing populations, and relatively unstable grid conditions [26]. 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 [27]. However, a complete understanding of the effects of ES and electricity interconnections in the power system requires the development of energy models and scenarios that allow the assessment of its performance. A considerable amount of literature has been published on this issue [22], but these are mainly focused on small-scale applications [28], island energy systems [29], [30] and specific markets with highly developed economies, such as European countries and the United States [31]–[33]. For instance, Cebulla et al. [34] analysed different energy storage and RES expansion investigations pertinent to the US and Europe. Victoria et al. [35] studied the storage requirements for the European power system as a function of the emission reduction targets by using the PyPSA-Eur-Sec-30 model. Bussar et al. [36] 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. [31] developed four future scenarios including energy storage and interconnections in the Great Britain power system. Andersen at al. [37] explored the effects of large-scale storage in Denmark. Limpens et al. [38] studied the different trade-offs between RES shares, storage and curtailment for Belgium, and Conolly et al. [39] investigated the benefits of pumped hydroelectric energy storage (PHES) and wind power in the Irish energy system.

In the case of countries with high share of hydropower in the electricity mix, such as the case of many Latin American countries, very few studies [40] have investigated the impact of utility-scale ES and international electricity interconnections for increasing the flexibility of the power system. Therefore, the second research question seeks to evaluate the techno-economic benefits of energy storage technologies and international interconnections in electricity markets with increasing renewables penetration. This part of the research is presented in Chapter 7, and it estimates the most suitable levels of energy storage that could be technically achievable in defined scenarios for the country.

RQ3. *To what extent the electrification of the transportation sector could be an effective solution for the integration of higher shares of variable renewable penetration and the mitigation of GHG generation in national energy systems?*

According to Lund et al. [41], the design of sustainable energy systems usually faces two major challenges: the integration of a high share of intermittent resources into the power system and the inclusion of the transport sector in the strategies. In this thesis, the first challenge is addressed by the two previous research questions, and the latter is addressed in this part of the study.

Sustainable transport is a significant concern if a reduction in the current levels of GHG is desired. Over 27% of the current energy consumption comes from the transport sector, including road, rail, aviation and marine transport [23]. In the case of Colombia, as seen in more detail in Chapter 4, this sector accounts for 39% of the GHG generated in the energy sector. Because of this, and given the recent surge in the electric vehicles industry, concerns have emerged about the impact of the transportation electrification in the integration of variable renewables and the reduction in the national GHG emissions [42], [43]. Nevertheless, this pathway represents a great challenge to the energy system and the resilience of the electricity sector because additional energy will be required and delivered in order to satisfy the total demand. Therefore, further research is needed in order to calculate the amount of additional energy required, the type of generation to cover the additional demand and how charging peaks can be managed. The outcomes generated from this research question seek to quantify the techno-economic benefits of different levels of transport electrification and other sustainable alternatives into the national energy system.

Based on the literature review and the assessment of the available options, EnergyPLAN was the modelling tool selected for this research in order to address the research questions. The tool is open source and its main purpose is to assist in the design of national and regional long-term planning strategies by simulating the complete energy system [44]. EnergyPLAN has been widely used in the relevant literature considering large-scale integration of RES [45], 100% renewable energy systems [41], [44], and in specific studies assessing the effects of different elements of the energy system such as energy storage [46], transport integration [47], [48] and demand-side response technologies [49].

1.2 Research scope and limitations

This research contributes to the field of renewable energy integration into energy systems. The methodology applied corresponds to the development and analysis of energy system scenarios, and the EnergyPLAN software was selected as the modelling tool for running the simulations. The geographical scope of the thesis is on the Colombian energy system, but the outcomes would be relevant to systems in other countries with similar characteristics. The main reason for this is that the results of renewable integration studies are very specific to the region or country being considered, and this is because the characteristics of the natural resources are highly dependent on the location [15]. Further, this research includes in the analysis the main sectors in the energy segment of national systems, namely heat, power, transport, and industrial sectors.

It is not the purpose of this research to propose a business model, market design or policy mechanisms to deliver a low-carbon national system. Instead, the main objective is to widen the knowledge of the fundamental challenges associated with increased renewable energy penetration into energy systems.

1.3 Thesis structure

This thesis is organised into nine chapters, including this introductory chapter:

Chapter 2 provides an overview of the main concepts related to variable renewable energy and its characteristics. This chapter introduces the concepts of renewable integration and system flexibility. It includes a description of the drivers for the energy transformation and the current trends in renewable energy penetration around the world. Further, a discussion on the main characteristics (identified by the International Energy Agency (IEA) [2]) of variable renewable energies and the associated challenges of large-scale penetration into the energy system are presented. Finally, a series of relevant flexibility options that can be implemented in order to support the integration of clean energy technologies are discussed.

Chapter 3 introduces the energy system modelling tools used in diverse energy system analysis, including the classification and selection of these models for specific purposes. Considering that this research is applied on a developing country, the existing differences of these energy systems with developed countries are discussed. Further, a description of some of the most commonly used modelling tools, their challenges for simulating variable renewable generation, and the most relevant criteria for their selection in specific applications are introduced.

Chapter 4 provides an overview of the characteristics of the Colombian energy system and its renewable energy potential. In order to better understand the contribution of each sector to climate change, a breakdown of the GHG emissions by sector is presented. Finally, the main regulations established by the Colombian government in order to support the integration of sustainable energy alternatives into the energy system are outlined. The objective of this chapter is to introduce the case study country analysed in this research to the reader.

Chapter 5 is concerned with the methodology used for selecting the modelling tool, building the energy system reference model and its validation process. EnergyPLAN is the modelling tool selected for analysing possible future scenarios in the Colombian energy systems towards the years 2030 and 2040. A description of the tool and the assessment criteria used for its selection are summarised. Further, this chapter introduces the general methodology applied in order to build the model for the Colombian energy system, including a detailed description of the main assumptions, data used and its validation against actual statistics.

Chapter 6 explores four different alternative scenarios for an energy system with increasing shares of variable renewable energy towards the year 2030. These scenarios are built from the reference model developed in Chapter 5, and their results are compared with the baseline scenario built by the Colombian government for the Paris agreement. Further, the maximum technical levels of RES penetration into the power sector are estimated. The main findings from the scenario results are discussed and analysed using different indicators, such as the annual GHG emissions, fuel consumption, the share of RES and energy curtailments.

Chapter 7 provides an analysis of the techno-economic effects of large-scale energy storage and cross-border interconnections in the integration of variable renewable energy. This chapter is focused only on the power sector, and it analyses the impact of these two flexibility options in the future system of Colombia. Initially, a parametric analysis is performed, followed by a multi-objective optimisation aimed to minimise the system costs and CO_2 emissions. Further, a new optimisation tool, developed by the author in MATLAB, is introduced and applied in the analysis.

Chapter 8 analyses the impact of the transport sector electrification into the Colombian energy system in longer term scenarios (towards 2040). It includes a complete description of the transport sector in Colombia and the main assumptions, data and strategies used for building the future scenarios. The results section outlines the implications of the research for policymakers.

Chapter 9 draws upon the entire thesis, providing an overview of the key findings and contributions of this research. It also summarises how each of the research questions was addressed, the main limitations of the methodology and modelling tool used, and recommendations for further work in the field. Finally, some concluding remarks and suggestions for policymakers are outlined.

Chapter 2 Variable Renewable Generation

2.1 Introduction

This chapter provides an introduction to the concepts and challenges related to renewable energy integration and flexibility into energy systems. The second section describes the drivers for the current energy transformation. Section 2.3 offers an overview of the growth of variable renewable energy (VRE) capacity and penetration around the world. Sections 2.4 introduces the concept of VRE penetration, and Section 2.5 provides an overview of the main characteristics of VRE and the associated challenges of large penetration into the power system. Finally, the last section discusses the main flexibility options that can be deployed in order to support the integration of clean energy technologies. The chapter serves as an introduction to the topic of renewable integration and system flexibility.

2.2 Drivers for the energy transformation

Climate change is considered one of the major concerns of this century and the energy sector is required to reduce its carbon emissions in order to avoid its negative effects [50]. As a consequence of the Paris Agreement in the COP 21, the world is seeking strategies to replace rapidly the use of conventional fossil fuels for low-carbon technologies. However, the reduction of current levels of CO_2 emissions is not the only reason for adopting the energy transformation, there are also other important drivers behind it:

- *Competitive renewables cost*: In the last few years, the average cost of electricity from the different renewable sources available have been falling steadily [51]. For instance, the levelized cost of electricity (LCOE) from solar PV fell by 82% between 2010 and 2019, while the cost from wind generators declined by 45% in the same period [50].

- *Air quality improvements*: The continuous use of unregulated, inefficient and polluting energy sources, such as fossil fuels, has caused a worldwide major public health crisis [52]. Switching to clean RES along with electromobility could contribute greatly to improve the air quality in big cities and reduce public health problems. These benefits could outweigh the total system costs of new RES capacity. According to IRENA [50], the total savings of a better public health, reduction in subsidies and lower climate change impacts would be worth approximately USD 160 trillion cumulatively over a thirty-years period.

- *Universalisation of energy access*: The lack of energy for many people across the globe is considered one of the causes of the current levels of inequality. Therefore, the implementation of RES technologies can be applied to remote areas where the grid access is limited, bringing rural electrification and distributed energy resources that can improve people’s lives and economies [50].
- *Energy security*: The enhancement of energy security is a key issue for every country, especially for those that highly depend on fossil fuels imports. An extended use of RES could provide an alternative to these conventional energy sources, assist in the energy mix diversification through distributed generation, and improve the flexibility of the national system.
- *Socio-economic benefits*: Shifting towards a renewable-based energy system would bring large socio-economic benefits. For instance, the development of a domestic RE industry could contribute to job creation for people from all disciplines and backgrounds. IRENA [53] estimates that the energy transformation could increase the gross domestic product (GDP) by 2.5% globally by 2050.

2.3 Variable Renewable Energy

As introduced in the previous section, renewables represent an established alternative source of energy. Their improving cost-competitiveness, better financing options, international policy initiatives, and environmental and energy security concerns have contributed to the sharp increase of these technologies, particularly in the power sector. Therefore, a large number of countries around the world have considered the inclusion of renewables technologies (Box 2.1) on their energy mix as a priority [54].

Box 2.1. Renewable energy resources and technologies

Renewable energy comprises a wide number of energy resources with specific characteristics and applications. Although these resources are widely distributed around the globe, its implementation is not an easy task. They include solar and geothermal, which are used to produce electricity and heat; wind and hydro for electricity generation, and biomass resources for liquid transport fuels and bioenergy production.

Some important distinctions must be made regarding the energy service provided by renewable resources [2]:

Variable and dispatchable renewables: some renewable sources are intermittent by nature (such as wind and solar) and cannot be used always when needed. Dispatchable renewables can be controlled and used to cope with either fluctuating demand or to assist variable forms of supply (this is the case of hydropower and bioenergy). Energy storage appears to be a possible solution for renewables variability, but in consequence, the capital cost increase. Hydropower is a reasonable dispatchable option, but in some cases (run-of-river, natural storage) their power output may be subject to seasonal variations.

Centralised or distributed generation: in the centralised generation the electricity is supplied on a large scale through the grid. Whereas, the distributed generation of electricity is done in a smaller scale, by distributed assets (rooftop solar PV, small wind turbines), which may be connected to the main grid.

Direct or indirect renewable energy: when the resource is used directly to provide an energy service, such as solar thermal to provide heat, is known as a direct renewable energy. In case the energy service is provided indirectly, such as renewables-based electricity for electric vehicles, is identified as indirect renewable energy.

2.3.1 The global context

Variable renewable generation capacity around the globe has grown rapidly over the past two decades. In 2019, the global supply of renewable energy rose by about 200 GW compared to the previous year, of which solar PV accounted for approximately 115 GW of the total added [55]. Wind and solar energy have been leading the latest growth in renewables capacity and are continuously more cost-competitive than fossil fuel power plants. Nevertheless, the biomass used in household activities (usually for cooking and heating in developing countries) and hydropower for electricity are the largest sources of renewables-based energy supply today.

Even though the deployment of renewable energy around the globe is currently increasing, the share of renewables in the total final energy consumption (TFEC) has evidenced a modest growth. In 2018, renewable energy (excluding traditional use of biomass) represented approximately 11% of the TFEC, as shown in Figure 2.1. Electricity from renewables accounted for 5.7% of the TFEC, followed by renewable heat (4.3%) and biofuels for transportation (1%) [55]. The main reason for the limited penetration of these RES in the end-uses of thermal and transport is attributed to the lack of available policies in these sectors.

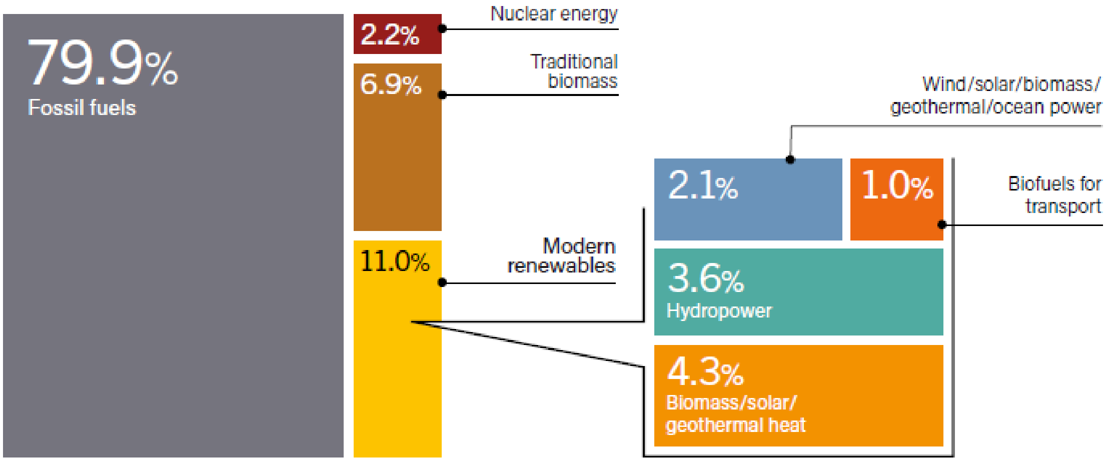

Figure 2.1. World share of renewable energy in the TFEC. Taken from [55]**.**

Two important triggers for the inclusion of renewables in any country are the development of policies and the market [2]. The former is an important driving force for the renewable energy progress, evidencing the determination to support renewables as an important share of the whole energy system. The latter is also critical because every system must achieve cost-competitiveness within the existing market.

Policy developments

Sustained government policies and support measures are key strategies for the development of renewables. These strategies lead to a development cycle, where policy support leads to renewables deployment that drives cost-competitiveness, which enables policymakers to support more renewable energy, taking into account the consumer affordability and public funds available.

During the last few years, over 150 countries have adopted different policies for renewable-based power, 75 for renewable-based heat and 72 for renewable-based in the transport sector [54]. COP21 provided an important number of measures that support the use of renewable energy. The most important is the commitment to hold the increase in global temperatures to “well below 2 degrees Celsius (C)”, followed by the 162 Nationally Determined Contributions (NDCs) to tackle climate change.

The evolution of the integration of renewables into the power sector is clear: the first policies were designed to cope with the large cost gap of these technologies, but nowadays the focus is on the reduction of risk in the capital investments. Diverse mechanisms, such as feed-in tariff and auctions, have been crucial in accelerating the deployment of renewables [54].

In the heat sector, the policies to promote the use of renewables remain insufficient. The most common measures are either fiscal incentives, such as energy efficiency linked to building renovation [56], or the establishment of building standards, where the regulations require a certain share of the heat supplied from renewables in new buildings [57].

The policies in transport have also experienced a slight growth during the past decades. These have focused their attention mainly on road transport and biofuels. In the case of biofuels, its production is supported by blending regulations, subsidies or a combination of both [58]. Although, in some regions, such as the European Union, the emphasis has been placed on the development of more advanced biofuels [59].

Market developments

The technological progress and cost reduction of renewable energy systems has positioned this industry as a new major global business. By 2015, the investment in renewables for electricity generation was about $288 billion, exceeding the fossil-fuel based generation investments [2]. The generation capacity based on renewables is currently higher than coal-based, with 1985 GW and 1950 GW, respectively. Nevertheless, the renewables electricity supply is 40% lower than from coal. The capacity additions are variable form year to year and is still highly dependent of external economic circumstances. However, the evidence supports the idea that an energy transition is taking place worldwide [2].

2.3.2 Competitiveness of renewable energy

The competitiveness of renewables is an essential aspect in determining the level of developing and deploying of a particular technology (Box 2.2). Different forms of renewables have offered competitive and cost-effective alternatives to generate electricity, heat and fuel for the transport sector. In terms of electricity production, hydropower is the principal among competitive technologies. It has been for many years the largest source of renewable energy supply, providing currently one sixth of the global power production [2]. Geothermal and bioenergy-based power plants have been implemented on a commercial scale in numerous markets.

Reaching competitiveness on a commercial scale is a significant achievement for clean technologies. However, renewable energy technologies must also help to mitigate CO_2 emissions, enhance energy security, reduce pollution levels and create jobs. All these further benefits have to be weighed in the balance [2].

Box 2.2. Key concepts in evaluating renewable energy

1. **Competitiveness:** This concept is used to indicate when the technology is profitable for investors without any external support (government or private companies).

2. **Financial attractiveness:** The inclusion of support distinguishes this concept from competitiveness. A project is financially attractive if the profitability of the project is guaranteed using support measures.

3. **Cost effectiveness:** This aspect applies mainly to the assessment of different ways to reach societal objectives that are placed beyond profits in terms of financial return.

The number of renewable projects that are economically feasible may be much larger than those that are financially attractive. This is because the current policies may not be sufficient to bridge the gap, as they do not usually consider the social benefits that renewables can deliver [2].

2.4 Variable renewable penetration in the power sector

Energy planners are continuously analysing the contribution of a set of technologies to the national systems supply and security. Renewable energy installed capacity data is commonly used to identify the growth and deployment of wind and solar energy across different regions; however, this information does not reflect the real contribution to the total energy supply. Thus, this research uses the renewable energy penetration level into the energy system as a key metric.

Holttinen et al. [60] explains that the penetration of renewable sources can be expressed as either power capacity (installed capacity share of peak load) or energy production (percentage of total generation). The latter definition is applied in this research as the main objective of the study is to explore different alternatives to increase energy production from clean sources that lead to more sustainable energy systems.

Figure 2.2 shows the combined (wind and solar PV) variable renewable installed capacity and penetration (as the contribution to the total production) for the leading countries in 2017 [61]. It is clear that having a large installed capacity does not necessarily imply high renewable energy penetration. This is also related to the size, level of development and total demand of the system. For instance, countries such as China, the US and India had total RE installed capacity of 295 GW, 129 GW and 50.7 GW, respectively. However, their total renewable participation is less than 10% of the total electricity produced in 2017. On the other hand, countries like Ireland, Portugal and Denmark have fewer renewable capacity installed but their contribution to the total energy produced is higher than 20% in all the cases.

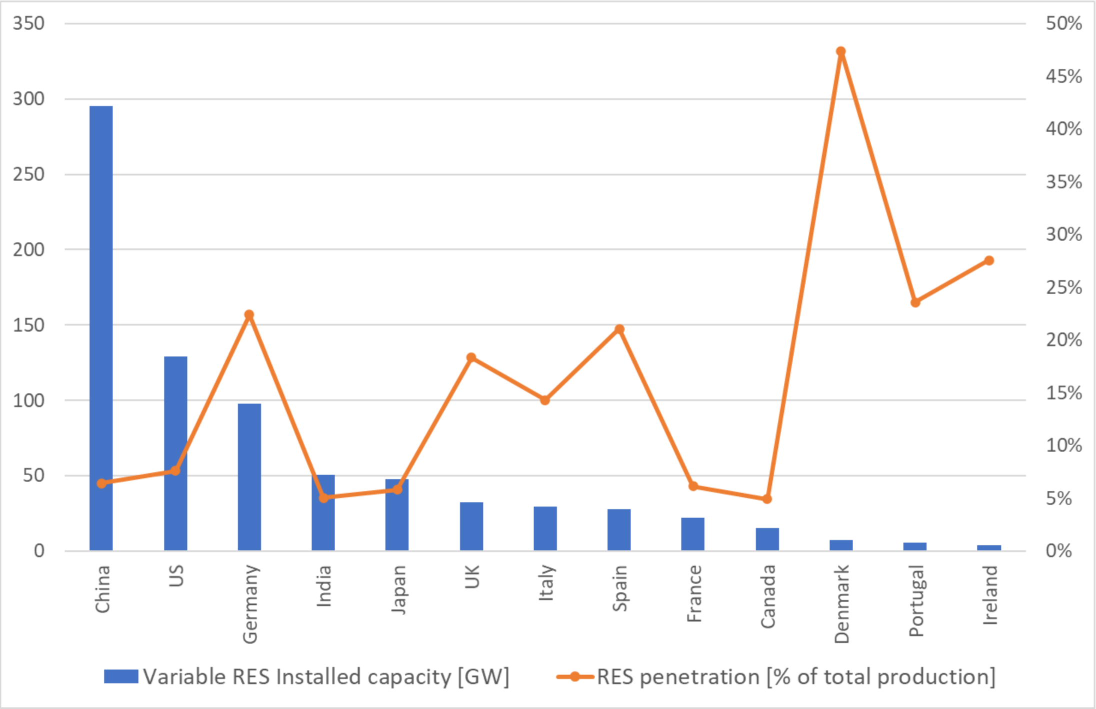

Figure 2.2. Variable renewable energy installed capacity and penetration in 2017 [61]**.**

It should be noted that the case of Denmark is significant because it has led the way in research and development of sustainable options and this is characterised by an important deployment and integration of wind energy into the power system [41].

The following sections will focus on the differences and challenges associated with renewable energy integration into the power system; this section only offers an introduction to the concept of renewable penetration in the power system and its importance when studying the renewables integration issues.

2.5 Characteristics of variable renewables and the integration challenge

This section provides an overview of the main characteristics of VRE and the associated challenges of large penetration into the power system. The IEA on its report about “The power of transformation” [62] has described five technical characteristics of VRE producers that influence their contribution to the system operation and investment: variability, uncertainty, location dependence, modularity, and non-synchrony. These characteristics are described with more detailed in the following sections.

2.5.1 Variability

Due to the random nature of weather conditions, wind and solar power outputs are subject to important levels of variability that generation operators cannot control. This is different from the behaviour of conventional power plants, such as hydro, gas or coal units, that are usually dispatchable and less sensitive to external variations. Wind and solar PV reveal distinct intermittency characteristics. Solar generation changes are mainly driven by regular day/night and seasonal cycles, cloud coverage, and fog and dust on a minor scale. The nature of wind is more stochastic in general and shows moderate daily changes and strong seasonal patterns [63].

According to the IEA [62], the aggregation of VRE outputs may reduce the variability considerably, but not completely even at large geographical scales. An important number of studies have been completed in order to better understand the variability and reliability of VRE [41], [63]–[65]. Coker et al. [66] identified the characteristics of variability in the wind, solar and tidal resources in a specific region in the UK. In particular, they explored four specific variability characteristics: persistence, distribution, frequency and correlation between supply and demand. From these, persistence and predictability were found to be more relevant for system balancing, whereas the statistical analysis is important when the utilisation and energy curtailment are the main focus. Also in the UK, Sinden [65] analysed data from different weather station over a three decades period and different time scales (annual, monthly and diurnal). He found that a significant level of variability was present on each of the time scales and that a larger spatial diversification of wind farms allows a reduction in the total output variability. These outcomes agree with the findings reported by Holttinen [67] in her study applied to Nordic countries. She concluded that large spatial distribution of wind farms increases predictability and reduced the probability of nil peak output.

The effects associated with variability usually occur over different time scales. The first is a short-term effect known as the "balancing effect" [62], and it refers to the volatility caused by the increase in the variable generation over the net load and the conventional plants cycles. The second is a long-term effect referred as the "utilisation effect", and it describes the displacement of conventional generation units during high renewable energy production.

Balancing effect

Power systems where significant VRE capacity is added evidence increasing changes in the magnitude and frequency of the net load. Therefore, these systems require a certain level of flexible resources in order to match these variations. This flexibility is mainly given by conventional power generators, such as hydro and thermal plants, that experience additional cycling and start-ups due to the VRE integration. A clear example of this is described by Denholm et al. [64] on their analysis of the well-known "CAISO duck chart" (Figure 2.3). The chart illustrates the challenge of increasing solar PV capacity added to the system and its potential for overgeneration and energy curtailment.

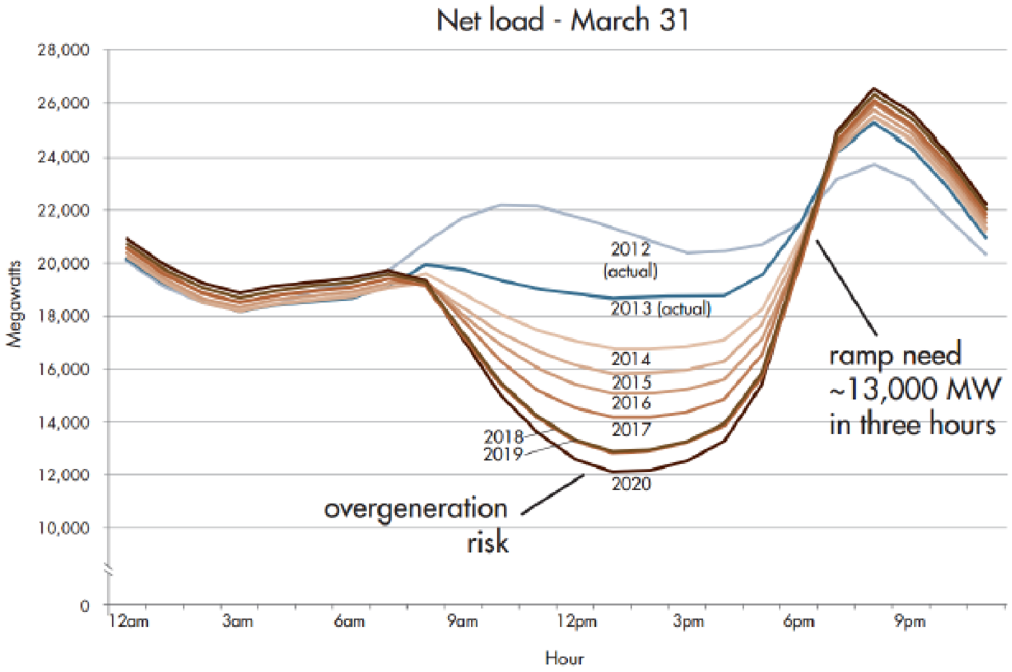

Figure 2.3. The California Independent System Operator (CAISO) duck chart. Taken from [64]**.**

Each line in Figure 2.3 represents the system net load[1], and it was estimated that by 2020 the “belly” of the curve would represent the period of lowest net load and maximum solar generation. Another important effect shown in the graph is the conventional power plants ramping-up requirements during early evening times when the sun sets and coincides with the load peak hours. It highlights the concerns about the ability of the traditional power system to meet the ramp rate and range required to fully integrate large shares of VRE. More details about flexibility measures that could help to overcome these imbalances are further discussed in Section 2.6.

Utilisation effect

This is a longer-term impact of the VRE related to the change in utilisation of conventional power generation, and it is primarily caused by the variability and low-short run cost of the VRE production [12]. In order to better illustrate this characteristic, a load duration curve (LDC) is shown in Figure 2.4. An LDC is used to illustrate the connection between the load and capacity utilisation, where the load is arranged in descending order of magnitude instead of chronological order for a period of usually one year [68].

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[1] Net load = Normal load – VRE generation.

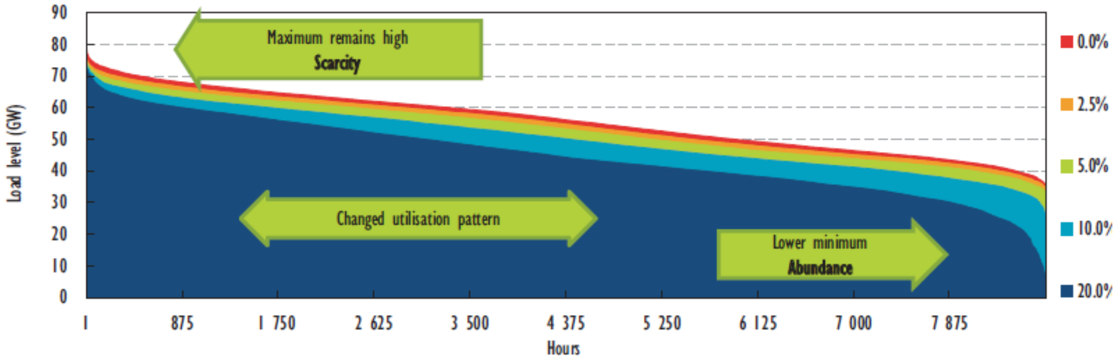

Figure 2.4. LDC for different annual shares of VRE. Taken from [12]**.**

At high shares of VRE penetration, the net LDC tend to steepen because of two reasons: firstly, the left side of the graph remains high due to periods of low VRE and high demand (scarcity); and secondly, elevated VRE production and low energy demand (abundance). Thus, the generation capacity of conventional power plants cannot achieve high capacity factors. This effect requires cost-effectiveness for conventional generation, where the optimal power mix moves towards more load following and peaking capacity [12].

2.5.2 Uncertainty

The energy production from VRE cannot be determined with certainty because it is not possible to predict with high precision wind speeds or solar irradiation in the cases of wind power or solar PV. The level of accuracy of these variables plays a significant role in the adequate daily energy dispatch and the successful integration of renewable energy. Thus, many recent studies have focused their attention on improving the quality of the forecast. Widen et al. [69] reviewed different studies on variability assessment and forecasting of wind, solar, wave and tidal energy resources. Gensler et al. [70] provide a comprehensive overview of various forms of representation of probabilistic forecasts for renewable energy and their behaviour. Further, Ahmed et al. [71], [72] analysed different techniques and optimisation models oriented towards solar PV forecasting.

2.5.3 Location constraints

Wind and solar resources are not equally distributed across the different regions of the globe, and one of the main differences with conventional fuels is that these latter can be stored and delivered easily to distant places. Potential generation locations with high renewables resources may not coincide with regions of elevated energy demand. For instance, Vergara et al. [73] reported that high wind resources for Colombia are located in the north region, but the highest energy demand is on the centre areas of the country. Therefore, the construction of transmission lines in order to connect distant wind production is required. However, this connection expansions can be expensive, and thus, there is often a trade-off between access to clean energy and the connection cost of distant VRE plants. The expansion of the transmission grid capacity as a flexibility option for increasing generation is discussed in more details in Section 2.6.3.

2.5.4 Modularity

This characteristic refers to the scale of individual VRE generation units compared to conventional power plants. Individual Solar PV units have rated capacities between 0.1 kW and 0.3 kW, while modern wind turbines rated power varies between 1 MW and 8 MW [12]. Those capacities are smaller and less complex than the typical thermal power plant, which rated power is between 100 MW and 1 GW. Thus, modularity leads to a more decentralised power system, and this can represent an important challenge at the distribution grid level. The distribution system has historically worked in one direction reacting passively to the electricity demand, however, increasing levels of distributed VRE production require a smart system capable of managing bi-directional flows and modular capacity [74].

2.5.5 Non-synchronous technology

Conventional power generators are synchronised in power systems in order to keep the system frequency within a defined range. This operation mode implies that for changes in the frequency target, an action must be followed by the generators in order to stabilise it. For instance, if the system frequency drops because of an increase in the electricity demand, the synchronous generator must adapt their speed to stabilise the frequency. However, variable renewable generators are not connected to the grid synchronously, and thus, different means for providing this service to keep the frequency target will be needed. In the future, it is expected that the deployment of very fast-responding storage systems could emulate the characteristics of synchronous generators [12].

2.6 Flexibility options for enabling high levels of VRE

As described in the previous section, shifting towards an energy system dominated by VRE comes with important challenges, and thus, some flexibility measures are required in order to overcome the negative effects of VRE integration. Cruz et al. [75] define flexibility as “the ability of a power system to cope with the imbalances in generation and demand created by abrupt changes in the system conditions”. Traditionally, flexibility has been supplied by conventional generation in the power system. However, this role has been changing in recent years, and flexible options will be key for achieving high generation efficiency, reliability, affordability and emission targets worldwide. In this section, the main existing flexibility options reported in the literature [76] are discussed. These options include Demand-Side Management (DSM), energy storage, network expansion, conventional generation, Smart Grids and sector coupling (Figure 2.5).

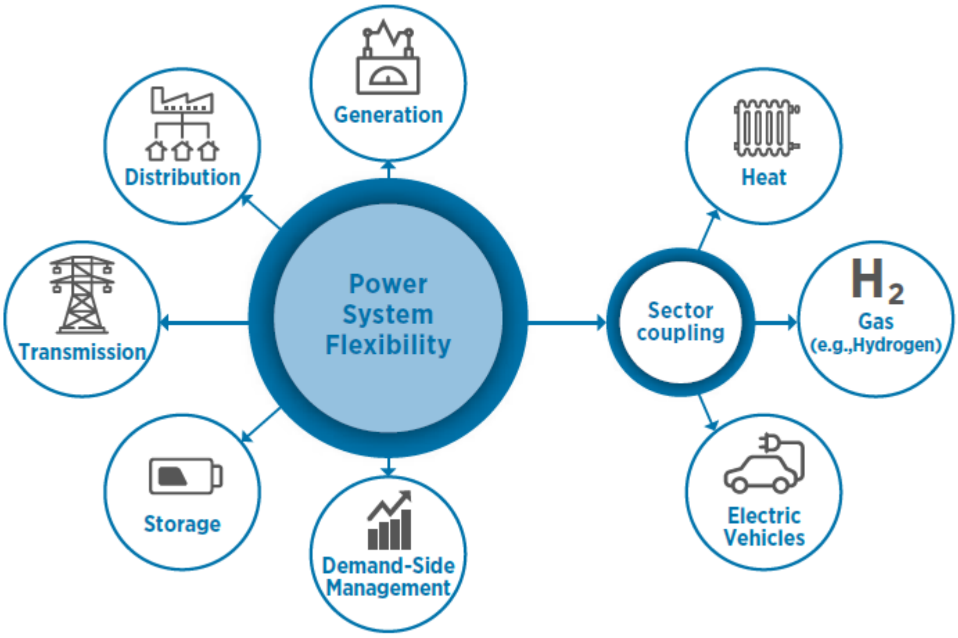

Figure 2.5. Flexibility options in the energy sector [76].

2.6.1 Demand-Side flexibility

The demand side has a big potential as a flexibility option in power systems because the strategies involving end-users have the ability to change the pattern and magnitude of the electricity demand [76]. Demand-side mechanisms are also considered as a cost-effective option for enhancing the system flexibility, and thus, assist in the integration of VRE. Some of the most prominent demand-side strategies include load shifting, peak shaving and energy efficiency [76]. There are many studies [12], [76], [77] that highlight the multiple benefits of these flexibility options for improving the integration of VRE. However, their implementation is not yet significant in many countries due to the lack of an appropriate market framework, control strategies and adequate forecasting tools [75].

2.6.2 Conventional generation

Conventional power plants have traditionally provided the balancing services in electricity systems by modifying their power outputs according to the grid requirements. These plants are classified as baseload, peaking and load following depending on their flexibility level [75]. Baseload plants include nuclear and coal, and usually run with a constant power output that cannot be altered easily due to operational and economic reasons. Peaking plants have irregular utilisation and run when high load demand is present. Finally, the load following generators include gas-fuel thermal, combined heat and power (CHP) and hydropower plants. Their quick response and ramping capability when abrupt demand changes occur make them suitable as balancing units in the system [64].

2.6.3 Network expansion and international interconnections

These flexibility options related to the internal and cross-border transmission lines capacity are considered key elements for reducing the energy curtailed from variable RES [31]. Network expansion planning strategies include improvement of existing transmission and distribution lines, installing power controllers and reactive power technologies in order to enhance the efficiency and performance of the grid [75]. Cross-border interconnections allow access to international energy markets that enable combined energy management strategies between the countries involved, which are key for large-scale VRE deployment. However, this latter option is considered a complex solution in many parts of the world due to geopolitical and economic issues [78].

2.6.4 Energy storage

The use of energy storage systems is considered to be one of the leading alternatives for providing flexibility in the power sector. In the past, many large-scale storage technologies were considered unfeasible due to economic and technical reasons.

However, the continuous decrease in the technology costs and improvement in their performance has proved the viability of this option [51]. Energy storage can be integrated both in the demand side and the supply side. During low demand periods, the excess of energy produced mainly by VRE can be stored and used during peak load hours, reducing the utilisation of peaking thermal plants which are more expensive to use at these times [75]. In addition, the fast response of some of the energy storage technologies make them suitable to support the grid fluctuations (usually caused by systems with high VRE shares) by controlling voltage and frequency. More details about the existing energy storage technologies are summarised in Appendix A. Further details of this flexibility options are discussed in Chapter 7, where the impacts of large-scale energy storage and interconnections for integrating VRE in the Colombian power sector are examined.

2.6.5 Sector coupling

The integration of different vectors within the energy sector is considered as one of the best options that could bring great benefits in the search of a sustainable energy future. Heating, cooling and transportation demands are mainly met by conventional fuels, and thus, contribute greatly to the GHG generation [75]. Therefore, the electrification of these sectors could be a game changer solution to mitigate the negative effects of climate change in the coming years. According to the IEA [79], the transport sector alone contributed to approximately 44% of the total CO_2 generation globally in 2017. Thus, its flexibility potential is immense, and this is the key in order to increase the level of VRE penetration in power systems. Recently, different initiatives, known as power-to-X, have been proposed to convert the excess of electricity to other forms of energy. For instance, Power-to-Gas (P2G) is a process where the electricity surplus is used to produce hydrogen (mainly by electrolysis) or methane (by methanation) for different applications [76]. Martinez et al. [80] modelled and optimised an energy system including gas, electricity and heat vectors, and found that they are a valuable source of demand-side flexibility. However, the planning process of integrated energy systems is extremely challenging, particularly in the presence of long-term uncertainty in the underlying energy vectors. In Chapter 8, the role of different levels of transport electrification towards a low carbon energy system is explored, using the Colombian system as a case study.

2.6.6 Smart Grids

Although there is no agreed definition for a Smart Grid, and the concept has been discussed by diverse organisations around the world [74], [81]–[83]. In general, smart grids are the result of the application of advanced communication devices to various segments of the actual electricity grid. Moretti et al. [84] define a Smart Grid as “an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers and those that do both) in order to efficiently deliver sustainable, economic and secure electricity supplies”. Smart grids are the next generation in the electricity system. They offer the capability to optimise the energy efficiency, including information technologies into the network and sharing real-time information between the supplier and customers [85]. Conventional generation systems around the world face a great number of challenges, including ageing infrastructure, increase in demand, integration of renewable energy sources and electric vehicles, reliability in the electricity supply and the commitments to reduce carbon emissions. This technology provides different options to tackle these challenges and to develop a more efficient, affordable and sustainable energy supply [74].

This chapter has provided an introduction to the main challenges associated with the integration of variable renewable energy into the energy system and the flexibility options that can assist in overcoming these challenges. The following chapter provides an overview of the models and techniques that are commonly used in order to better understand these challenges.

Chapter 3 Energy systems modelling

A reliable, sustainable and affordable energy supply is a key component of the development of the society. This issue concerns the entire globe, although the political barriers limit the discussion to individual countries or continents [10]. Furthermore, the growing concern of climate change has attracted the attention towards energy supply and demand.

The growing demand for energy and the recent commitments to limit the GHG emissions oblige participants within the energy systems to make difficult decisions based on risk assessments about the future. Because of this, and the specific objectives of each participant, support tools that assist in the decision-making process around energy systems are required.

This chapter focuses on one important branch of energy models, namely energy systems models. These models provide future energy systems structures constituted by diverse technologies at optimal costs. They first appeared after the 1970s oil crisis, aiming to maintain energy stability. At that time, there was not a defined variable generation structure and the storage technology was limited to fuel reserves. Nevertheless, with the evidence of climate change and the increasing levels of CO_2, the focus of the models has moved towards environmental issues. From a modelling point of view, there are a certain number of consequences: Firstly, the addition of VRE generation has cost impacts, represented in new infrastructure, demand balancing, etc. Secondly, there are long-term issues related to changes in the technology, which are not set to deal with variable generation sources in existing algorithms.

Pfenninger et al. [86] define an “energy system” as the “process chain (or a subset of it) from the extraction of primary energy to the use of final energy to supply services and goods”. The structure of a model includes technical, environmental and even social elements. Nevertheless, the greatest number of models focus on the first two issues.

Energy models are formulated using different approaches that vary in terms of the starting point and the type of questions they are designed to answer [9]. These models are usually able to provide good insights into energy systems, adopting theoretical and analytical methods from several disciplines including engineering, economics, operations research and management science. The development of energy models aims to provide an important contribution to the solution of many energy and environmental issues. The vision of low carbon (or even carbon-free) energy systems that has appeared over the last few years requires detailed studies of different scenarios. The technical constraints associated with the new technologies, their cost, efficiency and the timing of the commercial introduction is highly uncertain. Therefore, the main policy questions raised today are related to understand if energy policies are robust and flexible enough to deal with the uncertainties of the future [9]. The models should evidence the level of robustness that have to be considered in the near future and at the same time guarantee that the chosen path will not be regretted later in time.

This chapter offers an introduction to energy system modelling, including the classification and selection of these models for specific purposes. A description of some of the most commonly used modelling tools is included. Furthermore, some of the challenges related to the integration of variable renewable generation in these models is discussed.

3.1 Classification of energy systems models

Over the past two decades, many studies have attempted to classify energy systems models [5], [9], [10], [87]. Nevertheless, there is no standard way to characterise them [88]. Due to the large number of models, categorisation becomes an invaluable insight for selecting the appropriate tool for a given problem. Grubb et al. [88] developed one of the first detailed approaches to this issue. Here, he defined six dimensions to classify energy models, including (i) top-down vs bottom-up, (ii) time horizon, (iii) sectoral coverage, (iv) optimisation vs simulation techniques, (v) level of aggregation, and (vi) geographic coverage, trade and leakage. Afterwards, a more detailed form to categorise the models was establish by Van Beeck [89], who defined nine ways of classifying energy systems models (Table 3.1).

***Table 3.1 Nine ways of classifying energy systems models. Adapted from* [89].**

Model Approach	Characteristics
General and specific purposes of energy models	General purposes: (i) to predict the future, (ii) to explore the future, and (iii) to look back to the future from the present. Specific purposes: (i) energy demand, (ii) energy supply, (iii) impacts, (iv) appraisal, (v) integrated approach, and (vi) modular build up.
The model structure: internal assumptions and external assumptions	(i) Degree of endogenization, (ii) description of non-energy sectors, (iii) description of end-users, and (iv) description of supply technologies.
The analytical approach	(i) top-down, and (ii) bottom-up.
The underlying methodology	(i) econometric, (ii) macro-economic, (iii) economic equilibrium, (iv) optimisation, (v) simulation, (vi) spreadsheet/toolbox, (vii) backcasting, and (viii) multi-criteria.
The mathematical approach	(i) linear programming, (ii) mixed-integer, programming, and (iii) dynamic programming.
Geographical coverage	(i) global, (ii) regional, (iii) national and (iv) local or project.
Sectorial coverage	(i) energy sectors and (ii) overall economy
The time horizon	(i) short, (ii) medium, and (iii) long term.
Data requirements	(i) qualitative, (ii) quantitative, (iii) monetary, (iv) aggregated, and (v) disaggregated.

Pfenninger et al. [86] describe four model groups: (i) energy systems optimisation models, (ii) energy systems simulation models, (iii) power systems and electricity market models, and (iv) qualitative and mixed-methods scenarios (Table 3.2). In particular, the former two models have a prediction approach, while the last two are more focused on a normative approach.

***Table 3.2 Energy model families according to Pfenninger* [86].**

Model family	Cases	Primary focus
Energy system optimisation models	MESSAGE, MARKAL, TIMES	Normative scenarios
Energy system simulation models	LEAP, NEMS, PRIMES	Projections, predictions
Power systems and electricity market models	PLEXOS, ELMOND, WASP	Operational decisions
Qualitative and mixed-methods scenarios	DECC 2050 pathways	Narrative scenarios

3.1.1 Energy system optimisation models

The bottom-up optimisation model approach has been key to energy systems modelling. These models use a detailed description of the technical components of the energy systems [86]. MARKAL/TIMES and MESSAGE are two important bottom-up model families, being MARKAL one of the most widely used for general purposes. These model families aim to determine possible evolutions of the energy system on a national, regional or global basis over long periods, without describing the evolution of the system. Both models adopted the linear optimisation methods to minimise the total energy system cost.

The development of hybrid models in the 1990s represented a valuable improvement. These hybrids combine rich bottom-up models with top-down general equilibrium economic models, characterising economy-wide movements in response to energy system changes. Nevertheless, despite the advances in these models, and their ability to deliver insights that pure bottom-up models cannot, computational constraints only allow solutions that need a balance between the technical and economic detail [86].

3.1.2 Energy system simulation models

The energy system simulation models are based on simulation methods that focus on predicting the most probable evolution of the system. In comparison to the rigid mathematical formulation of optimisation models, these models can be built modularly and incorporate a range of methods (for instance, submodules that include optimisation procedures). NEMS (the US Energy Information Administration’s National Energy Modelling System) and PRIMES (a similar model used by the EU) are examples of this family. NEMS is used in the Annual Energy Outlook development, which helps support decisions on US energy policy. On the other hand, PRIMES is used by all European countries, assisting in finding an equilibrium solution for energy supply, demand, cross-border energy trade and emissions [86].

Another important model is LEAP (the Long-range Energy Alternatives Planning System). It was developed by the Stockholm Environment Institute in the late 1980s, and is commonly used in both the public and private sectors [90].

3.1.3 Power systems and electricity market models

Power system models are focused on the electricity aspect of energy. These are commonly used in the power sector business to make decisions ranging from investment planning to operational strategies such as generator dispatch [91]. The range of applications can be related to normative optimisation and predictive simulation approaches. In general, these models are characterised by more detail and attention to temporal variations, conceding that a critical element of a functioning power system is a constant balance between supply and demand [86].

Two of the most traditional power system models are WASP and PLEXOS. WASP (Wien Automatic System Planner) is used by the International Atomic Energy Agency (IAEA), and was used for the first time in 1973. Its main purpose is to develop expansion planning for generation, using a custom dynamic programming algorithm. PLEXOS is a mixed-integer linear programming tool that includes detailed modules for different power generators, the transmission grid, market planning and capacity expansion. Both models are commercial, and are used mostly for large scale power plants [86].

3.1.4 Qualitative and mixed-methods scenarios

The principal objective of an energy system model is to produce feasible or probable scenarios. One way to obtain this is by using the quantitative approach. Nevertheless, the combination of qualitative and quantitative approaches represents a reasonable approach to face the problem. A notable example of these scenarios is the UK Department for Energy and Climate Change 2050 pathways to achieve the decarbonisation goals [86].

3.2 Energy systems in developing countries

For an accurate description of the energy systems of any individual country it is necessary to acknowledge the wide disparity that exists between developed countries and developing countries. According to Urban et al. [15], developing countries are characterised by an average income below $10,065 GNI (Gross National Income) per capita, an under-developed infrastructure and a poor HDI (Human Development Index).

Energy systems in industrialised countries involve universal access to electricity, low losses in transmission and distribution, a constant match in supply and demand, predominance of modern energy carriers, and similar structural premises in rural and urban regions. In terms of finances and investment decisions, adequate subsidies and profit-making utility companies exist with a low extent of informal economies [92]. In contrast, energy systems in developing countries are characterised by a poor performance in the power sector, extensive use of traditional fuels, and structural differences in the society and economy. These characteristics represent important issues when selecting the best tools for energy modelling.

3.2.1 Poor performance of the power sector

One of the main characteristics of energy systems in emerging economies is the poor performance of the power sector and this is due to a number of supply, demand and economic reasons [15]:

i) *Power system configurations are often far from optimal levels:* these systems usually do not match the demand, although an excess in capacity may exist. This is due to the poor condition of the generation and distribution equipment, lack of planning, inadequate operational performance and maintenance, and high level of technical and non-technical losses. As a result, the service is unreliable, thus leading to regular plant breakdowns, outages and voltage fluctuations that cause major economic losses. Another problem that affect a reliable electricity supply is the electricity losses. In countries such as India, the level of electricity losses is about 27% [93], the average in Latin America is about 17%, and only in Colombia these losses are almost 20% [94].

ii) *Limited access to electricity:* this is a predominant characteristic of developing countries, especially in poorer rural regions. Only 43% of the sub-Saharan African population had access to electricity in 2014 [95]. Assuming a direct relationship between income and access to electricity is unrealistic. In developing countries the income is usually distributed unequally, governments may refuse to improve the electric infrastructure, and technical limitations for grid connections exist due to complicated geographies [15].

iii) *Traditional use of biomass:* predominant fuels in the poorest regions are still traditional biomass, such as wood, roots, crop residues, and agricultural waste. These fuels are commonly used in domestic applications for cooking and heating [96].

iv) *Financial deficiencies:* poor sector financing is common with tariffs below long-term marginal costs of production represented by losses for the utility companies due to non-paid bills [97]. Theft of electricity is another important reason. In such as India, the power sector faces a high risk of bankruptcy due to unpaid bills, theft and distribution losses [93].

3.2.2 Transition from traditional to modern economies

The good quality of life in modern cities is leading to a transition in many developing countries from the traditional rural-based economy to a modern economy based mainly on industry and service companies. Two important concepts are part of this transition: informal economy and non-monetary transactions. These describe a series of unofficial transactions that are not commonly reported in official economic indicators, such as the GDP [15]. Informal economies are present in almost all countries around the globe, but they are usually larger in developing countries. The lack of accurate data due to this issue makes it a more difficult task to represent the economies and energy systems of these countries [92].

3.2.3 Structural deficiencies in society, economy and energy systems

The traditional division between the rural and urban sectors is one of the main structural problems in developing economies. Marked differences between these sectors affect access to energy, fuel, education, potable water, health services and sanitation [97].

Inadequate planning is another major structural problem, resulting in bad investments due to inaccurate forecasting techniques [15].

In conclusion, energy systems in developing countries require an adequate energy planning to face their complexity and challenges. This is only possible through the appropriate selection of energy modelling tools for each particular case.

3.3 Energy Model comparisons

Each model presents its own strengths and weaknesses. The energy analysts, decision makers or each user in general should identify first a set of questions that need an answer from these models. This is very important in identifying the most appropriate modelling tool, considering that each tool has its specific purpose and characteristics.

As this work is aimed to assess the integration of variable renewable generation into the energy system of a developing country, a specific representation of the energy sectors and technology choices is required. Therefore, this study considers bottom-up models. These models integrate detailed engineering interactions between technology activity and energy use [9]. A bottom-up approach for developing countries can be useful, mainly because the model is independent of the market behaviour and production frontiers and different technologies are explicitly modelled [15].

As mentioned in Section 3.2, most of the energy models have been built and used in industrialised countries. Therefore, the criteria of energy systems for emerging economies are mainly based on experience from the energy systems of developed countries. These systems are characterised by a sustained match of supply and demand, high efficiencies of transmission and distribution, modern energy carriers, homogenous structural premises in urban and rural areas, and suitable subsidies and profitable utility companies with a low extent of informal economies [15].

Because of the complexity of the existing modelling tools, a comparison to analyse their purposes and performances is needed. A further description of the model selection for this work is discussed in Section 3.4. Table 3.3 offers an example of models categorisation according to the characteristics defined by Van Beeck [89]. EnergyPLAN, LEAP, MARKAL, MESSAGE and ORCED are discussed in the following sections.

Table 3.3 An example of energy modelling tools categorisation.

Model (Developer)	Perspective on the future	Specific purpose	Geographical coverage	Sectoral coverage	Time horizon	Analytical approach	Time step	Used for a developing country?
EnergyPLAN* (Aalborg University)	Exploring	Energy supply and demand, with focus on future options	National, state, regional	Electricity, heat and transport	Medium, long term	Bottom-up	Hourly	Yes
LEAP (Stockholm environmental institute Boston, USA)	Exploring, forecasting	Demand, supply, environmental impacts. Integrated approach	Global, national, regional, local	All sectors	Medium, long term	Hybrid (demand: top-down; supply: bottom-up)	Annual	Yes
MARKAL (IEA/ETSAP)	Exploring	Energy supply with constraints	National, local	Energy sector	Medium, long term	Bottom-up	User-defined	Yes
MESSAGE (IIASA)	Exploring	Energy demand and supply, environmental impacts	National, local	Energy sector	Long, medium and short term	Bottom-up	User-defined, but a multiple number of years	Yes
ORCED (Energy Information Administration)	Exploring, forecasting	Dispatches the power plant to meet the electricity demand for any given year up to 2030	National/state/regional	Electricity sector	Yearly	Bottom-up	Hourly	Yes

3.3.1 Overview of EnergyPLAN

EnergyPLAN is an energy system simulation tool that has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark [98]. The tool is programmed in Delphi Pascal and it has a user-friendly environment. Its main purpose is to assist in the design of national or local energy planning strategies by simulating the complete energy-system: this includes the heat, power, transport and industrial sectors. EnergyPLAN is able to model a variety of renewable, storage and transport technologies and their associated costs. It is a deterministic input/output tool and the required inputs include sectors' demands, renewable energy generation, power plant capacities, costs, and several regulation strategies for import/export and excess electricity production. The main model outputs include energy balances and annual productions, fuel consumption, imports/exports of electricity and total annual system costs [99].

Since its development, EnergyPLAN has been used in many different applications: analysing the large scale integration of wind [100], as well as combinations of renewable energy sources [101], distribution of surplus electricity [102], renewable energy strategies for sustainable development [103], the use of waste for energy purposes [104], and the effect of energy storage [98], [105], [106]. Furthermore, EnergyPLAN has been used to simulate a 100% renewable energy-system in Croatia [107], Ireland [44] and Denmark [41].

3.3.2 Overview of LEAP

LEAP (Long-range Energy Alternatives Planning) is an integrated modelling tool that can be used to analyse energy supply, demand and resource extraction in all the sectors of a system. This model was developed in 1980 in the US and is currently maintained by the Stockholm Environment Institute [90].

LEAP is normally used to investigate national energy systems. It operates using annual time-steps, and the time horizon can be extended for an unlimited number of years (typically between 20 and 50). The tool supports different modelling methodologies: on the demand side, these methods vary from bottom-up, end-use accounting techniques to top-down macroeconomic modelling. On the supply side, the tool offers different accounting and simulation methodologies for modelling electricity generation and capacity expansion planning. LEAP does not currently support optimisation modelling. The resulting scenarios are self-consistent storylines of how an energy system might evolve over time. The results include fuel demands, costs, unit productions, GHG emissions, air-pollutants, etc. Usually, these results are then used to compare an active policy scenario versus a policy neutral business-as-usual scenario [90].

This model has been used for an analysis of the potential reductions in energy demand and GHG emissions within road transport in China [108], identifying the feasible penetration of sustainable energy in Greece [109], and benefits of improved building energy efficiencies in China [110].

3.3.3 Overview of MARKAL/TIMES

TIMES (The integrated MARKAL-EFOM sytem) and MARKAL (MARKet ALlocation) are well recognised energy system optimisation models. They have been developed as part of the Energy Technology and Analysis Program (ETSAP), established by the IEA in 1976 [111]. MARKAL/TIMES are able to represent energy systems over periods of 20, 50 or 100 years based on the inputs, and their geographical coverage includes global, national or regional level. Several renewable, storage, thermal and transportation technologies can be simulated in MARKAL/TIMES. Further, the aim of the tools is to find the best reference energy system for each time period by minimising the total discounted system cost over the selected planning horizon. All this, considering the technical constraints and user-defined policies [111].

This model has been used in different applications [112]: investigating the future prospects of hydrogen and fuel cells [113], [114], assessing the future role of nuclear power [115] and nuclear fusion [116], and the impacts of wind power on the future use of fuels [117].

3.3.4 Overview of MESSAGE

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) has been developed by the International Institute for Applied Systems Analysis (IIASA) in Austria since the 1980s [118]. This model provides a system optimisation tool that can be applied for the planning of medium to long-term energy systems. Further, this tool can be used for analysing climate change policies, and to develop scenarios at national or global scale. MESSAGE uses a five or ten years time-steps in order to simulate a maximum of 120 years, and it can simulate thermal power plants, renewable technologies, storage/conversion systems, transport sector, carbon capture and storage (CCS) and costs (including SO_2 and NO_X costs) [118].

MESSAGE has been used to develop GHG emission scenarios for the Intergovernmental Panel on Climate Change (IPCC) [119]. Other studies include scenario assessment with a focus on climate stabilization [120], [121], national studies of innovation programs on the Iranian electricity sector [122], policy options for increasing the use of renewable energy [123] and designing a sustainable energy plan for Cuba [124].

3.3.5 Overview of ORCED

The ORCED (Oak Ridge Competitive Electricity Dispatch) is a modelling tool used for dispatching power plants aimed to match the electricity demand for any year up to 2030. The Oak Ridge National Laboratory (ORNL) in the US have developed three versions of the tool since the first release in 1996 [125]. This model uses public sources of data describing electric power units. The simulation balances supply and demand using hourly time steps, and it assumes no internal transmission constraints and limited cross-border interconnections. Most of the renewable and thermal generation power plants are included, but wave and tidal. Regarding electricity storage technologies, only pumped-hydroelectric energy storage is considered [125].

ORCED has been used for evaluating the effects of plug-in hybrid electric vehicles [126], to identify the benefits of hydropower in reducing CO_2 emissions, and to design policies for a transition to cleaner national energy systems [5].

3.4 Challenges for energy systems models

The integration of VRE generation and the requirement for decarbonisation creates new and complex challenges to the modelling tools. Pfenninger et al. [86] report four different modelling challenges for the twenty-first century: resolving the details in time and space, uncertainty, complexity and optimisation across the different scales, and capturing the human dimension.

3.4.1 Resolving details in time and space

The first important challenge is related to balancing the model resolution with the available data and computational tractability. A rough spatial and temporal resolution is needed to keep the simulations solvable within a reasonable time and to reduce calibration and other input data requirements. However, it is also a sensitive simplification when temporal variations are not important. This is the case of fossil fuels or nuclear plant systems, which are by default assumed as baseload or dispatchable at will, without considering external influences (such as the weather).

Nevertheless, most of the renewable energy sources are variable in time by nature, making energy demand more actively managed in future energy systems. Therefore, spatial detail is a critical issue for renewables due to their high dependence on location for its economic potential and generation costs [86].

3.4.2 Uncertainty

A great number of models have to deal with certain levels of uncertainty. In the case of energy systems, the demand forecast and electricity supply experience the highest levels of unpredictability. For instance, power plants can experience sudden shutdowns or unexpected slumps in electricity demand in short periods of time. Forecasts for supply and demand have been improved in recent years, but the level of uncertainty in power systems is still considerable.

As explained in the previous chapter, the increased integration of VRE generation concerns the energy modellers because the uncertainty in renewables poses challenges in both the short and long terms. In the short term this is due to the balancing effects, while in the longer term the utilisation is the most important issue [86].

3.4.3 Complexity and optimisation across scales

Energy systems are a good example of complex systems. The complexity usually increases when they grow more decentralized, being dependent on more diverse sources and expand their networks across the frontiers. These concerns, and the low capacity of current tools to deal with them, have led to the development of a new power grid science [127]. Another important aspect that is commonly linked with complexity is the issue of scale. The integration of information across different scales with the adequate resolution is still a challenge due to the computational limitations. This is a topic that requires further research to obtain the most convenient and cost-effective approach to its solution.

3.4.4 Capturing the human dimension

Many of the factors that affect the deployment of a technology are the political will, public acceptance, human behaviour and other non-financial barriers. Nevertheless, the main trend in modelling is to focus on technological and economic factors. For instance, Hughes et al. [128] found that in the UK there are few low-carbon scenarios that consider either the social or political aspects. The converse is also common, having scenarios with social aspects that contain little detail on economic and technological issues. This fact, where the social factors are not well understood in the models, contributes to high levels of uncertainty [86].

3.5 Energy models selection

Energy system developers have attempted to deal with some of the challenges described in the previous section. The selection of models that adequately represent the main characteristics of an energy system and its economy is a key issue for any renewable integration study. In the preceding sections, some general aspects of energy systems modelling tools and the main characteristics of some widely use models were discussed. This section addresses the most relevant criteria for selecting these models in specific applications.

Before examining the ability of modelling tools to deal with the specific research topics, several key general points must be considered (see Table 3.4): accessibility, appearance in the technical literature, training requirements, data requirements, and computational complexity.

Table 3.4. Key general points of the modelling tools.

Modelling tool accessibility	Considering the number of resources available, it is preferable to use an open-source model or a software that can be licensed at a reasonable cost. Cost is often a key issue when selecting the appropriate modelling tool [5]. Some models such as PRIMES or H_2RES, are not publicly available, whilst others require the purchase of commercial solvers (MARKAL and TIMES).
Appearance in technical literature	The application of modelling tools that have been used in similar works offers the opportunity to make additional contributions to a specific topic of interest [10]. In addition, this fact allows further validation for future studies.
Training requirements	Some modelling tools require a high level of knowledge that can take several months, or years, of advanced training to acquire proficiency. Energy systems models are often managed by large institutions, such as IIASA or ETSAP [5]. Developers and supporters of these tools consist of a number of high-qualified staff, involving PhD students, post-doctoral researchers, research associates and professors from different backgrounds (engineering, economics, computer science, mathematics and physics). Therefore, it is necessary to consider the organisation experience when selecting any modelling tool.
Data requirements	Some models are data intensive and require detailed information to generate its results [89]. Models such as EnergyPLAN simulate a single year in hourly time-steps, therefore it requires 8784 data points as input [129]. Additionally, several national economic data, such as GDP, equipment cost, etc. are needed. All this makes it necessary to know the availability and importance of each group of data before selecting the model.
Computational complexity	The computational resource required depends on the modelling tool and the application. For instance, running a model with a large number of technical constraints at sub-hourly time resolution (five minutes interval) will demand mixed integer programming, thus making this model very complex to solve. Whereas, running a one year model in EnergyPLAN with a few constraints will not be computationally intensive.

In addition to the key general points explained in Table 3.4, some key technical factors must be considered to ensure that the modelling tool is appropriate to the research objectives. These include spatial and temporal resolution, purpose of the model, geographical and sectoral coverage, planning horizon and the applicability in developing countries (see Table 3.5).

Table 3.5 Key technical points of the modelling tools

Spatial and temporal resolution	The model must run at a spatial and temporal resolution that considers the variability of renewable generation [86].
Purpose of the model	Forecasting models are commonly applied for analysing relatively short-term impacts. For generation expansion planning, scenario analysis models are more appropriate for exploring the future [89].
Geographical and sectoral coverage	A key factor in establishing the structure of the model is the characterisation of the geographical and sectoral coverage. The former reflects the level on which the model will focus, such as global, national, regional, local or individual project. The latter indicates the sectors included in the study (energy, transport, residential) [89].
Planning time horizon	The planning time horizon usually determines the structure and objectives of the modelling tool. The different socio-economic and environmental process evidence changes at different time scales [89]. Plans that represent a wide political commitment to integrate renewable energy are often linked with medium to long-term targets [4].
Applicability in developing countries	Energy systems in developing countries must be modelled differently, including the distinctive features of these regions. Bottom-up or hybrid models appears to be the best approaches for these cases [15].

This section has summarised some of the most important general and technical aspects that must be considered when selecting energy modelling tools that are capable of addressing the research objectives of this study. The next chapter will present an overview of the Colombian energy system, including a description of the current system, its potential in terms of renewable energy sources and the GHG emissions of the country.

Chapter 4 Energy landscape in Colombia

4.1 Introduction

The previous chapters provided a description of the relevant literature examined for this work. The main attributes and challenges of variable renewable generation and energy system models were discussed.

This chapter introduces the main characteristics of the Colombian energy system, its renewable energy potential and a breakdown of GHG emissions by sector. Further, a summary of the national policies oriented to support a sustainable development in the country is presented.

4.2 Background

The Republic of Colombia is located in the northwest of South America with a coastline on both the Pacific and the Atlantic oceans. It has an extension of approximately 1.142 million km^2, which is about five times the size of the UK. The country is bordered by Venezuela, Brazil, Panama, Ecuador and Peru (Figure 4.1). Because of its topography, characterised by high differences in elevation, Colombia has an extensive temperature range (7 °C - 35 °C on average) with little seasonal variation. Precipitation is moderate to heavy with considerable yearly and regional variations [130]. Colombia is considered the second most biodiverse country in the world and it is characterised by abundant water resources and vast extents of arable land [131]. The country has a population of almost 48.3 million, mostly concentrated in urban regions (77.8%), and the rest (22.2%) in rural regions [132].

During the last three decades, Colombia has shifted from an agriculture-based economy to an extractive-based economy (minerals and multiple energy resources). This change allowed the country to have an average GDP growth of about 3.8% during the last decade [132]. Nevertheless, widespread corruption, lack of effective policies and weak institutions have obstructed a better wealth distribution. Further, after 50 years of internal conflict with several armed groups, in 2017 the country signed a peace agreement with the largest guerrilla group FARC (Revolutionary Armed Forces of Colombia). Even though this agreement is still in the implementation phase, it is expected to have a positive effect on the development of the country [131].

Figure 4.1. Geographic location of Colombia.

Colombia is considered to have the fourth-largest economy in Latin America, only behind Brazil, Mexico and Argentina. According to the OEDC, in 2018 the GDP was approximately USD 331.5 billion. Despite this, Colombia remains as one of the most unequal countries worldwide because of its large informal employment, low levels of education and share of the population living under the poverty line (19.3%) [132].

4.3 Characteristics of the Colombian energy system

This section presents an overview of the Colombian energy system. It includes a description of the current system, and more details of the power and transport sector are also discussed.

Multiple political and socioeconomic transformations have caused rapid changes in the energy sector in Colombia during the last decades [131]. 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% [133], [134]. 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 [135]. Fossil fuels dominate the total primary energy mix (see Figure 4.2), with coal, oil and natural gas collectively representing about 93% of the primary demand in 2014 [135]. 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 [136].

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 [137].

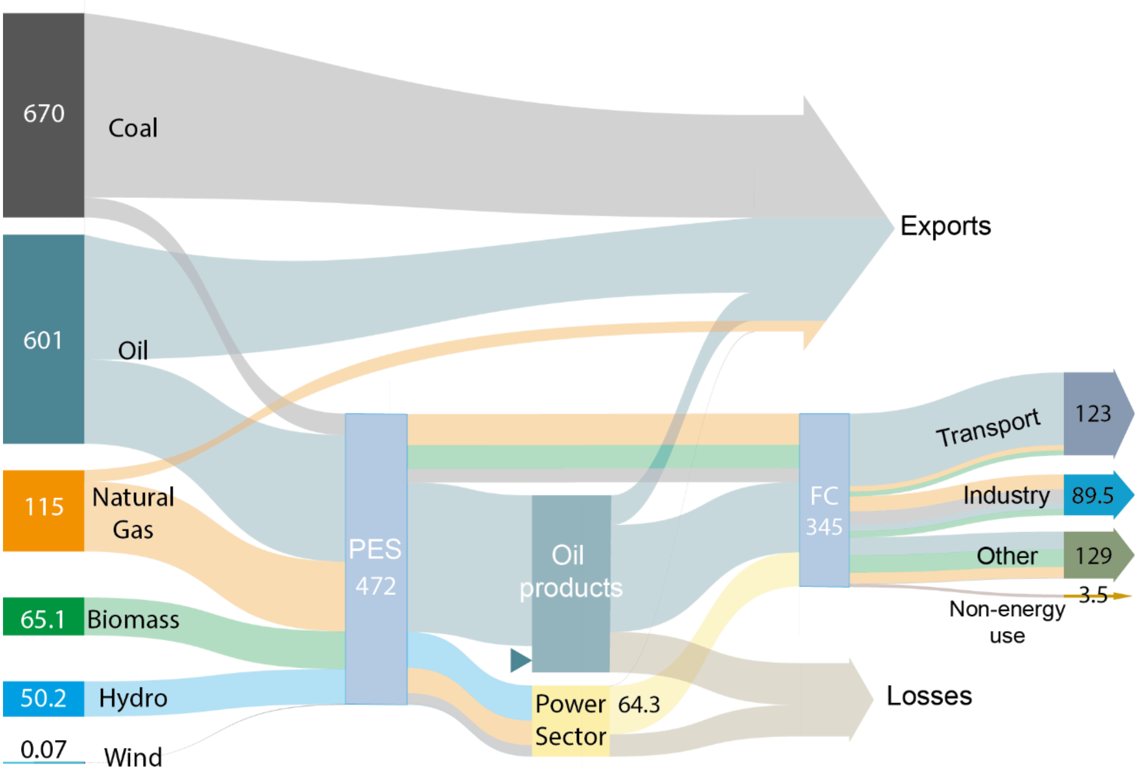

Figure 4.2. Colombian energy balance in 2014. All units in TWh. Adapted from [138]**.**

4.3.1 Power sector

The electricity sector in Colombia accounts for 17% of the total energy consumption of the country [21]. 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 [95], [139].

Historically, hydro and thermal generation have dominated the sector with average contributions of 71% and 28%, respectively during the last 20 years [21] 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 [16]. 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 [16]. Figure 4.3 shows the installed capacity by fuel type from 2006 to 2016.

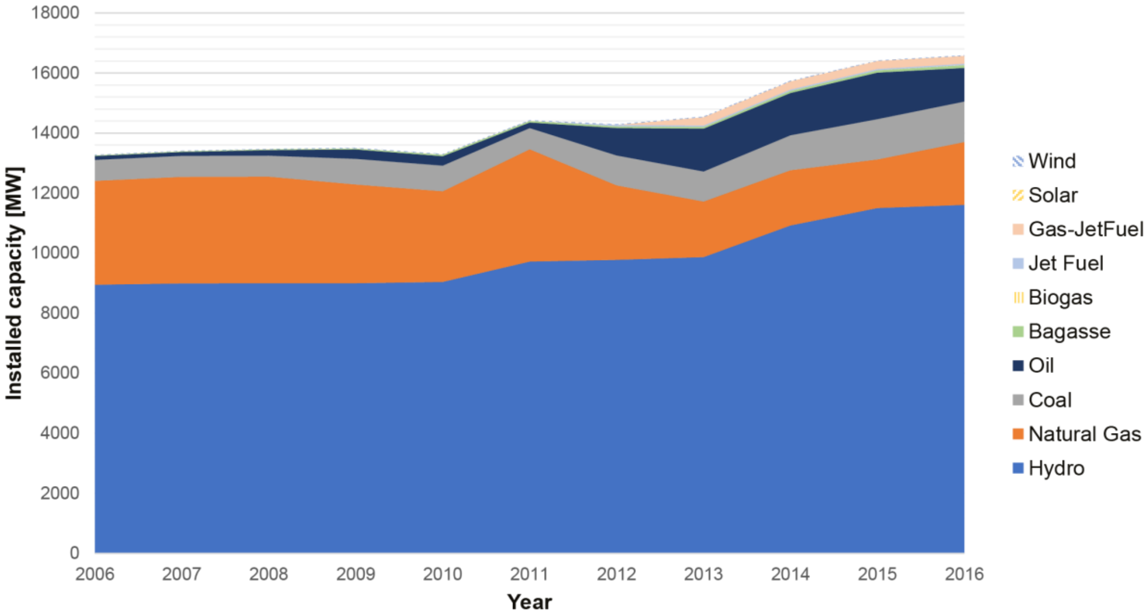

Figure 4.3. Historical installed capacity by fuel type [140]**.**

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 [141]. Figure 4.4 illustrates the location of conventional and renewable power plants with an installed capacity greater than 19.5 MW in 2014. In addition, the rural regions without access to electricity or Not-Interconnected Zones (ZNI) and regions in the National Interconnected System (SIN) are also shown in Figure 4.4.

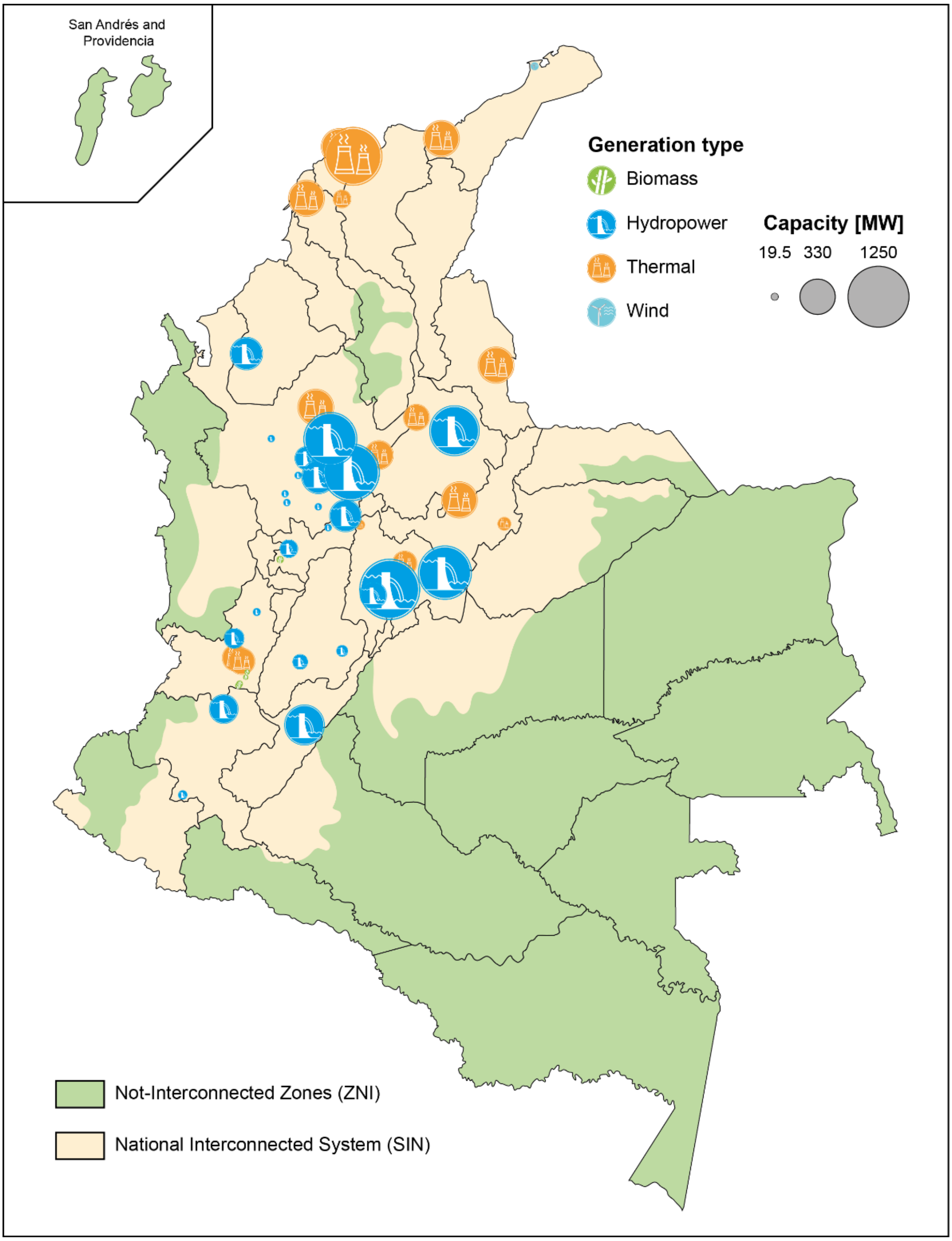

Figure 4.4. Grid-connected (SIN) areas and power plant locations in 2014. Author's figure based on [142], [143]**.**

4.3.2 Transport sector

The transport sector accounts for 4% of the national GDP and it is the largest energy consumer in the country with 39% of the total consumption, followed by industry and the residential sectors [144]. Transportation is particularly complex due to the topography of the country, with three cordilleras of the Andes that run from south to north and vast extensions of jungle in the Darien and Amazon regions. These characteristics represent a major impediment to the development of domestic road networks and international connections, and this is evidenced by the poor transportation infrastructure of the country [130].

The sector is divided into four categories (road, aviation, waterborne and rail) for freight and passengers transportation. In terms of energy demand, the road segment consumes the most energy (approximately 88% of the total in 2018), followed by aviation, waterborne and rail as shown in Figure 4.5.

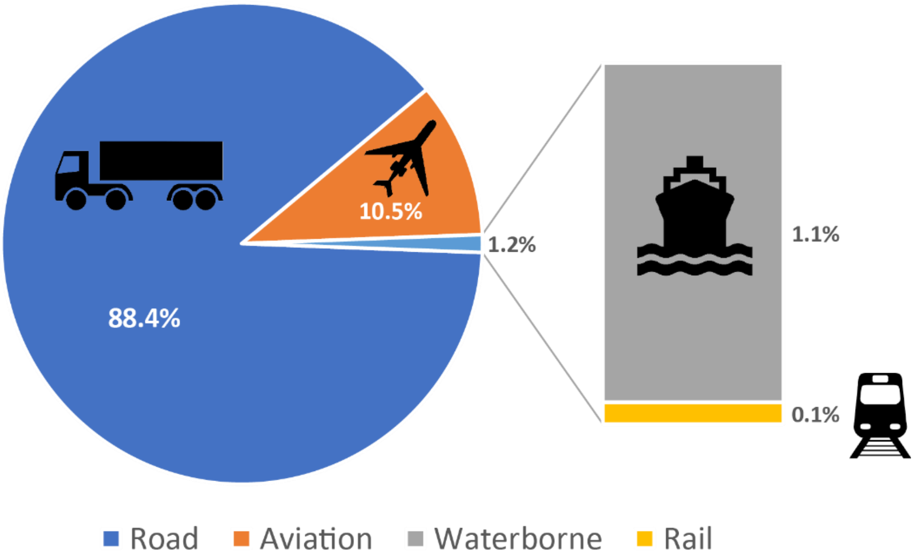

Figure 4.5. Energy consumption in the transport sector by category in 2018 [145]**.**

Road transport has historically had the largest growth between the different transport categories, while river and rail transportation lag far behind. This is mainly caused by the topography of the country, its internal market size and lack of interest by transport-related policymakers. Currently, 73% of the existing rail network is inactive and the remaining 27% is used for freight transport only [130]. In Chapter 8, more details of the energy consumption and supply in this sector are further discussed.

4.4 GHG emissions

The electricity generation matrix in Colombia is considered to be very clean because of the high share of hydro generation and low energy consumption levels, which are below the international averages [144]. Power generation accounts for only 8.5% of the total emissions, compared to the global average of 42% in the same sector [146]. Historically, the AFOLU (Agriculture, Forestry and Other Land Use) and Energy sectors have presented the highest contribution to the national emissions (see Figure 4.6). Deforestation appears to be the principal driver in the AFOLU sector, while in the energy sector, transport and energy industries are the main drivers [144], [147]. 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 [148], [149]. 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 [137], [148].

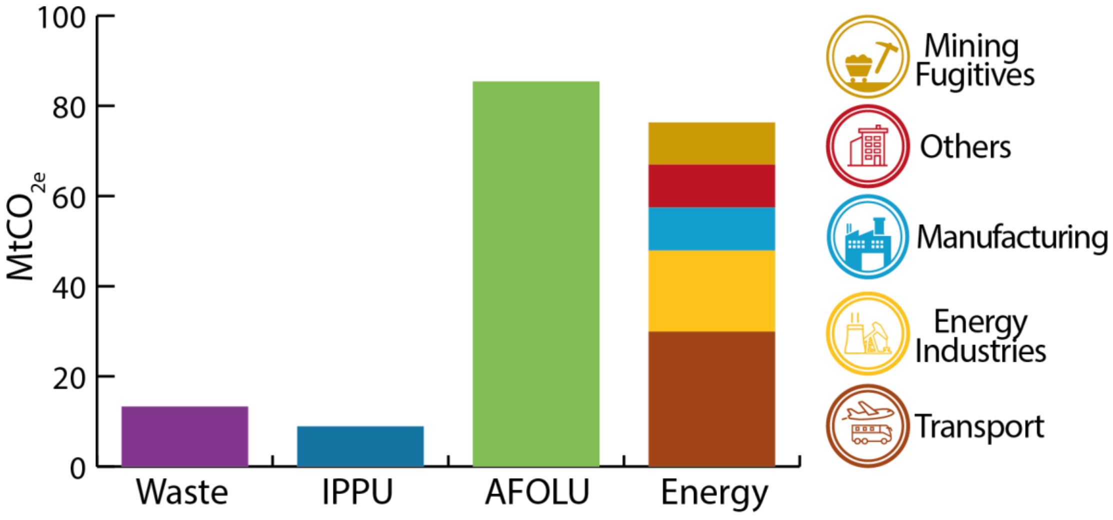

Figure 4.6. Colombian GHG inventory in 2012. Adapted from [147], [150]**.**

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 [144] (see Figure 4.7). If mitigation measures are not implemented, the government estimates the total GHG emissions to reach 335 MtCO2e in 2030 (BaU scenario), from which 110 MtCO2e are expected to be produced in the energy sector only [144].

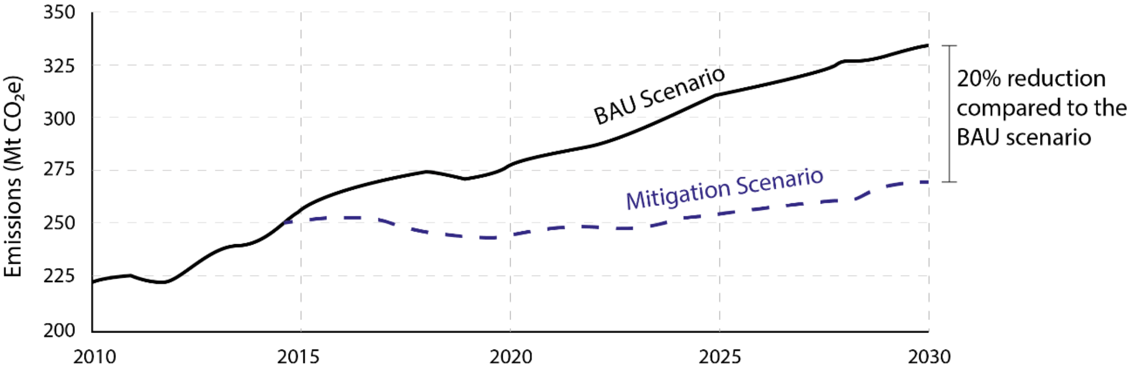

Figure 4.7. Mitigation target for Colombia [144]**.**

4.5 Renewable energy

As described in the previous section, Colombia has an electrical system with low carbon emissions compared to many other countries (less than 0.1% of the total world emissions) [150]. However, there are some clear reasons to consider the implementation of renewables:

COP21 Commitments: Colombia adopted a legally binding agreement in Paris where it committed to a 20% reduction on its GHG emissions by 2030, with reference to the projected Business as Usual scenario. The country is strongly sensitive to climate change impacts due to its diverse geography. Furthermore, this risk makes its economy extremely vulnerable because of its high dependence on natural resources [151].

Hydropower risk: The high dependence on hydroelectric resources of the country is an important factor to consider, representing a systematic risk of shortage and elevated energy prices. This is the case in the energy crisis that occurred during the years 1992, 1993 and 2015 due to the El Nino-southern oscillation (ENSO), and the recent surge in the energy cost in the last few years. Furthermore, according to a forecast revealed by the Colombian Hydrology, Meteorology and Environmental Studies Institute (IDEAM), the sensitivity to droughts will grow significantly in the country because of climate change [152].

Electricity and natural gas price growth: During the last few years, there has been a steady increase in the price of electrical energy. One reason for this trend is the decline in the hydroelectric generation and the growth in the natural gas price. By 2030, it is expected that a 40% increase in the cost of this commodity, and this is due to the need to import this resource in the short term [21].

Economic development opportunities: The use of renewable energy can also be used as a strategy for economic development. For instance, the deployment of technologies such as solar PV creates more jobs than investments in fossil fuel generation projects. Furthermore, distributed generation projects provide a significant opportunity to save energy for business and industries, avoid overcharging due to fuel price volatility and compete more effectively internationally [153]. In addition, some fiscal policies have been implemented since 2014 to incentivise investment in renewable energy [21].

Energy generation potential: Colombia has some of the highest energy potential in Latin America due to its climate and geography [151], [154], which are well suited for investment in renewable energy generation (see Section 4.5.1).

Renewables cost trend: In recent years, the development of VRE technologies have contributed to the reduction of its cost, especially in the case of solar PV. According to the IEA [2], the PV cost in the power sector is expected to decline continuously over the next 25 years, thus representing a real opportunity for developing countries.

4.5.1 Renewable energy potential

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 [21], [137], [155]. 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. Tidal and wave power are not included despite their potential due to the lack of interest of investors in these technologies [156].

Hydropower

Hydropower is the main renewable energy source for electricity generation in the world [157]. 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 [139]. 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 [16]. According to the grid interconnection company (ISA) [158], 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 [139].

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 [159].

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 [156], [158]. Most of the resource is located in the northern part of the country, especially in La Guajira region [73], [160]. Here, the average wind speed at 80 meters above sea level is about 9 m/s [161].

Previous studies [21], [73], [160] 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 [73].

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 [162]. 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 [16]. 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) [162].

The solar atlas of Colombia [163] 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 [164].

Bioenergy

After hydro generation, bioenergy is the second largest renewable resource for energy production in Colombia [131]. In 2017, electricity generation using biomass accounted for 804 GWh, representing 1.3% of the total produced [16]. 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 [131]. There are currently two blending regulations designed to reduce GHG emissions in the sector: a 8-10% bioethanol blending by volume for transport gasoline fuel, and 8-10% biodiesel blending for road transport diesel [134], [165].

Also there is a vast biomass energy potential untapped in Colombia [21]. Gonzalez-Salazar et al. [131] 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.

Geothermal

Multiple studies [166]–[168] have been reported on geothermal resources for energy production in Colombia. However, there is no current power plant installed in the country yet. According to Battocletti [169], the geothermal potential is estimated to be 2.2 GW and this may be used for electricity generation only. A project in the planning stage and led by ISAGEN is expected to be built in the department of Caldas and its installed capacity will be 50 MW [168].

4.6 Policies for supporting a sustainable development

During the past decade, the Colombian government has defined a set of new regulations in order to support the integration of sustainable alternatives into the energy system. These policies are part of the Colombian Low-Carbon Development Strategy (ECDBC), which seeks to formulate and implement low-carbon development plans for the energy, mining, agriculture, waste and construction sectors [170]. The ECDBC is the result of the commitments made during the COP21 and presented as the National Determined Contributions (NDC). Table 4.1 summarises the main laws developed during the last few years which are oriented to mitigate the negative effects of climate change and favour the integration of renewable energy into the Colombian energy system.

Table 4.1. Colombian Low-Carbon Development Strategy policies [170], [171]**.**

Policy	Overview and context
Law 1715 - 2014 to promote the integration of clean energy projects and energy efficiency	The law initiated the legal framework and mechanisms to stimulate the use of variable RES and encourage the investment, research and development of clean energy technologies and energy efficiency. Its main features include: - Fiscal incentives to projects that involve clean energy technologies (Special income tax deductions, VAT exemption and accelerated depreciation). - Replacement of fossil-fuelled electricity generation in ZNI. - Sale of energy surplus into the grid by small-scale generators. - Substitution of low efficiency electric motors and heat recovery projects. - Incentives for clean transportation projects.
Law 1819 - 2016, decrees 1625/2016 and 926/2017 on carbon tax	The National Tax Authority (DIAN) established the general rules applicable to the carbon tax created by the Law 1819 of 2016: - A national carbon tax on liquid fuels for combustion processes was created. - The initial tariff was set to approximately 5 USD/tCO_2 and considers individual emission factors. - The fund collected from the tax will be used for climate change adaptation purposes.
Law 1931 of 2018 on the guidelines for climate change management	This law defines specific guidelines for both mitigation and adaptation to climate change in all the administrative regions of the country. A new Emissions Trading Scheme (ETS) was created in order to collect funds for financing the adaptation and mitigation plans in line with the Colombian Low-Carbon Development Strategy.

This chapter has summarised the characteristics of the Colombian energy system and highlighted the relevance and potential of RES in the country. The following chapter describes the methodology applied in this study for selecting the modelling tool and building the reference energy system model.

Chapter 5 Modelling the Colombian energy system

5.1 Introduction

Chapter 3 highlighted how the modelling of possible future scenarios has become an essential planning tool, especially in the energy sector [4]. In Chapter 4, the energy landscape of Colombia was introduced, and the main features that make the Colombian energy mix different from the great majority of countries around the globe were discussed. Some models for countries with a similar electricity mix to Colombia have been developed for Brazil [17], [18], Norway [19], and New Zealand [20]. The need for research oriented towards the development of a diversified energy matrix has been raised by the Mining and Energy Planning Unit (UPME) [21]. 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 had estimated the RES penetration limit into the Colombian electric power system. Vergara et al. [73] investigated the correlation between wind and hydro resources for future energy generation in the country. Gonzalez-Salazar et al. [131] used LEAP (Long-range Energy Alternatives Planning) to evaluate the impact of bioenergy in future scenarios. Paez et al. [172] developed an economic model in LEAP to assess future energy demand scenarios for Colombia. Chavez et al. [173] 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. [174] 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 [5], [44], [175] 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 elevated intermittency. This part of the research aims to describe the process for building the Colombian energy system model. The analysis of the impacts of integrated renewable sources in future scenarios is presented in Chapter 6. The research presented in both chapters is based on two published works by the author available in [176], [177].

This chapter is organised into five sections. Section 5.2 provides a description of the modelling tool selection process. The EnergyPLAN modelling tool was used to develop the model and build the scenarios. Technical details about this tool are explained in section 5.3. The methodology used in order to build the model for the Colombian energy system, including the data sources and assumptions are outlined in Section 5.4. Finally, the last section summarises the validation process of the model in EnergyPLAN.

5.2 Modelling tool selection

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 policymaker. This study adopted a bottom-up approach, integrating detailed engineering interactions between technology activities and energy use [9]. The use of an energy modelling tool to explore alternative solutions to each objective is needed. This approach has been proposed in similar works [46], [178]–[180]. The main reason for this is the complexity of the analysis, which considers a significant range of data and technologies. A great number of models for analysing energy systems are available nowadays [5], [10], and this makes the identification of a modelling tool a complex process for any renewable integration research. Therefore, the first stage of the research focused its attention on selecting the most appropriate modelling tool for representing the Colombian energy system based on the review of the tools presented in Chapter 3. A complete description of the defined assessment criteria for selecting the modelling tool is detailed in the following section.

5.2.1 Assessment criteria

All the aspects mentioned previously in Section 3.4 must be considered when selecting a modelling tool for any particular study. Therefore, a clear understanding of both the capabilities and restrictions of the models are necessary. As Deane et al. [181] indicate, no individual modelling tool is capable of addressing the totality of the energy system challenges. However, energy modellers can take advantage of the strengths of multiple models for developing deeper insights.

In order to identify the full landscape of the existing energy modelling tools, an extensive literature search was performed. As a result, 52 present-day energy models were identified in [5], [10], [15], [101], which are all either well-known or medium-well-known models currently used worldwide. Then, eleven criteria for comparability were established (see Table 5.1). The list of models was classified based on an adapted version of the Van Beeck categorisation typology [89], [182] and the special characteristics needed in developing countries [15]. The Appendix B includes the complete list of models and some of the evaluation criteria.

Table 5.1. Modelling tools assessment criteria

(i)	Exploring models are ideal to analyse different scenarios than can be compared with business-as-usual reference scenario.
(ii)	The model uses energy supply and demand as specific purpose.
(iii)	The model is applied at a national scale.
(iv)	The model includes the main categories in the energy sector (electricity, heat and transportation).
(v)	The model is focused on the medium, long term.
(vi)	The model is characterised as bottom-up or hybrid (analytical approach).
(vii)	The model is used to simulate and optimise energy systems.
(viii)	The model takes into account developing countries.
(ix)	The model is cited in relevant scientific literature.
(x)	The model includes renewable and storage technologies.
(xi)	The model is open-source or can be licensed to researchers at a reasonable cost.

The model had to fulfil all the eleven criteria to be selected. After the screening of the 52 models according to the selection criteria, five models were chosen: EnergyPLAN, LEAP, MARKAL, MESSAGE and ORCED. The selection was constrained to the energy and electricity models only and dismissed models entirely focused on climate change, carbon management, energy markets, investment and regulations.

From the five models chosen, EnergyPLAN was selected as the modelling tool for the study because of three key reasons: Firstly, the modelling tool considers the three primary sectors of any regular energy system, namely power, heat and transport [31]. In

Colombia, these sectors are completely segregated. In the future, these three sectors must synergise in order to achieve an efficient penetration of RES [175]. 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 [175], [183], and in some cases where the electricity mix is hydro dominated [19], [184]. Finally, the tool has been widely used in the relevant literature considering large-scale integration of RES [45], 100% renewable energy systems [41], [44], and in specific studies assessing the effects of different elements of the energy system such as energy storage [46], transport integration [47], [48] and demand response technologies [49].

5.3 EnergyPLAN modelling tool

The main purpose of EnergyPLAN is to assist in the design of national, regional or local long-term energy planning strategies by simulating the complete energy system [44]. This open source tool was developed at Alborg University in Denmark [183]. The tool 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 simulated system 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 5.1. Data is provided as annual aggregates combined with its distribution profiles and these profiles include hourly data for a complete year.

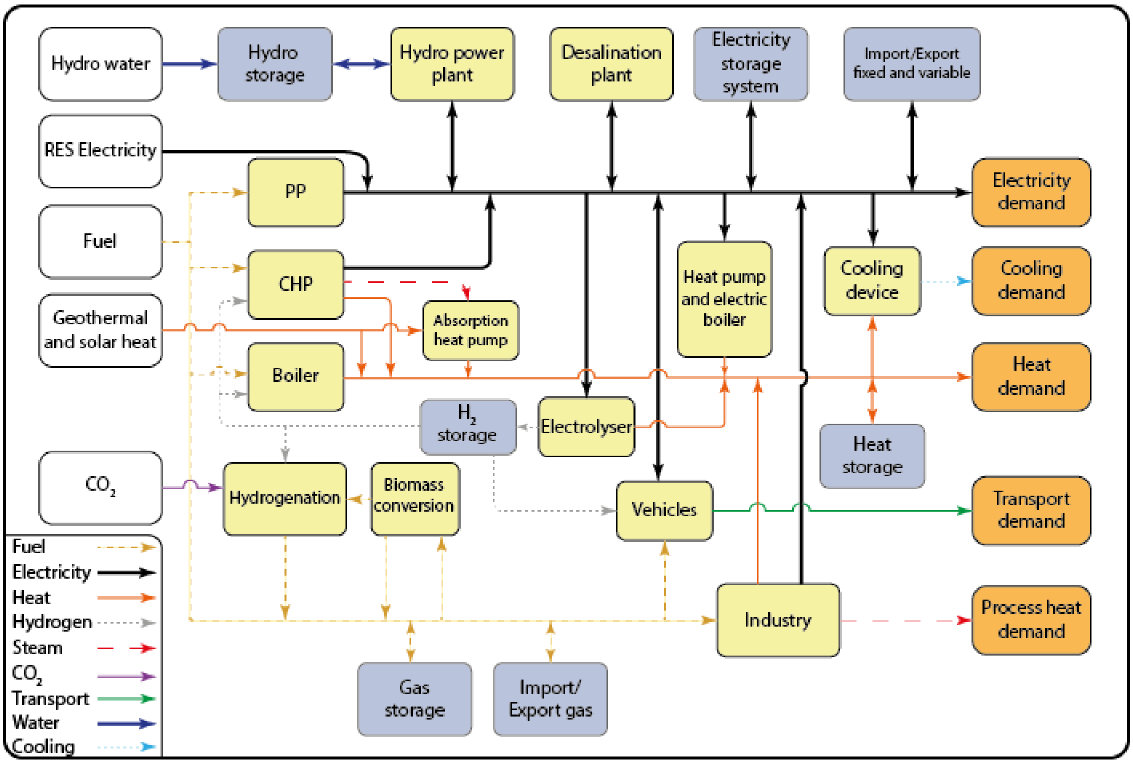

Figure 5.1. Schematic diagram of the EnergyPLAN tool [183]**.**

The tool calculates the results based on two operation strategies: technical or market-economic regulation strategies. The objective of the technical strategy is to identify 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. 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.

5.4 Methodology

This section presents a description of the methodology applied in order to build the model for the Colombian energy system, including a detailed description of the main assumptions and data used. The next sections are organised following the same order as the data is supplied into EnergyPLAN in order to facilitate its understanding and reproducibility.

The EnergyPLAN tool requires many inputs and assumptions, and therefore it is important to validate the model against actual data [31]. Connolly [129] provides a complete description of the validation process, and this is described for the Colombian model in Section 5.5. 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.

5.4.1 Energy demand

The energy demand data presented in this section includes electricity, cooling, transportation, industry, residential and commercial.

Electricity hourly demand historical data were obtained from XM (Market experts company) through its PORTAL BI [185]. 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, and its behaviour during a typical week in 2014 can be seen in Figure 5.2. The data represents the total load from Sunday to Saturday and the peak and minimum power requirements are evidenced.

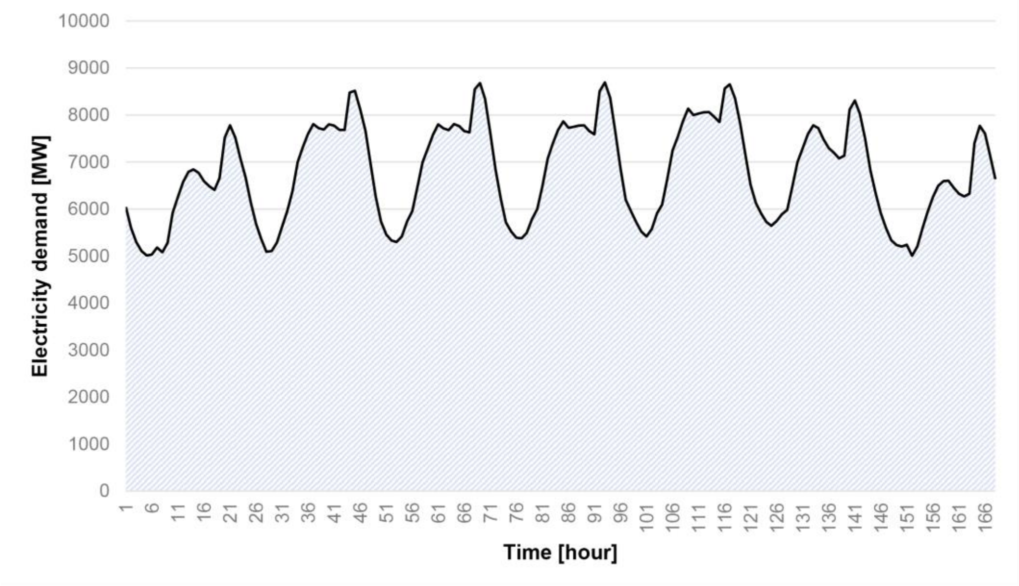

Figure 5.2. Electricity load in a typical week (Sunday to Saturday) in 2014 [177]**.**

To the best knowledge of the author, there is no existing distribution for electricity *heating and cooling demand* in the country. However, according to UPME [134] the share of electricity used for heating and cooling is approximately 1.6% and 8.5% of the total generated, respectively. Therefore, these values are assumed to be constant throughout the year (see Table 5.2).

Table 5.2. Electricity load by sector in 2014.

Load	**Consumption [TWh]**
Electric cooling	5.50
Electric heating (Individual)	1.05
Net export	0.84
Total Demand	64.37

The energy consumption from the *industry*, *transport*, *residential and commercial* sectors was acquired from the Colombian energy balance in 2014 (see Tables 5.3 and 5.4). This document is completed every year by UPME and available in [133].

Table 5.3. Industry and other sectors fuel demand.

Fuel	**Industry [TWh]**	**Various [TWh]**
Coal	18.71	0.85
Oil products	9.62	24.76
Natural gas	21.18	14.11
Biomass and waste	8.64	24.90

Table 5.4. Transport sector fuel demand.

Fuel	**Demand [TWh]**
JP (Jet Fuel)	11.77
Diesel	43.53
of which Biodiesel	4.71
Petrol	47.65
of which bioethanol	2.35
Natural gas	7.65
Electricity	0.08

5.4.2 Energy supply

In this section, the inputs related to the power generation are described. These include both conventional and renewable energy generators and their corresponding distributions and fuels.

The capacity and efficiency of each power plant are available in the Colombian Electrical Information System (SIEL) [16]. Table 5.5 summarises the installed capacity in 2014. As described previously in Section 4.3, 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 the electricity demand patterns. Therefore, modelling the Colombian hydropower system requires the use of natural inflow time series, which are available in the PORTAL BI [185].

Table 5.5. Power plants production installed capacity in 2014.

Type	Capacity [MW]
Thermal power plants	4735
Hydropower	10920
Onshore wind	19.5
Solar PV	0

Wind power was the only variable RES used to generate electricity to the national grid in 2014. According to SIEL [16], the Jepirachi project with an installed capacity of 19.5 MW generated 70.23 GWh that year, and its hourly distribution was obtained in [185]. The total installed capacity of solar photovoltaic (PV) in 2019 was estimated to be 17.96 MW with two projects connected to the national grid (Celsia solar Yumbo and Celsia solar Bolivar) [143]. EnergyPLAN requires the installed capacity and hourly power production for each source. This later was built using a combination of actual generation and estimated with weather data, and the methodology applied is described in the following section.

Variable renewable energy generation dataset

The RES datasets for wind and solar energy were built using meteorological data by considering major current and future renewable energy generation sites. As described in

Section 2.5, increasing the spatial diversity can reduce the variability significantly. 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). Figure 5.3 shows the locations considered in [176] in order to build the hourly distributions. Future generation sites and capacities were taken from the list of projects registered in SIEL [16]. The following sections describe the methodology applied in order to estimate the wind and solar PV energy outputs.

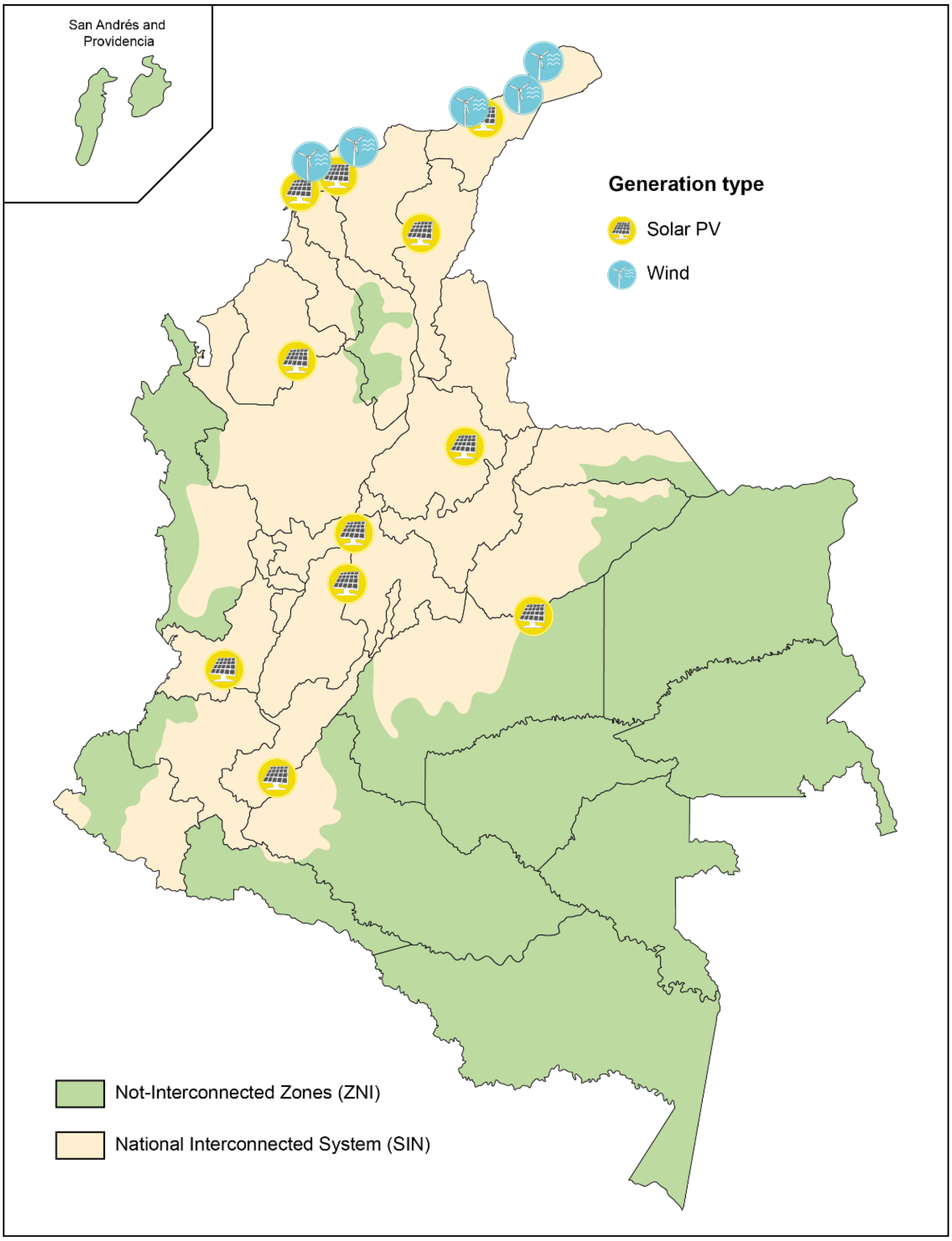

Figure 5.3. RES generation sites registered in SIEL [16]**.**

Wind power

The wind power output was estimated following the procedure shown in Figure 5.4. Initially, average hourly wind speed data (over 5 years dataset) at each of the locations shown in Figure 5.3 were computed and extrapolated to the turbine hub height using the Power Law (equation 5.1):

$$v_H = \left(\frac{z_H}{z_r}\right)^{\alpha} v_r \qquad (5.1)$$

where v_H and v_r are wind velocities at the hub height z_H and reference height z_r, respectively. The power law index (α) is assumed constant and its value for open land with only softly rounded hills is used (α=0.143) [68]. The reference height is usually 10 meters above sea level and meteorological data at this height was supplied by IDEAM and the National Renewable Energy Laboratory (NREL) database [186].

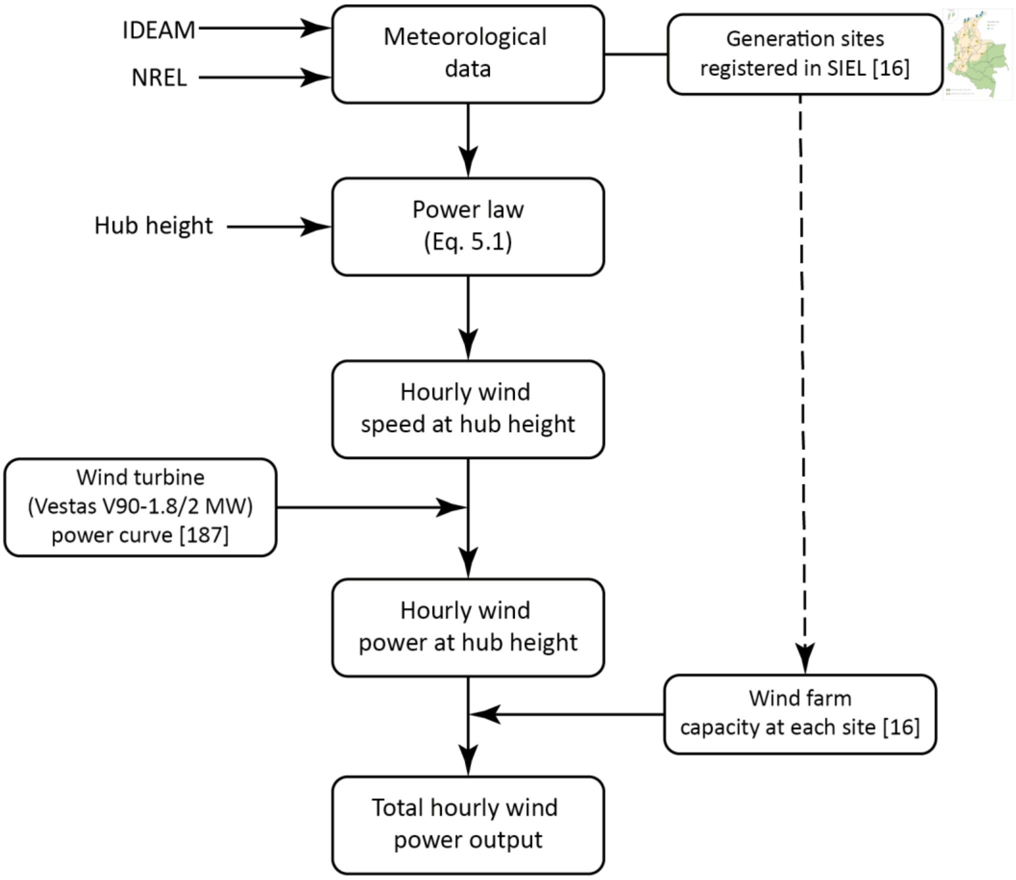

Figure 5.4. Wind power calculation procedure.

After obtaining the hourly wind speed at the hub height, the characteristics of a standard and commercially available wind turbine (Vestas V90-1.8/2 MW and hub height 95 m [187]) were used to estimate the hourly wind power output at each location. Then, a weighted addition of these results, based on the installed capacity reported by SIEL [16] at each site, was performed in order to obtain the total hourly wind power output [177].

Solar PV power

The solar PV power output requires hourly incident irradiance and module temperature data. The major sites considered for these calculations are shown in Figure 5.3. In order to obtain the hourly power generation at each location, the authors have used the model described by Hund et al. in [188]. The crystalline silicon cells (c-Si) modules are assumed as the technology used and the model is given by the following equation:

$$P(G^*, T^*) = G^*\left(P_{STC,m} + k_1 \ln(G^*) + k_2 \ln(G^*)^2 + k_3 T^* + k_4 T^* \ln(G^*) + k_5 T^* \ln(G^*)^2 + k_6 {T^*}^2\right) \tag{5.2}$$

where the normalised in-plane irradiance G^* and module temperature T^* are given by equations 5.3 and 5.4, respectively.

$$G^* = \frac{G}{1000\ Wm^{-2}} \tag{5.3}$$

$$T^* = T_{mod} - 25°\mathrm{C} \tag{5.4}$$

where G is the in-plane irradiance and T_{mod} is the temperature of the module. This latter is calculated using the approach suggested by Faiman [189]. Irradiance and ambient temperature values for each site were supplied by IDEAM and the National Solar Radiation Database (NSRDB) [186] through PVGIS [190]. The values for the coefficients k_1 to k_6 used in equation (5.2) for c-Si modules are taken from [188].

Finally, hourly solar outputs at each location were aggregated based on their installed capacities in order to obtain the solar PV distribution [177].

5.4.3 CO_2 emissions

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 [129], [191]. Therefore, the GHG emission factors for Colombia (Table 5.6) reported in [192] were incorporated into the EnergyPLAN model. Following the IPCC guidelines for national GHG inventories in the energy sector [191], only the emissions associated with the direct combustion of fuel nationwide were considered.

Table 5.6. CO_{2e} emission factors by fuel.

Fuel	**Emission factor [kg/GJ]**
Coal	88.0
Oil products	76.7
Natural Gas	56.7
Liquified Petroleum Gas (LPG)	59.6

5.5 Model validation

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 validation process has been described in detail by Connolly [193]. This procedure involves a comparison between the reference model outputs and the actual figures reported by different international and domestic agencies [16], [194]. Table 5.7 shows a comparison between the calculated monthly electricity demand on EnergyPLAN and the actual demand reported by SIEL in 2014 [16]. In this case, the difference is less than 0.5% for all months.

Table 5.7. Monthly electricity demand validation.

Month	Modelled in EnergyPLAN [MW]	Actual [16] [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 5.8. The actual total energy-related emissions for Colombia in 2014 were reported to be 65.96 $MtCO_{2e}$ by the International Energy Agency (IEA) [194]. EnergyPLAN calculated the emissions for the same period as 65.06 $MtCO_{2e}$.

Table 5.8. Fuel consumption and annual electricity production validation.

	Modelled in EnergyPLAN	Actual data [195]	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 lead to the conclusion that the reference model accurately simulates the Colombian energy system and can be used with confidence to build future energy scenarios for the country.

In this chapter, a new model with a high temporal resolution for the Colombian energy system was developed using the EnergyPLAN tool. The accuracy of the model was verified considering actual data and used as the reference for building future scenarios. In the next chapter, these alternative future scenarios towards 2030 are analysed and compared. In Chapter 7, the focus is on the power system only, and the effects of large-scale energy storage and cross-border interconnections are analysed. Finally, Chapter 8 explores longer-term alternatives (towards 2040) for an energy system in which the electrification of the transport sector plays an important role as a mitigation strategy.

Chapter 6 Alternative future scenarios for the Colombian energy system

6.1 Introduction

The previous chapter described the methodology for building the reference model for the Colombian energy system and its validation process. This chapter explores different alternatives future scenarios for a Colombian system with increasing shares of variable renewable energy options into its energy mix.

The chapter is divided in four sections. Section 6.2 describes the baseline and alternative scenarios used in this chapter. In Section 6.3, 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. The research presented in this chapter is based on the published work by the author and this is available in [176].

6.2 Methodology

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 6.1) based on the characteristics of the Colombian system, previous works [131], [174] and the inputs from different specialised agencies [134], [136], [144].

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 are 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 [144]. 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.

Table 6.1. 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)	5.50	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)	72	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

2. *UPME 2030:* This scenario is built from the generation and transmission expansion plan (high progression scenario) developed by UPME towards 2030 [136]. 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 author (see Section 6.3.1 for more details).
4. *High solar:* Built from the BaU 2030, this scenario includes the maximum technically feasible solar photovoltaics capacity estimated by the author (see Section 6.3.2 for more details).
5. *RES combination:* this scenario includes inputs developed by Gonzalez-Salazar et al. [131] 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 author was included in the electricity mix. The list of actions set for this scenario is presented in detail in Table 6.2.

Table 6.2. 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.

The overall structure of the model for the Colombian system used in this analysis is illustrated in Figure 6.1.

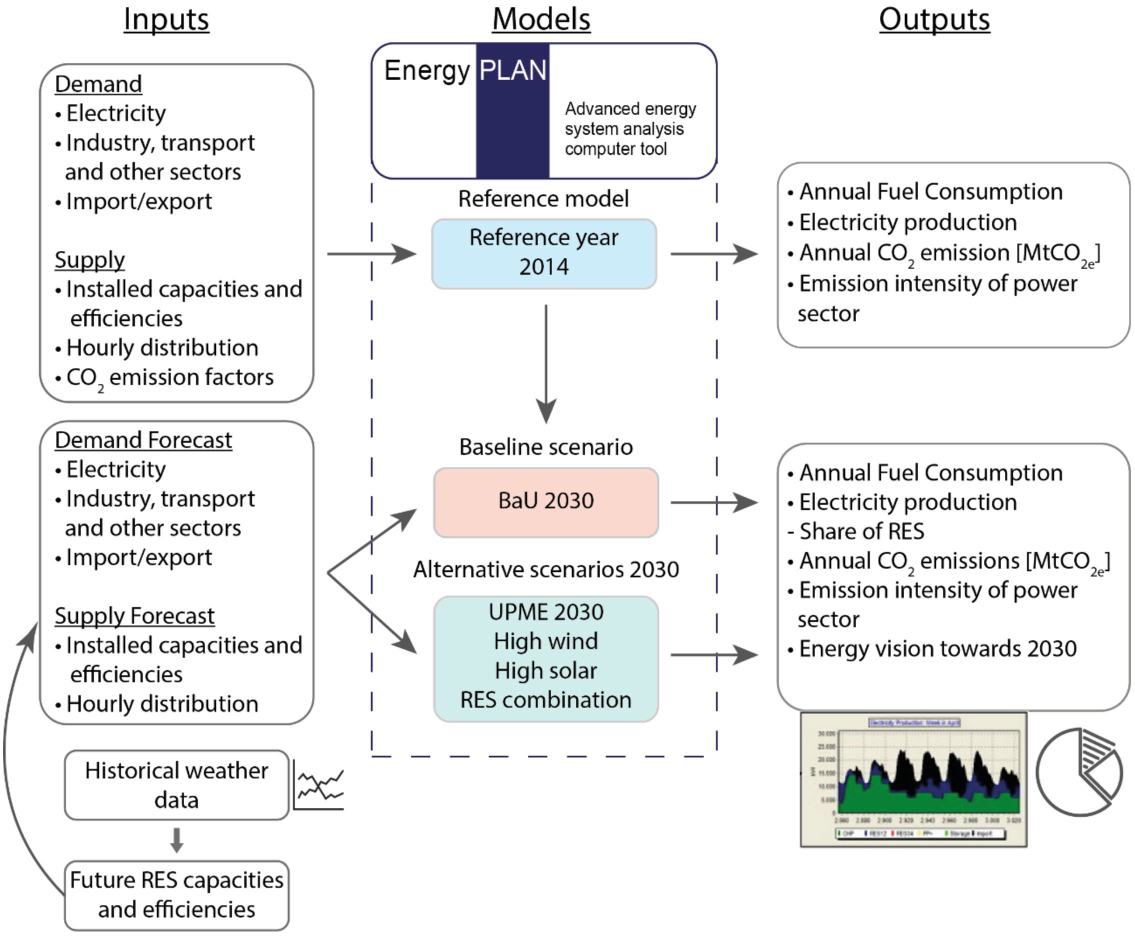

Figure 6.1. Structure of the Colombian model in EnergyPLAN [176]**.**

6.3 Maximum feasible RES penetration in the Colombian power 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 (i.e. high wind and 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 [48]. 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 by using some flexibility measures such as electricity storage systems or increasing transmission line capacity with neighbouring countries [31].

Conolly et al. [193] 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 (equation 6.1). This coefficient has been extensively used in similar works [31], [44], [48], [196].

$$COMP = \frac{\Delta PES}{\Delta CEEP} \tag{6.1}$$

6.3.1 Maximum technical wind penetration

The behaviour of CEEP and PES when wind penetration increases is shown in Figure 6.2. 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.

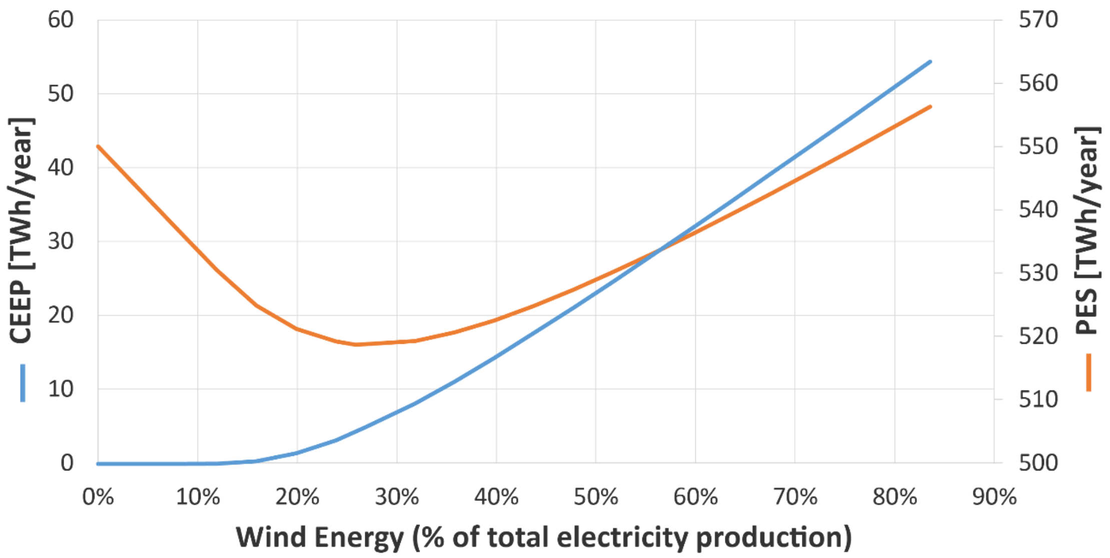

Figure 6.2. Curtailment and PES change with increasing wind penetration in the power system.

The change in the COMP coefficient with increasing levels of wind penetration can be observed in Table 6.3. An increment in the annual wind production from 22 to 23 TWh elevates the CEEP by 0.45 TWh and reduces the PES by 0.50 TWh. In this case, the CEEP gradient is greater than the PES gradient and the maximum technical level has been surpassed. When the PES reduction is greater than the CEEP increase, the result is a COMP > 1. On the contrary, a PES reduction lower than the CEEP growth results in a COMP < 1 [193]. Consequently, the largest technical wind penetration is found when COMP is close to one. For the baseline scenario, that level is approximately 22.5%, which represents a wind installed capacity of about 7845 MW.

Table 6.3. CEEP, PES and COMP for increasing wind power levels.

Wind prod [TWh/year]	Wind power [MW]	CEEP [TWh/year]	PES [TWh/year]	COMP
20.0	6975	1.45	521.3	-
20.5	7149	1.63	521.0	1.83
21.0	7323	1.82	520.7	1.58
21.5	7497	2.03	520.4	1.38
22.0	7671	2.24	520.2	1.24
22.5	7845	2.46	519.9	**1.00**
23.0	8019	2.69	519.7	0.91
23.5	8193	2.93	519.6	0.75
24.0	8367	3.18	519.4	0.64
24.5	8541	3.44	519.3	0.54
25.0	8715	3.7	519.1	0.46

6.3.2 Maximum technical solar PV penetration

The analysis of the solar PV penetration follows the same procedure as for the case of wind. Figure 6.3 illustrates the behaviour of CEEP and PES when the 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.

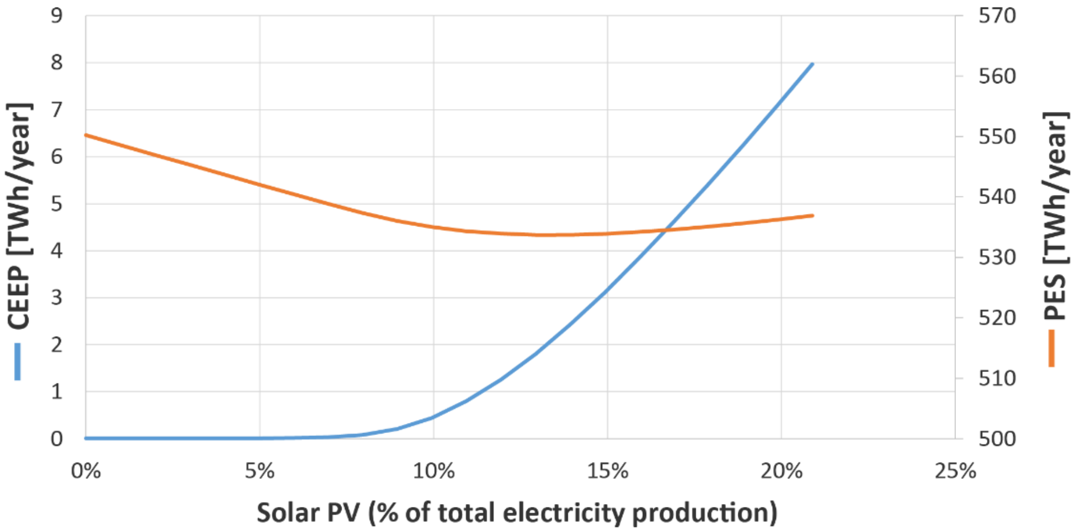

Figure 6.3. Curtailment and PES change with increasing solar PV penetration in the power system.

6.4 Scenario results and discussions

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 $MtCO_2e$ in 2014 to 108 $MtCO_2e$ 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 results obtained 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 [197]. Similarly, Calderon et al. [174] 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 [144].

The UPME 2030 scenario evidences a reduction of 1.5% in PES compared to the baseline scenario (see Figure 6.4). 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 power system does not have a significant impact on the total emissions reduction in the energy system.

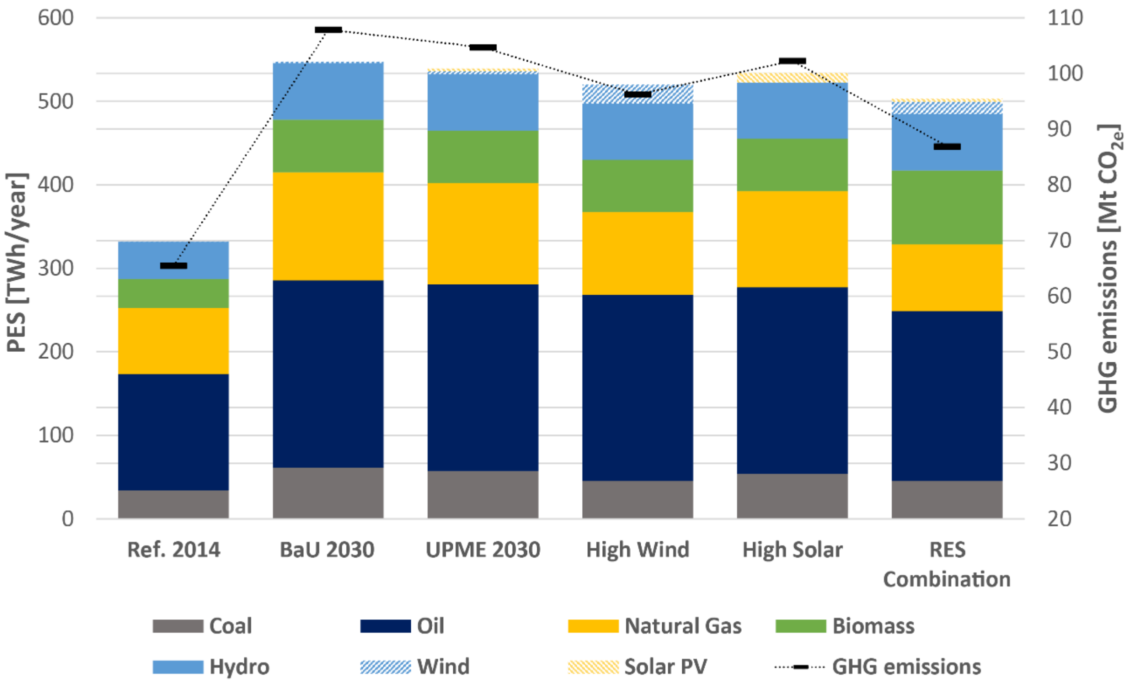

Figure 6.4. PES and CO_{2e} emissions for all the scenarios.

The alternative scenarios 3 and 4 represent the maximum technical penetration level of wind and solar power as explained in detail in Section 6.3. 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 a 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 90% 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 policymakers 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.

6.4.1 Electricity production results

Figure 6.5 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 [136]. 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 [19], [184].

Figure 6.5 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.

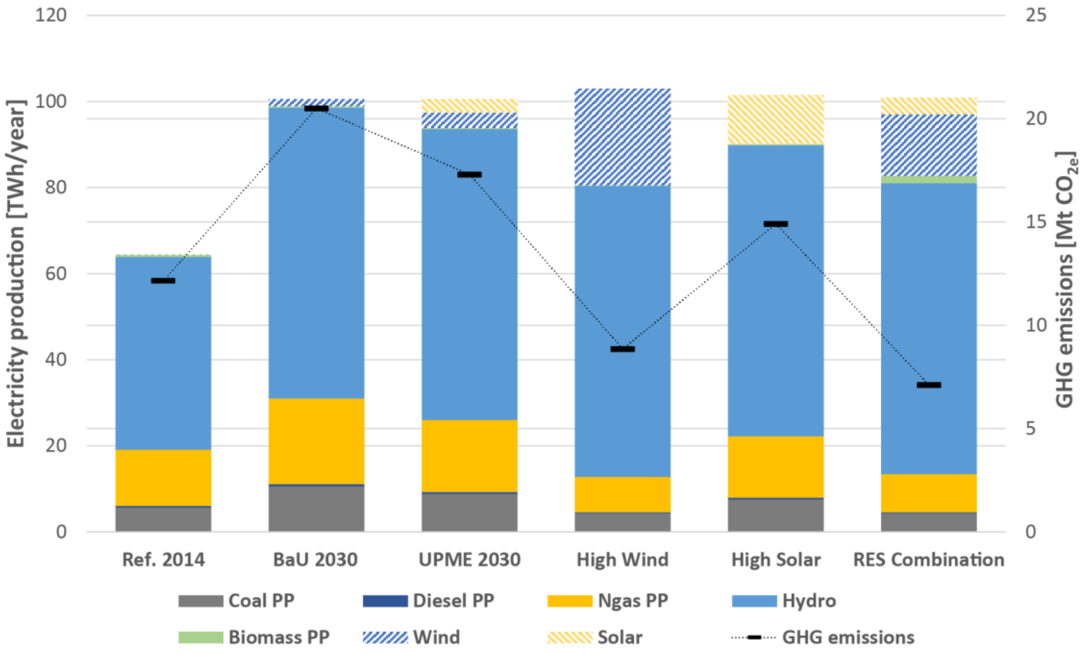

Figure 6.5. Electricity production and CO_{2e} emissions for all the scenarios.

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 6.6 to 6.9 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 4.2, 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 6.6 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.

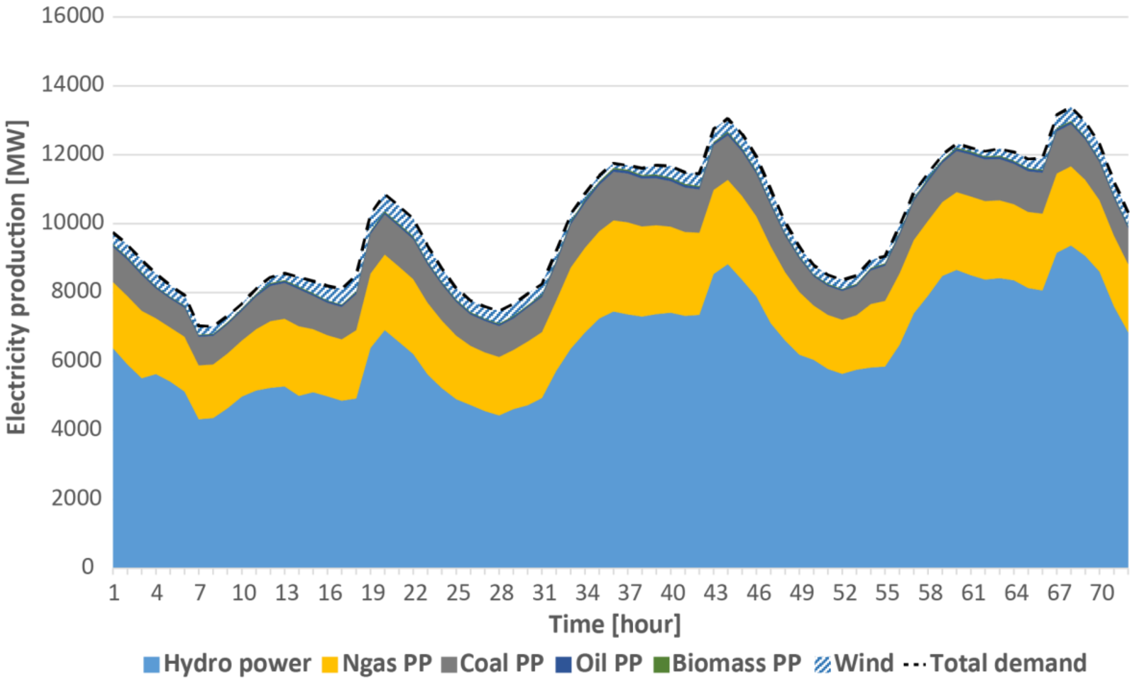

Figure 6.6. Hourly distribution of energy supply and demand for the baseline scenario (BaU 2030).

Figures 6.7 and 6.8 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.

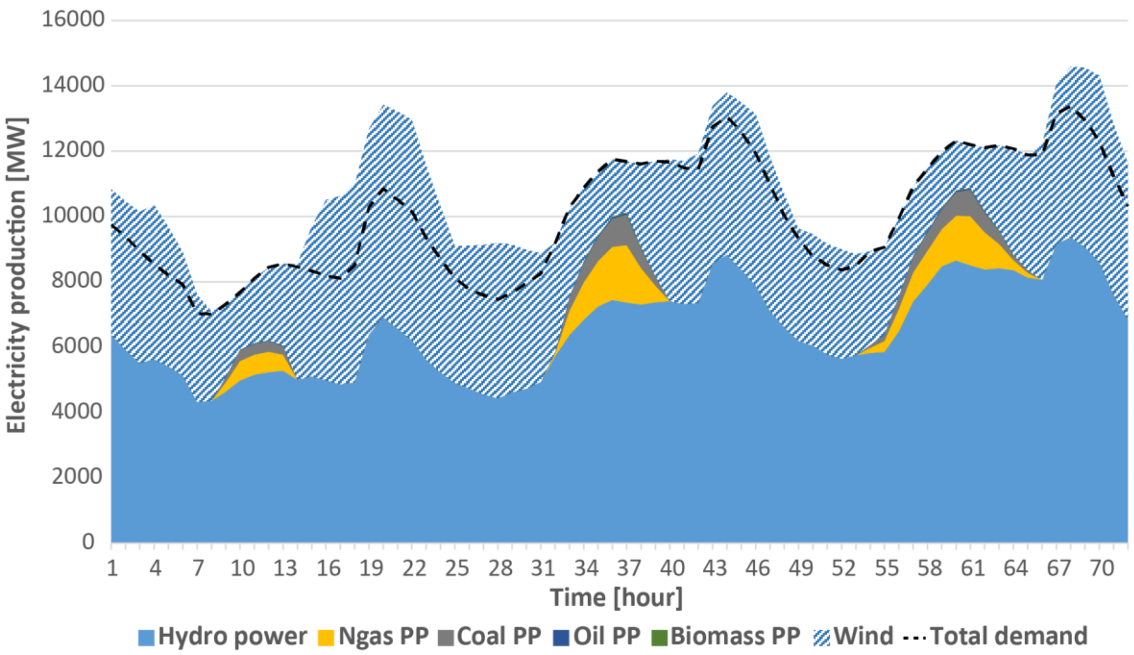

Figure 6.7. Hourly distribution of supply and demand for the high wind scenario.

Figure 6.8 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 that 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.

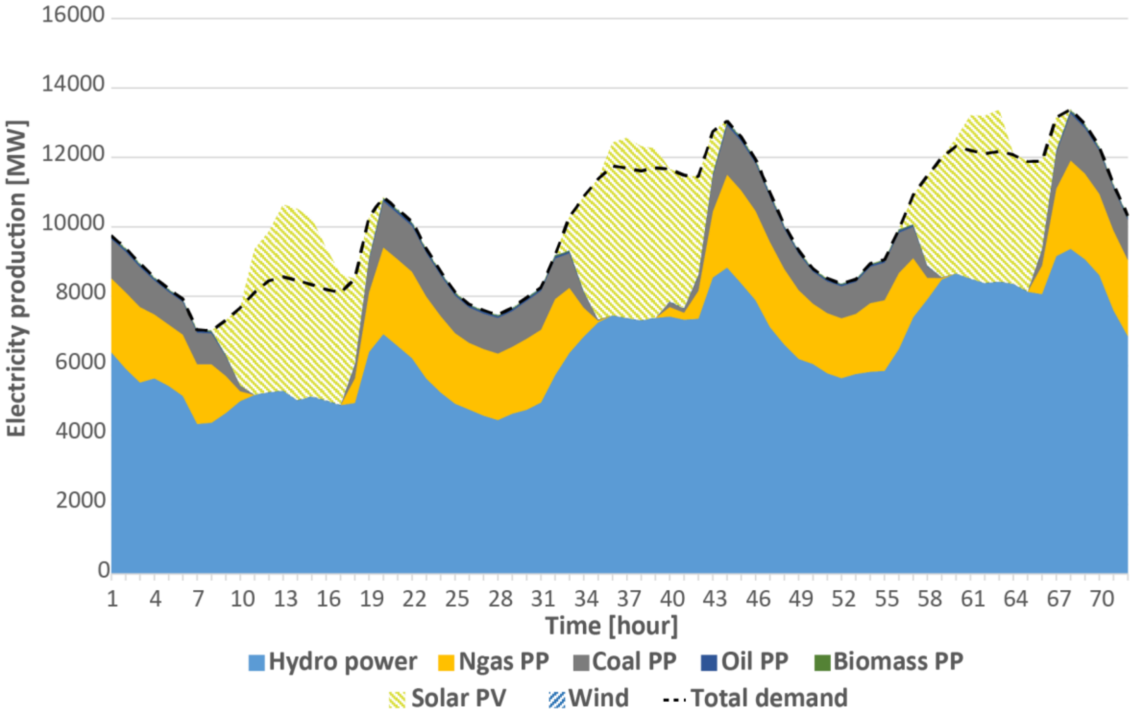

Figure 6.8. Hourly distribution of supply and demand for the high solar PV scenario.

The RES combination hourly results are shown in Figure 6.9 and 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 in any of the RES. This is important in order to guarantee the reliability of the electricity system.

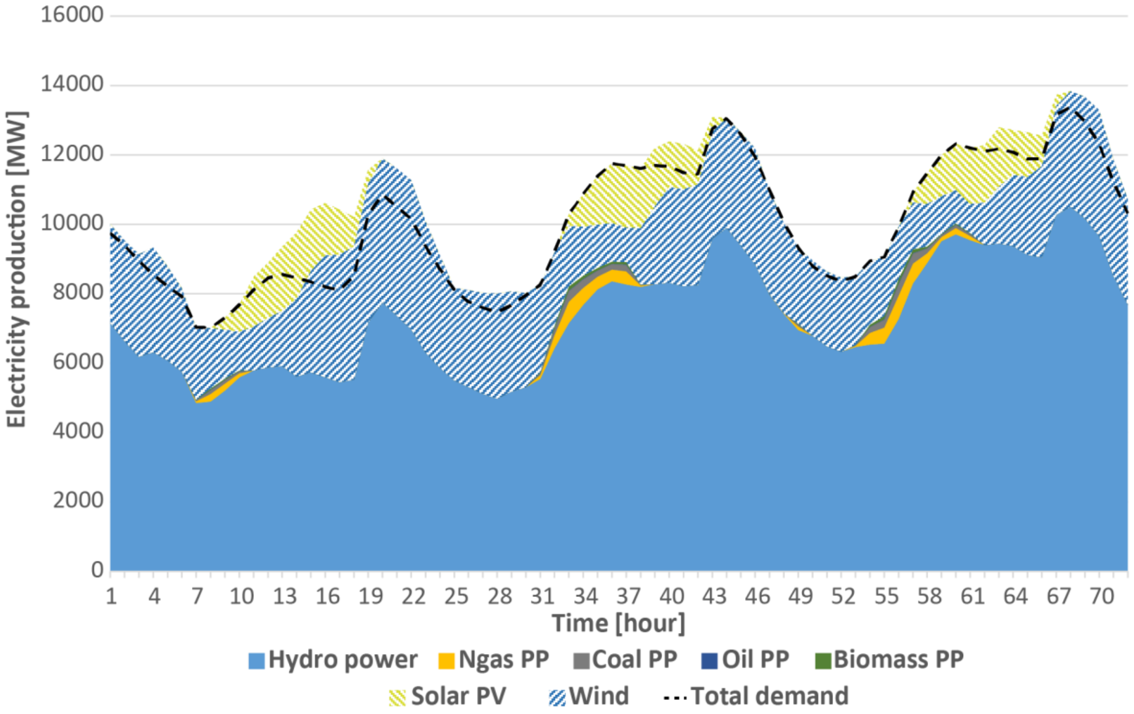

Figure 6.9. Hourly distribution of supply and demand for the RES Combination scenario.

The effects of large-scale RES integration on conventional thermal power plants require special attention. The results shown in Figure 6.8 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 research. 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.

6.5 Sensitivity analysis

This section presents a sensitivity analysis for the future power 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 4.3, 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 power 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 [185]. The aim of this analysis was to examine the power system performance in the case of any of these events.

Figure 6.10 shows the results of the sensitivity analysis. As expected, during dry years (El Niño) the 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 [73], [160], and this is confirmed in the present results. Wind production might grow to approximately 15.4% during dry years, and its generation could decrease to about 19.6% during wet years.

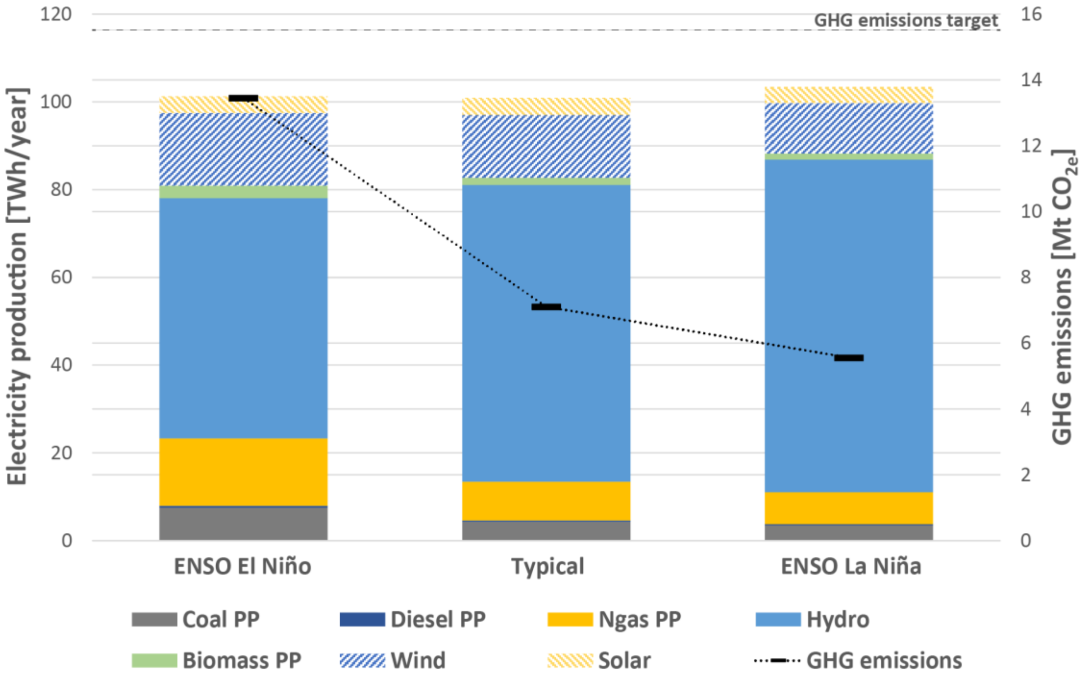

Figure 6.10. Electricity production and CO$_{2e}$ emissions for the sensitivity analysis.

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 power sector. The results show an upsurge of about 89% compared to a typical 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.

6.6 Conclusions

The purpose of this chapter was to analyse the technical impacts of different integrated renewable sources on four possible future alternative energy scenarios. The general results of this chapter agree with those from earlier studies produced for Colombia [131], [174], [197] and other countries with a similar electricity mix [19], [184].

The 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 for these scenarios were estimated to be 22% and 11%, respectively. Higher levels of penetration could result in over generation that might limit the feasibility of the 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. Significant levels of electrification of this sector are not considered in the government plans towards 2030 due to the lack of infrastructure and the high capital costs required to shift to these systems [176]. Therefore, longer-term scenarios that consider this strategy are further explored in Chapter 8.

It should be noted that the alternatives assessed in this chapter do not include neither the economic analysis nor the effects of energy storage and the expansion of international interconnections. These aspects are further discussed in the Chapter 7.

Chapter 7 Energy storage and cross-border interconnections for increasing the flexibility of future power systems

7.1 Introduction

As described in Chapter 2, 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 COP21 in Paris. The integration of large amounts of variable RES into the power grid poses important techno-economic challenges due to their highly intermittent energy generation [198]. Thus, a flexible power system is required in order to reach renewable integration targets without affecting the reliability and efficiency of the grid. This chapter focuses its attention on utility-scale electricity storage (ES) and grid capacity expansion, which are considered to be two of the main technologies suited to assist in the effective integration of high share of RES, especially in countries with weak grid infrastructure [22]. It should be noted that this chapter focuses on the power sector only, and this is because the other sectors in the energy system are not affected in the scenarios analysed.

As explained in more detailed in Chapter one, very few studies [40] have investigated the impact of utility-scale ES and international electricity interconnections for increasing the flexibility of the power system in countries with a high share of hydropower in their electricity mix. Regarding the interconnection issue, the main focus of previous works has been on the market behaviour rather than the impact of RES penetration [78]. Therefore, in this chapter the techno-economic effects of large-scale energy storage and interconnections in the integration of variable renewable energy, by using the Colombian power system as a case study, are analysed. 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. Further, a new optimisation model, named MOEA Eplan and developed by the author in MATLAB, is introduced and used for the analysis. Technical details of these tools are further explained in Section 7.3.

In the literature, some studies have already introduced some optimisation tools linked to the EnergyPLAN simulation software [199]. For instance, Bjelic et al. [200] used the optimisation tool GenOpt linked to EnergyPLAN for the planning of national energy systems under the EU framework. Eurac Research [201] developed the EPLANopt model that couples EnergyPLAN with Python, and applied it to optimise energy efficiency scenarios in buildings. Manhub et al. [202] also developed an optimisation model written in Java in order to design future scenarios, and applied it to the city of Aalborg in Denmark. However, 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 by the scientific community (MATLAB) in order to run the optimisations and no previous knowledge of coding is required for its execution.

This chapter is divided into five sections. Section 7.2 presents an overview of the current Colombian power system and its cross-border interconnection capacity. Section 7.3 is concerned with the methodology applied in order to simulate the scenarios and perform the techno-economic optimisation. Section 7.4 presents the results from the simulated scenarios and the Pareto front obtained. Finally, the conclusions provide a final discussion of the main findings. Part of the results presented in this chapter are based on the published work by the author available in [203].

7.2 Energy storage and interconnections in Colombia

In Chapter 4 the main characteristics of the power sector in Colombia are introduced. In this chapter, more details about energy storage and cross-border interconnections are presented. Regarding the former, 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, they can only be used for long-term purposes because their short-term operations are constrained due to the system configuration. The high reliance on hydro resources makes the system vulnerable to strong droughts caused by ENSO [204], and during these periods, the electricity production by the hydropower plants can fluctuate between 45% and 95% due to the changes in the natural water inflows to the dams [156]. Conventional fossil fuel generation 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 interconnections, the first agreement was reached between Colombia and Venezuela in 1992 with two main projects (Cuatricentenario and Corozo) as shown in Table 7.1. These projects were developed by governmental companies due to the lack of international regulation [205], 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 [78]. These countries have historically shared a similar organisational structure in 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 [27]. As shown in Table 7.1, Colombia and Ecuador share four transmission lines with a maximum export capacity of 535 MW [177]. The interconnection between Colombia and Panama is expected to start operations by the end of 2020 with a maximum capacity of 300 MW [206]. 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 hydrological complementarity patterns [78].

Table 7.1. Cross-border interconnection capacity in Colombia [177], [185]**.**

	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

7.3 Methodology

This section describes the methods used in order to simulate the flexibility options proposed and analyse their techno-economic impacts in the future Colombian electricity system.

7.3.1 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 system (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) [207], [208]. 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) [209]. Therefore, the primary objective is to integrate the maximum feasible levels of variable renewable penetration [39].

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 the equation (7.1). In addition, the energy stored after the charging process is estimated applying the equation (7.2).

$$e_C = min\left[e_{CEEP}, \frac{C_S - S_S}{\eta_C}, Cc\right] \tag{7.1}$$

$$S_S = S_S + (e_c \eta_c) \tag{7.2}$$

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 the equation (7.3). Subsequently, the energy remaining in the system after discharging is calculated using equation (7.4) as follows:

$$e_T = min[e_{PP}, (S_S \eta_G), C_T] \tag{7.3}$$

$$S_S = S_S - \frac{e_T}{\eta_G} \tag{7.4}$$

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.

In general, the simulation strategy seeks to use the RES production directly when it is available to match the electricity demand. However, in the case of energy surplus the energy excess will be stored and used when needed. Additional information about the equations and simulation strategies available in the EnergyPLAN tool can be found in [183].

7.3.2 Techno-economic assessment (TEA)

The economic assessment is an important part of every renewable integration analysis. In this study, the cost associated with the power system was calculated as differential cost [30]. Thus, only the investment costs associated with new capacity added to the reference system model (2014) were considered, and these represent the total transition costs from the reference to the future system proposed in the defined scenarios. This TEA follows a bottom-up approach using the structure illustrated in Figure 7.1. EnergyPLAN requires a series of inputs in order to estimate the total annual cost of the energy system. The first group of inputs are required to calculate the annual investment costs (CAPEX). These include the capacity specifications for each of the production units (fossil fuel-based or renewable), discount rate (i), current or future unit price and plant lifetime. The second group of inputs are used to estimate the total operation and maintenance (fixed and variable), fuel and CO_2 costs.

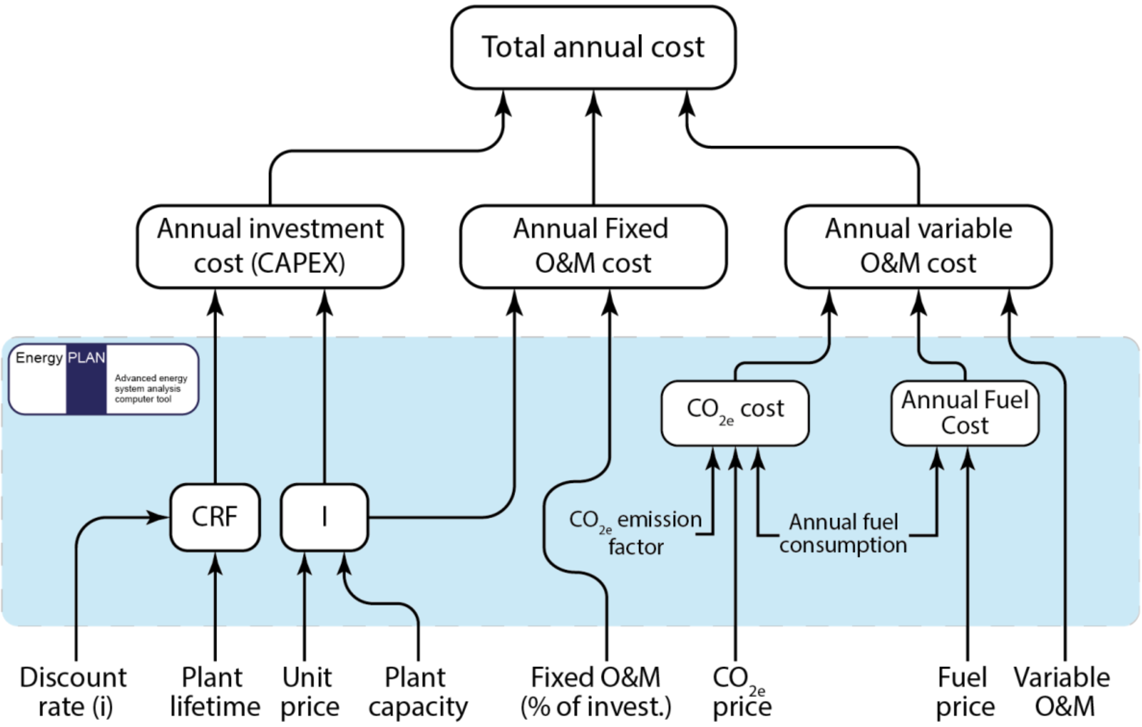

Figure 7.1. Structure of the TEA approach followed.

Capital costs (CAPEX)

The capital investment or capital cost of a power production plant is the amount of money incurred on purchasing, building and installing the plant and its auxiliary facilities [210]. Capital costs are annualised using the total investment (I) and the capital recovery factor (CRF). The total investment of each production unit is calculated using equation (7.5). The CRF is a ratio applied to estimate the present value of a series of equal annual cash flows. It includes two key parameters: the discount rate (i) per year and the plant lifetime (n) [183] and is calculated for each production unit using equation 7.6.

$$I = C_{plant} P_{unit} \tag{7.5}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{7.6}$$

where $i = discount\ rate\ (\%),\ n = plant\ lifetime\ (years)$

Discount rate (i)

The discount rate refers to the interest rate used in order to calculate the present value of future cash flows from an investment [211]. A discount rate of 8%, which has been used in similar RES analysis for Colombia [21], [203], was defined into the model.

Plant lifetime

This parameter indicates the number of service years of the plant. For this TEA, the lifetime of each production unit is presented in Table 7.2.

Finally, the individual annualised capital costs for each production unit are aggregated to obtain the total annual investment costs of the power system (equation 7).

$$Annual\ investment\ costs\ (CAPEX) = \sum_{All\ plants} (I)(CRF) \tag{7.7}$$

Operation and maintenance (O&M) costs

The operation and maintenance costs (O&M) in energy production are the expenses incurred to run the power plant and obtain the energy output. These costs are usually classified as fixed and variable costs. The former are independent of the production rate, and the latter depend on the amount of energy generated [210], [212].

Fixed operation and maintenance costs

The fixed O&M costs include labour, plant overheads, capital charges, maintenance activities, insurance, royalties and licence fees [213]. In EnergyPLAN these costs are represented as a proportion of the investment cost for each production unit and calculated using equation 7.8.

$$Annual\ fixed\ O\&M\ = P_{Fixed\ O\&M} I \tag{7.8}$$

Variable operation and maintenance costs

The variable O&M costs are estimated using equation (7.9). These costs include fuel, taxes and carbon and other variable operational costs [183]. Fuel costs are supplied to the tool using international market price projections plus local handling costs.

$$Variable\ O\&M = Fuel\ costs + Marginal\ operation\ costs + Carbon\ cost \quad (7.9)$$

where,

$Fuel\ costs = Fuel\ price \cdot Annual\ fuel\ consumption$

$Marginal\ operation\ costs = Annual\ electricity\ generation \cdot Variable\ O\&M\ costs$

$Carbon\ cost = Annual\ fuel\ consumption \cdot CO_{2e} emission\ factor \cdot Carbon\ price$

All the future technology efficiencies and technology and fuel costs are based on the 2030 projections by IRENA [51], the EnergyPLAN cost database [183] and the energy technology reference indicator projections (ETRI) from the European Commission [214]. An estimated CO_2 price for 2030 of 40 €/tCO_{2e} [215] was defined into the model. Table 7.2 shows the list of projected costs towards 2030 for all the technologies considered in this research.

Table 7.2. Projected capital investment and O&M costs for 2030 [51], [183], [214].

Production type	**Capital investments [M€/unit]**	**Lifetime [Years]**	**O&M [% of invest.]**
Large power plants [MW]	0.83	25	3.35
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
ES technology			
PHES power related [MW]	0.6	50	1.5
PHES energy related [GWh]	7.5		
CAES power related [MW]	0.9	40	2
CAES energy related [GWh]	132		
Pb-acid BES power related [MW]	0.7	15	2.5
Pb-acid BES energy related [GWh]	270		

7.3.3 Future scenarios

The same reference model as described in Section 5.4 is used in this chapter. Using only the power sector data, a baseline scenario and two alternatives were built for the Colombian system in 2030 (see Table 7.3). These scenarios were developed based on the inputs from previous studies [78], [131], [174], [176], [216] and different specialised governmental and private organisations [134], [136] as follows:

1. Scenario 1 (baseline): As described previously in Chapter 5, this scenario is commonly known as the BaU scenario and it is based on the outlook defined by the Colombian government in order to define the iNDC presented in the COP21 [144]. It assumes that the current trends in the electricity demand and supply will remain unaffected.

2. Scenario 2 (COL 2030 + ES): This scenario was built from the results of Section 7.4.1, and it suggests further penetration of wind and solar PV in the power mix with energy 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 7.4.1. 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 [136].

Table 7.3. Input data for the reference and future scenarios.

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

Energy storage and cross-border interconnections

In order to quantify the technical effects of grid-scale energy storage and interconnections in power 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 the 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 [216]. During the optimisation process, different levels of power and energy storage capacities were explored in order to find the best system configurations (see Section 7.4.4).

After assessing the technical impacts of adding energy storage to the Colombian system, three different technologies are selected in order to estimate its cost and feasibility. These technologies are pumped hydro energy storage (PHES), compressed air energy storage (CAES) and lead-acid battery storage (BES). They were selected due to their current level of development [217], suitability for assisting in the integration of large-scale RES [40], [216] and the great potential reported [216], [217] for use in countries with similar characteristics to Colombia. Further details of this assessment are discussed in Section 7.4.3.

Regarding the interconnections, the current capacity was discussed in Section 7.2. The interconnection level in Colombia could increase in the coming years, however, the ability to rely on an external energy supply will depend on the market arrangements and electricity mix within the linked countries [218]. Some studies [219] have analysed the feasibility of an inter-regional grid for the Americas, and for the case of Colombia, Ochoa et al. [216] 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 effect on the national power system.

7.3.4 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 author developed a MATLAB app, called MOEA Eplan, that can be accessed freely from the open access repository Zenodo in [220]. This app integrates the EnergyPLAN modelling tool with the Multi-objective evolutionary algorithm (MOEA) used by the MATLAB optimisation toolbox [221] in order to provide a framework for energy scenario analysis and design (more details can be found in the Appendix C). The MOEA is a meta-heuristic optimisation algorithm that was inspired by the natural selection principle. This optimisation method was selected over other alternatives because of two main aspects: Firstly, the number of decision variables involved in the optimisation process includes a large search domain that requires advanced optimisation techniques at a feasible computational demand. Secondly, the optimisation of national energy systems usually deals with multiple criteria which are not necessarily compatible. For instance, the existing trade-offs between annual CO_2 emissions and the total system cost. Therefore, large-scale energy system optimisation problems require multi-objective optimisation methods due to its high level of complexity. Meta-heuristic evolutionary algorithms (EA) are especially appropriate for these kinds of applications [202]. EA were mostly used on single-objective optimisation problems at the end of the last century. However, in the last years, they have been mainly applied to solve multi-objective optimisation problems and they are known as multi-objective evolutionary algorithms (MOEA). There are multiple advantages of EA compared to traditional optimisation algorithms, such as their ability to tackle complex problems, parallelism and calculation accuracy [222]. Further, MOEA operate on numerous solutions during each iteration and their generalisation in finding the optimal is usually simpler than for traditional algorithms [223]. MOEA Eplan uses an elitist and controlled variant of the Non-Dominated Sorting Genetic Algorithm (NSGA-II) described by Deb in [224]. Figure 7.2 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 [201].

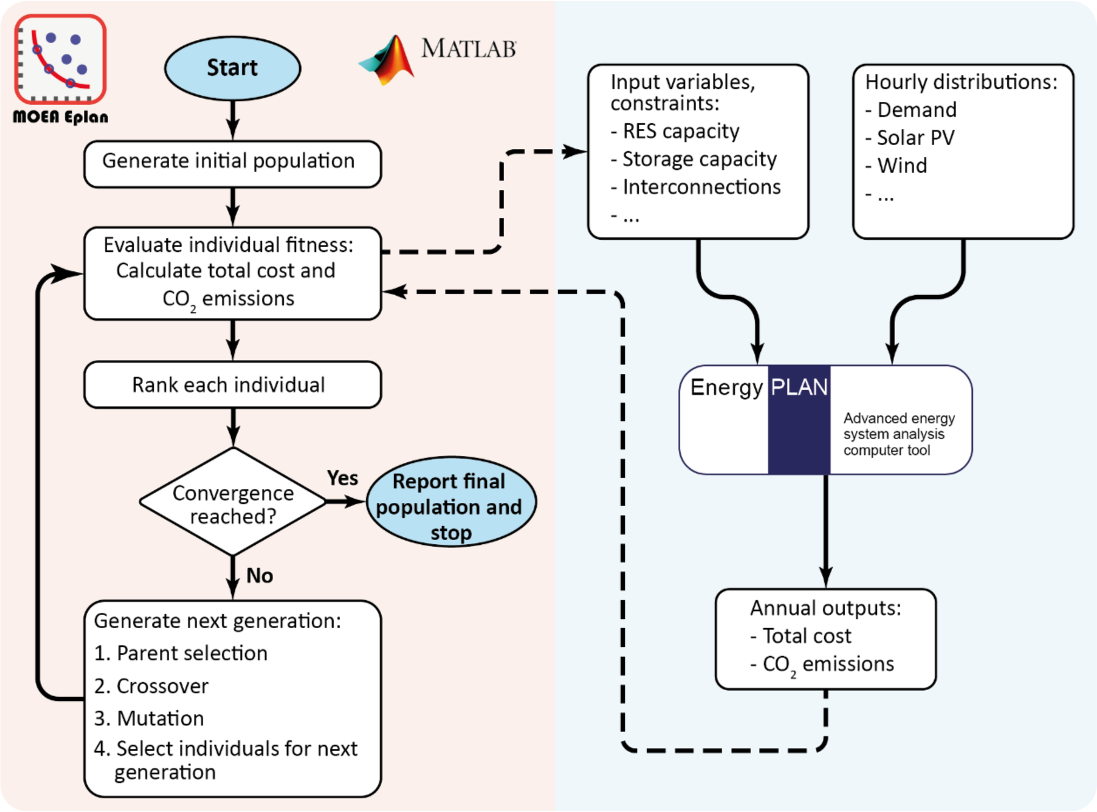

Figure 7.2. Diagram of the algorithm followed by the MOEA Eplan tool.

In this case, 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 7.4. The cross-border transmission capacity is considered a constraint rather than an input in this study because its expansion usually depends on international agreements.

Table 7.4. 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	6,000
Turbine power [MW]	0	6,000
Storage energy capacity [GWh]	0	60

7.4 Results and discussions

In this section, the results of the simulated scenarios and the optimisation process are introduced. Section 7.4.1 summarises the results of adding energy storage and interconnection capacity into a power system with increasing RES penetration. Sections 7.4.2 and 7.4.3 present the most important findings from the scenario simulations. In Section 7.4.4, the techno-economic optimisation outputs using the MOEA Eplan tool are discussed, and finally, the last section summarises the main findings from the sensitivity analysis.

7.4.1 Energy storage and interconnections

As observed in Chapter 6, 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, energy 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.

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 Figure 7.3. 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 [208]. This leads to a technical penetration limit to the technology that is estimated following the procedure described in Section 6.3. 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 usable 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% in the wind power capacity (shaded region in Figure 7.3) could be accommodated in the system without wasting energy and this represents a reduction of 14.7% and 8.4% in the CO_2 emissions and energy curtailed, respectively.

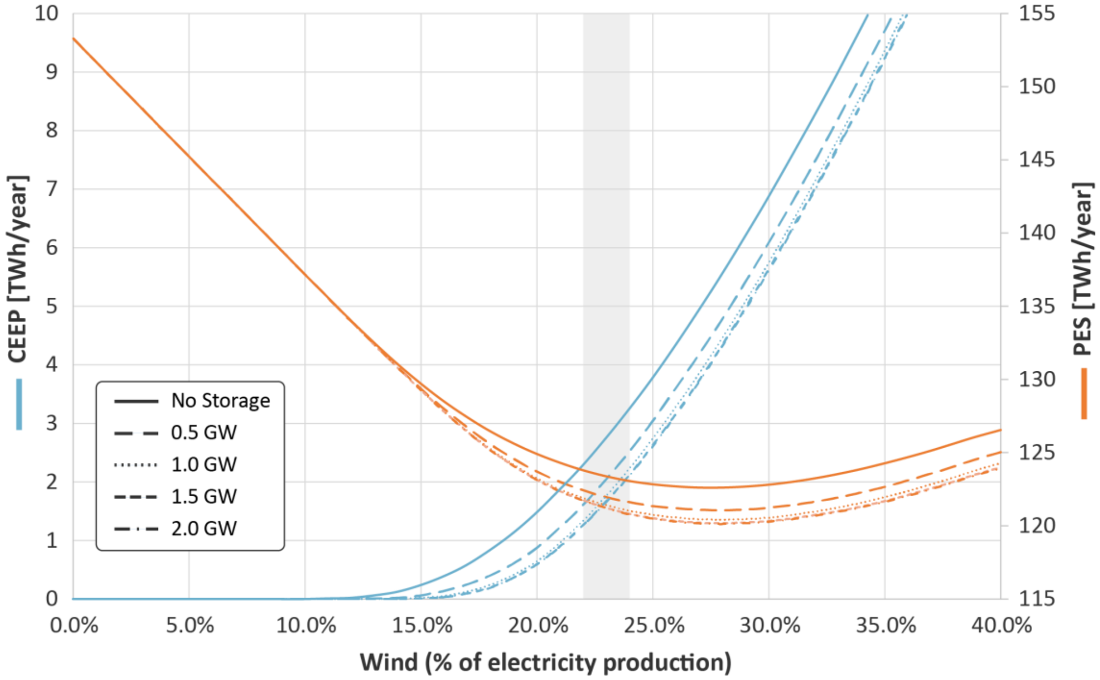

Figure 7.3. Changes in CEEP and PES with increasing wind and energy storage power capacities.

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. Figure 7.4 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% to 16% (5.82 to 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.

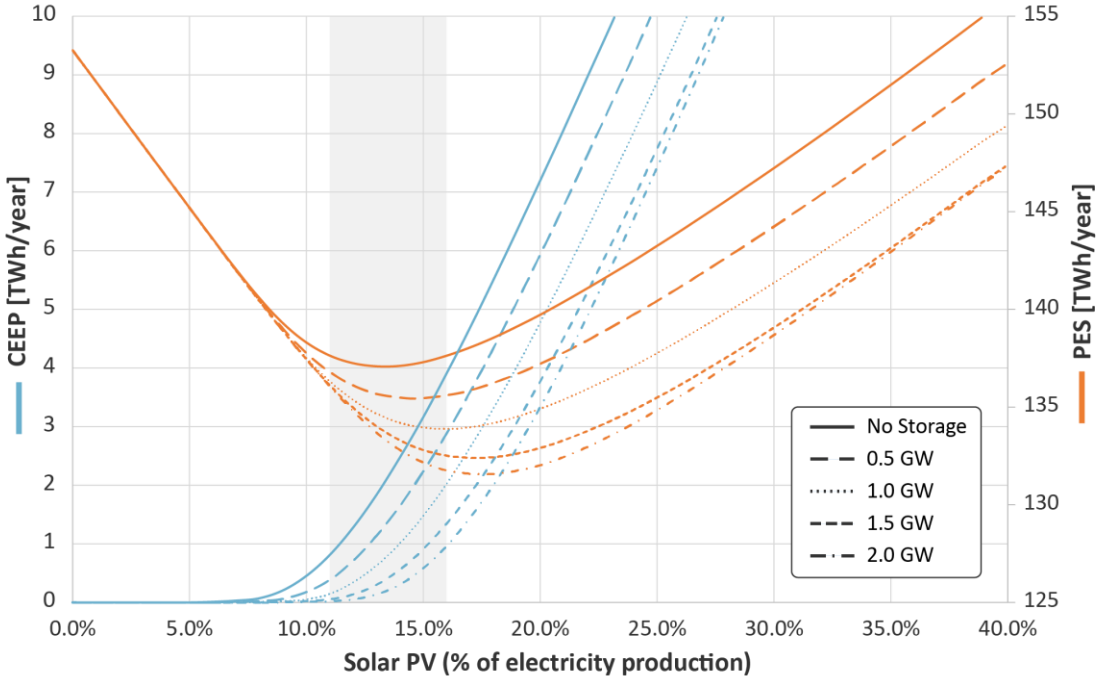

Figure 7.4. Changes in CEEP and PES with increasing Solar PV and energy storage power capacities.

An increase in both wind and solar PV installed capacity is a more realistic scenario and combine the benefits of the two technologies [176]. The results illustrated in Figure 7.5 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 do not result in important changes to the system and the combined (wind and solar) technically feasible RES penetration increases from approximately 19% to 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.

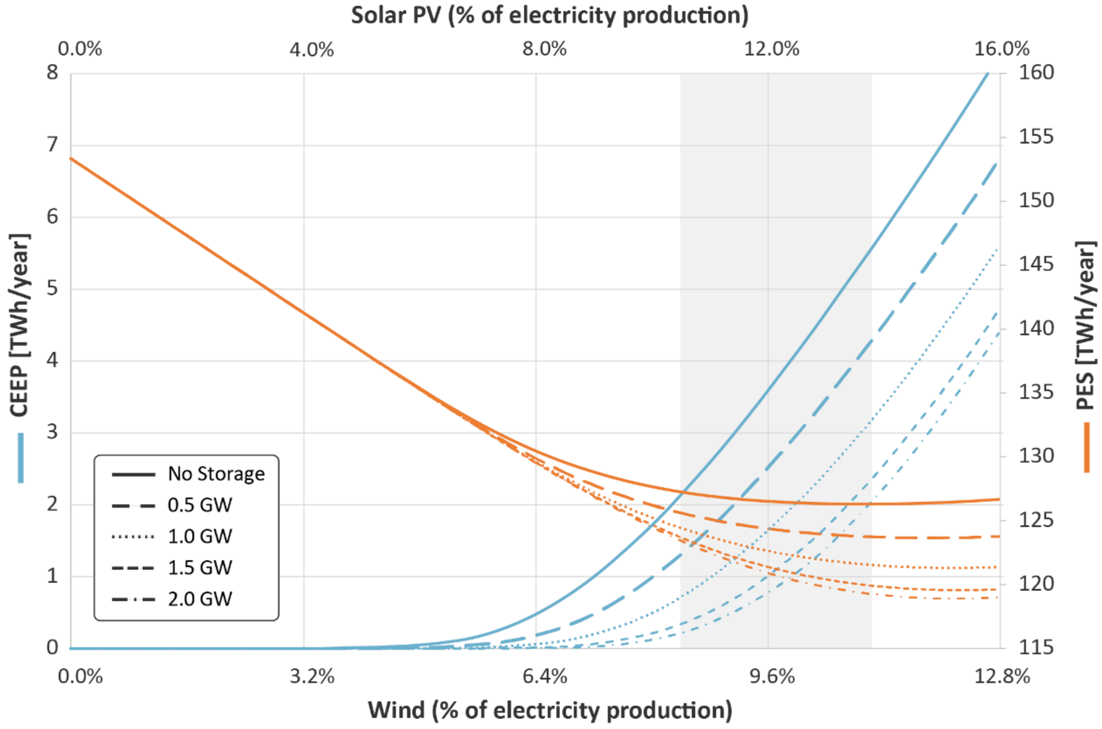

Figure 7.5. Changes in CEEP and PES with increasing combined RES and storage power capacities.

Cross-border interconnection

As outlined in Section 7.2, 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. Figure 7.6 shows the impact of increasing the 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 approximately 19% to 24% of the total electricity production. Further, a drop of approximately 17.7% in CO_2 emissions is evidenced with the PES levels remaining unchanged.

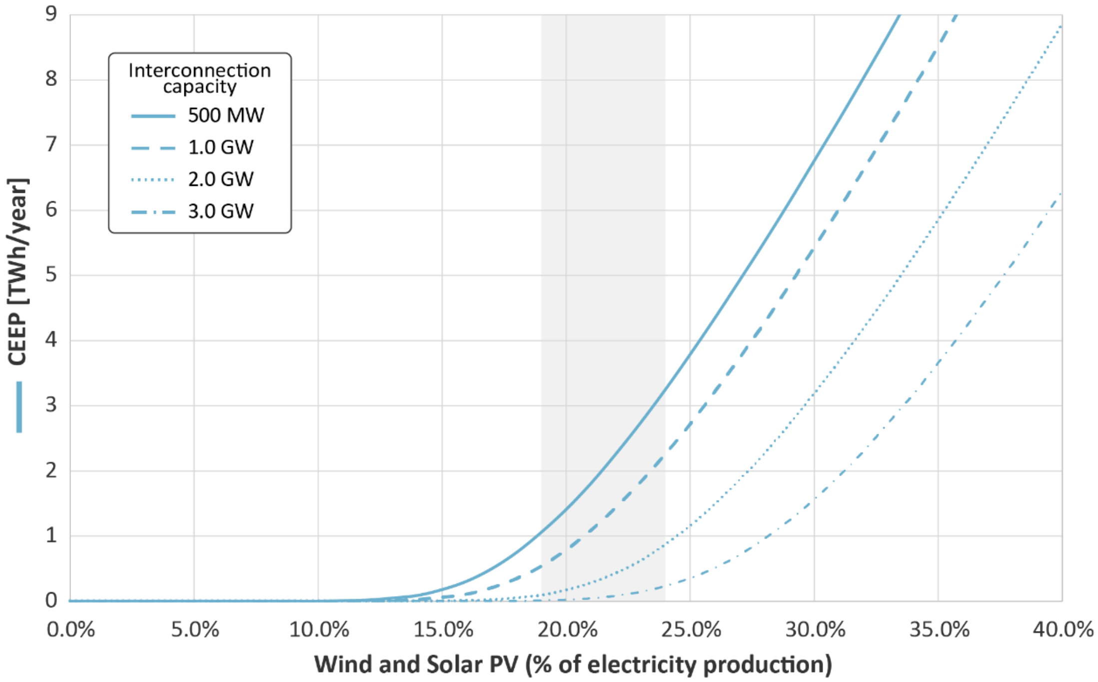

Figure 7.6. Change in CEEP with increasing cross-border interconnection capacity.

7.4.2 Scenario results

This section presents the results obtained from simulating the three scenarios described in Section 7.3.3. The results have been analysed comparing key energy indicators such as annual GHG emissions, fuel consumption, energy curtailed and RES share. Figure 7.7 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 illustrate the benefits of adding variable RES with ES into the power system represented in a reduction of about 67% in the GHG emissions of the sector and an increase in the RES share to be approximately 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 emission remains 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).

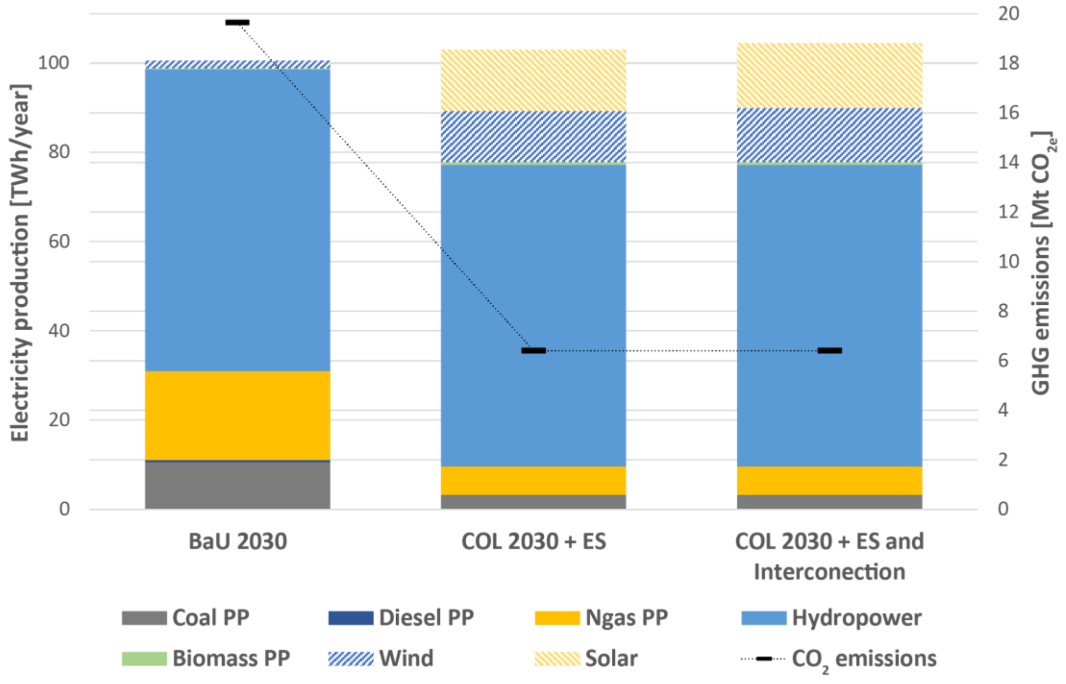

Figure 7.7. Electricity production and GHG emissions for all the scenarios.

7.4.3 Electricity storage technologies cost analysis

After discussing the technical impacts of adding energy storage to the Colombian system, pumped hydro energy storage (PHES), compressed air energy storage (CAES) and lead-acid battery storage were selected to be introduced into the power system in order to estimate its cost and feasibility. These technologies were considered due to their current level of development [217], suitability for assisting in the integration of large-scale RES [40], [216] and the great potential reported [216], [217] for use in countries such as Colombia. The scenario 3 was used to simulate the selected storage technologies and their cost and efficiencies were modified accordingly. All the future technology efficiencies are based on 2030 projections by IRENA [51] the EnergyPLAN database [183] and ETRI [214]. The PHES, CAES and lead-acid battery round-trip efficiency used in this study were 85%, 60% and 85%, respectively.

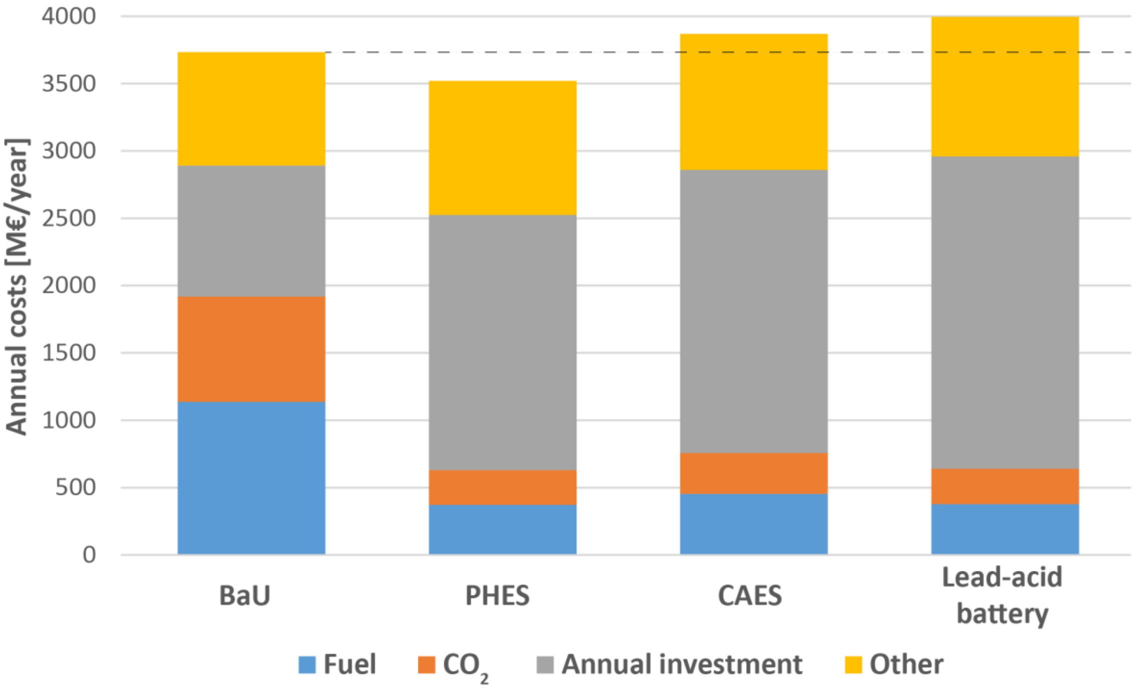

Figure 7.8. Estimated costs of the evaluated energy storage technologies.

The total annual cost of the power system and each of its components are illustrated in Figure 7.8. PHES is found to be the most cost-effective storage alternative, and this is mainly because of its low annual investment cost and the fuel savings (approximately 68% compared to the baseline scenario). Due to the topography of the country and the characteristics of the power system infrastructure, the capital cost of PHES could be further reduced if the current reservoirs are used as part of the storage system. The CAES technology is the least-attractive option in terms of fuel savings and its capital cost is higher compared with PHES. Lead-acid battery technology is the least-cost effective of all the alternatives, but it could represent an attractive option if its capital cost falls in the future due to technology improvements [203]. It should be noted that these results highly depend on the inputs and assumptions defined in Section 7.3. In particular, the CO_2 price has a significant impact on the final outcome. Thus, a sensitivity analysis was performed by modifying this parameter. It was found that for CO_2 prices below 26 €/tCO_{2e}, all the alternatives result in higher total annual costs than the baseline scenario. This fact highlights the importance that policies set by national governments have in supporting the future feasibility of these technologies.

7.4.4 Techno-economic optimisation

In this section, the results from the techno-economic optimisation are presented. As discussed in Section 7.3.4, 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 that used for the 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 [202] in order to provide enough convergence time for the optimisation and guarantee a Pareto-optimal front that does not stay trapped in local optimums. Figure 7.9 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 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 [202]. This allows policymakers and energy planners to identify a range of different options between optimal scenarios when designing future national strategies.

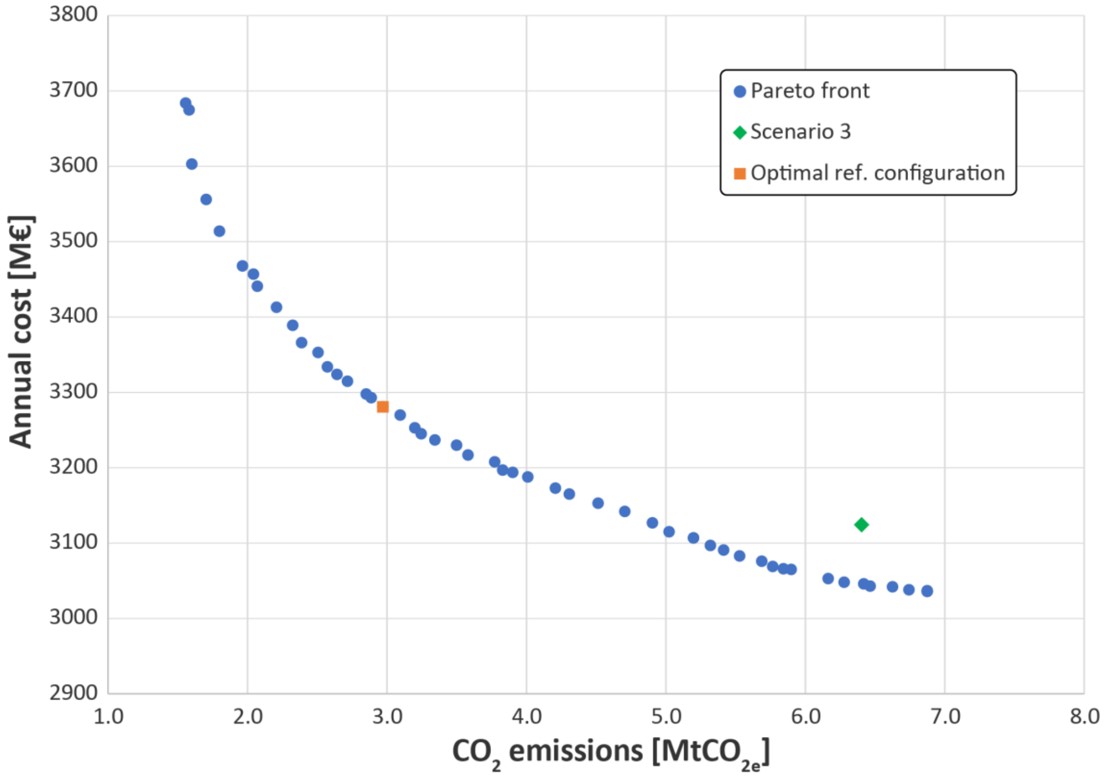

Figure 7.9. Pareto front for best system configurations.

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 with an almost 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 Figure 7.9 corresponds to scenario 3 described in the previous section. It should be noted 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. Figure 7.10 and 7.11 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.

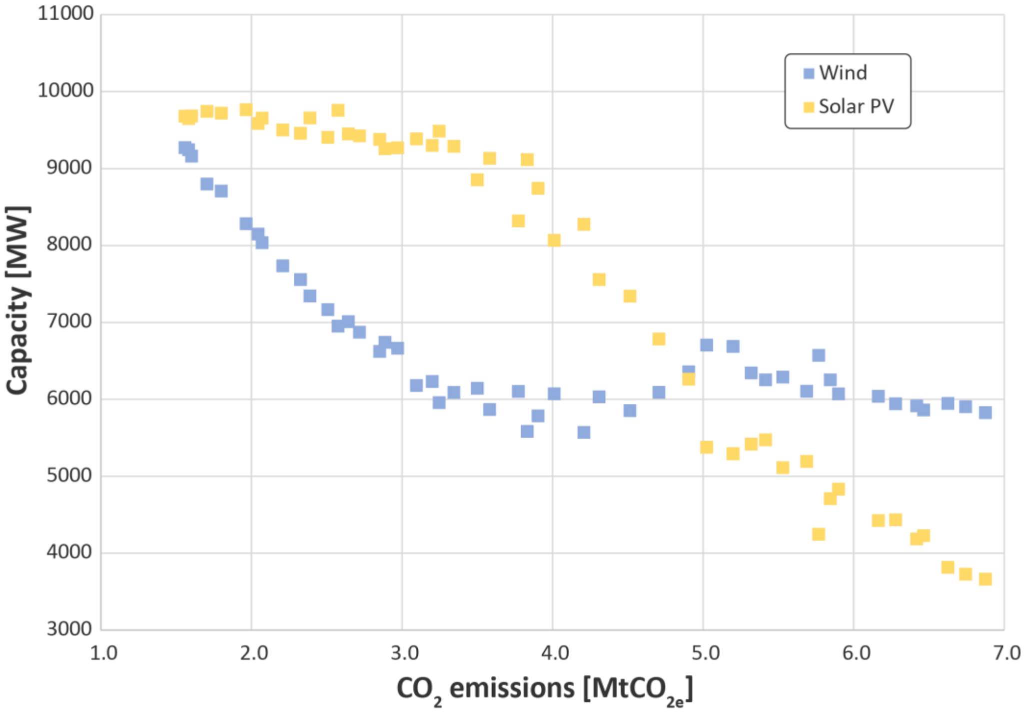

Figure 7.10. Wind and solar PV capacities on the Pareto front.

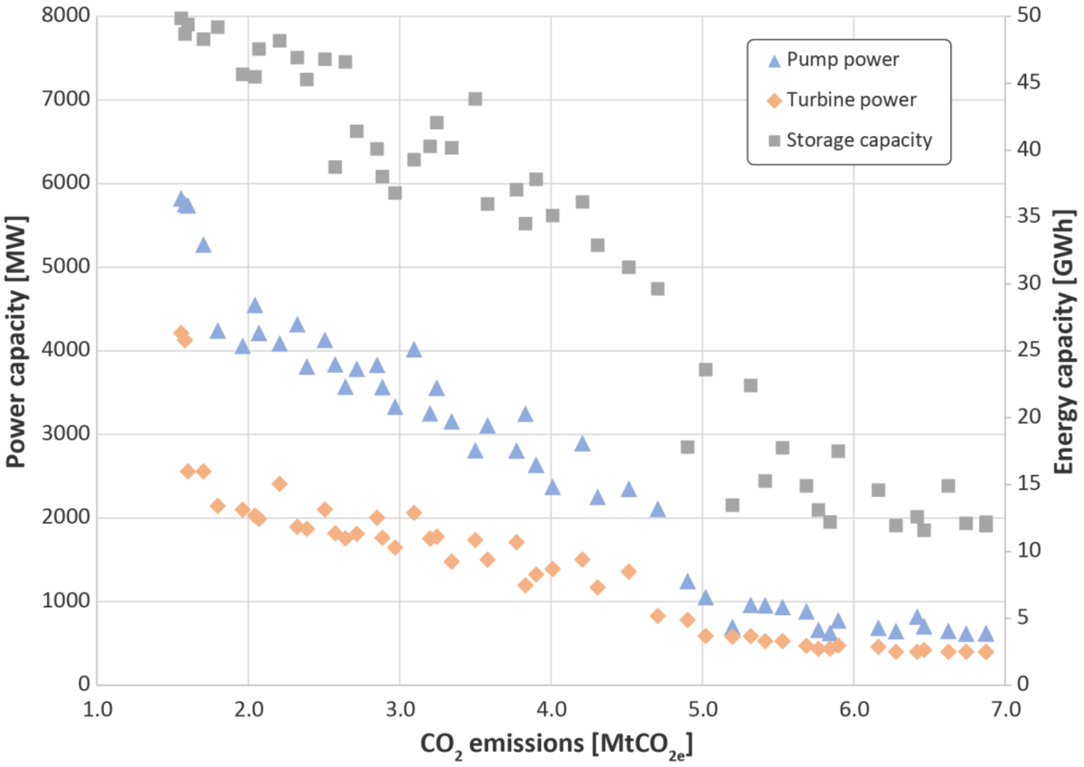

Figure 7.11. PHES components capacity on the Pareto front.

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 the power and energy levels show 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 Figure 7.12). Regarding the economic aspect of PHES, the 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.

Figure 7.12 and 7.13 show the hourly electricity supply and demand profiles for three consecutive days (two working days and a weekend) in two different cases. Figure 7.12 illustrates the results from the 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 [176]. 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.

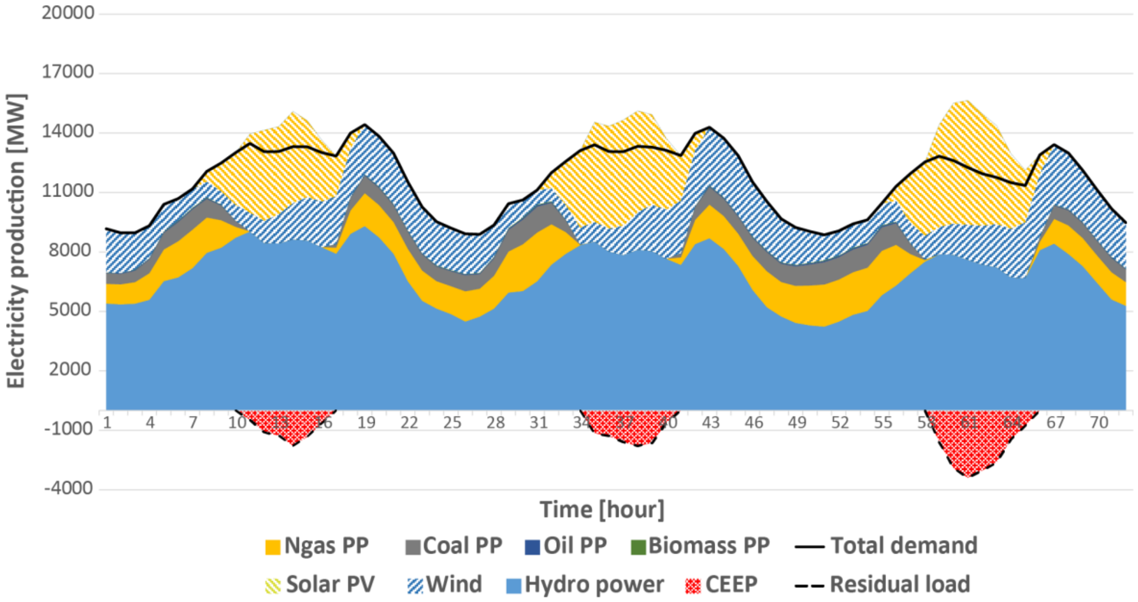

Figure 7.12. Hourly distribution of supply and demand for scenario 2 without ES.

The impact of adding flexibility measures, such as ES and interconnections, into the power system is observed in Figure 7.13, 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 the 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 returned to the grid (ES discharging) when it 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.

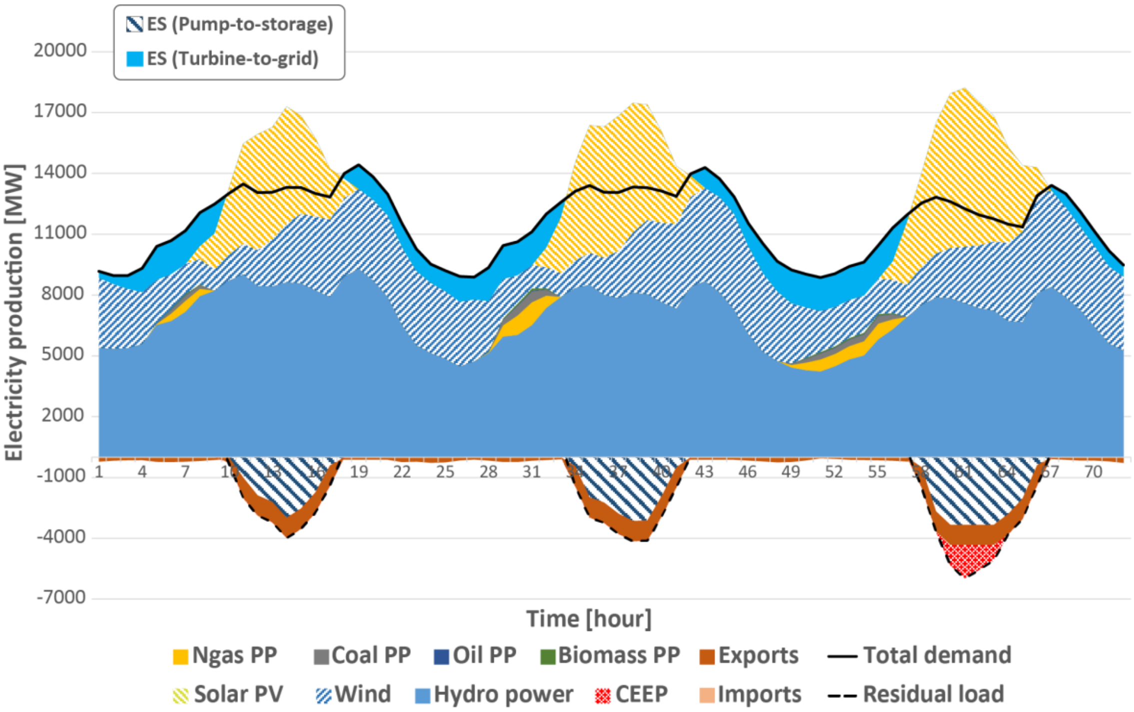

Figure 7.13. Hourly distribution of supply and demand for the optimal reference configuration.

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 in the power sector of about 26.5 gCO_{2e}/kWh.

As shown previously in Chapter 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. Figure 7.14 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 then 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 a regional level seeking to define clear frameworks that could allow a further integration in the region. 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 [78]. 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.

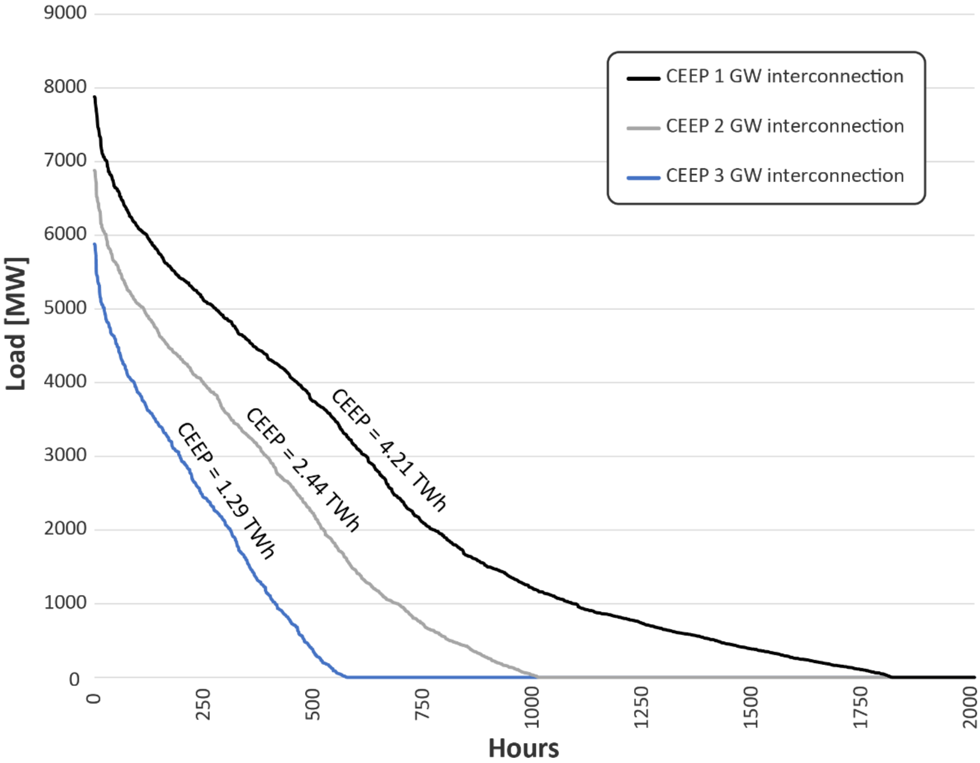

Figure 7.14. Load-duration curves of CEEP for different cross-border interconnection capacities at the reference configuration.

7.4.5 Sensitivity analysis

As described previously in Section 6.5, a sensitivity analysis is necessary due to the high reliance on the power system on hydro generation and the presence of extreme weather events caused by ENSO. Therefore, the same methodology is applied in this section in order to examine the system performance in case of any of these events occur. Figures 7.15 and 7.16 show the hourly distribution of electricity supply and demand for the optimal reference configuration during dry (ENSO El Niño) and wet years (ENSO La Niña), respectively.

During dry years (Figure 7.15), the reduction of hydropower generation is replaced by thermal power and intermittent renewable energy. Further, the ES system plays a key role in reducing the energy curtailed and acts as a backup during peak hours. It is evident that this scenario represents an important challenge for thermal generation due to the steep ramps produce mainly by the increase (during early hours of the day) and decline (during the sunset) of solar PV generation.

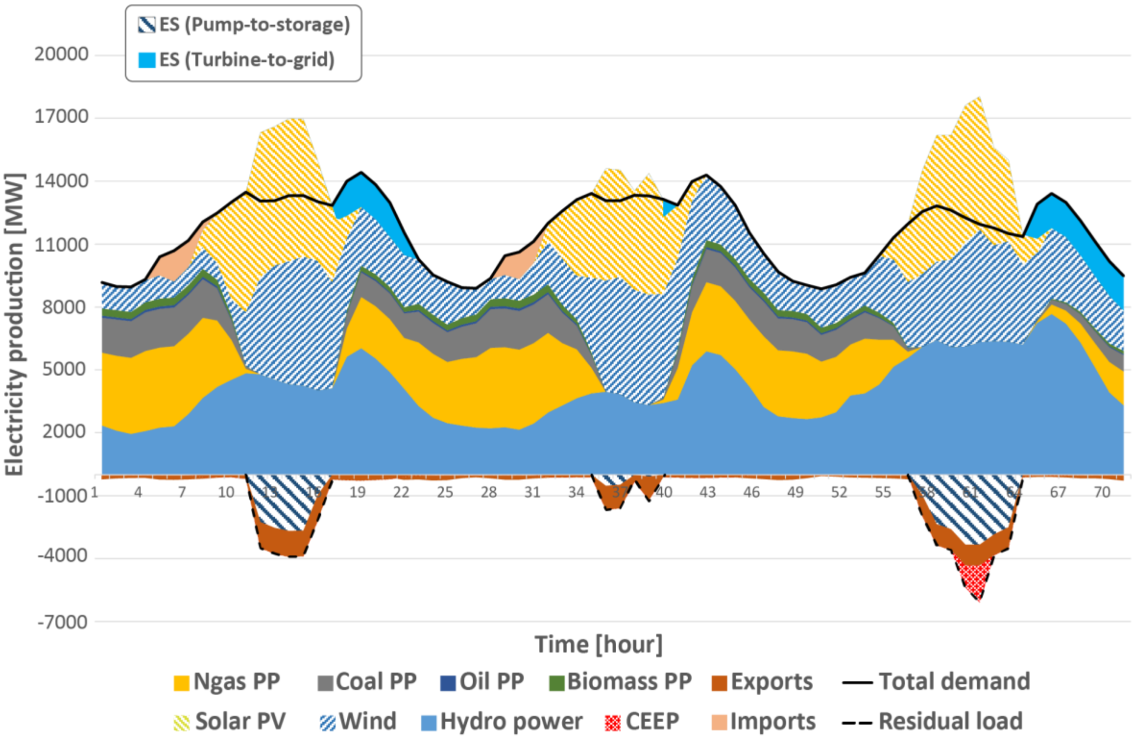

Figure 7.15. Hourly distribution of supply and demand for optimal reference configuration during ENSO El Nino.

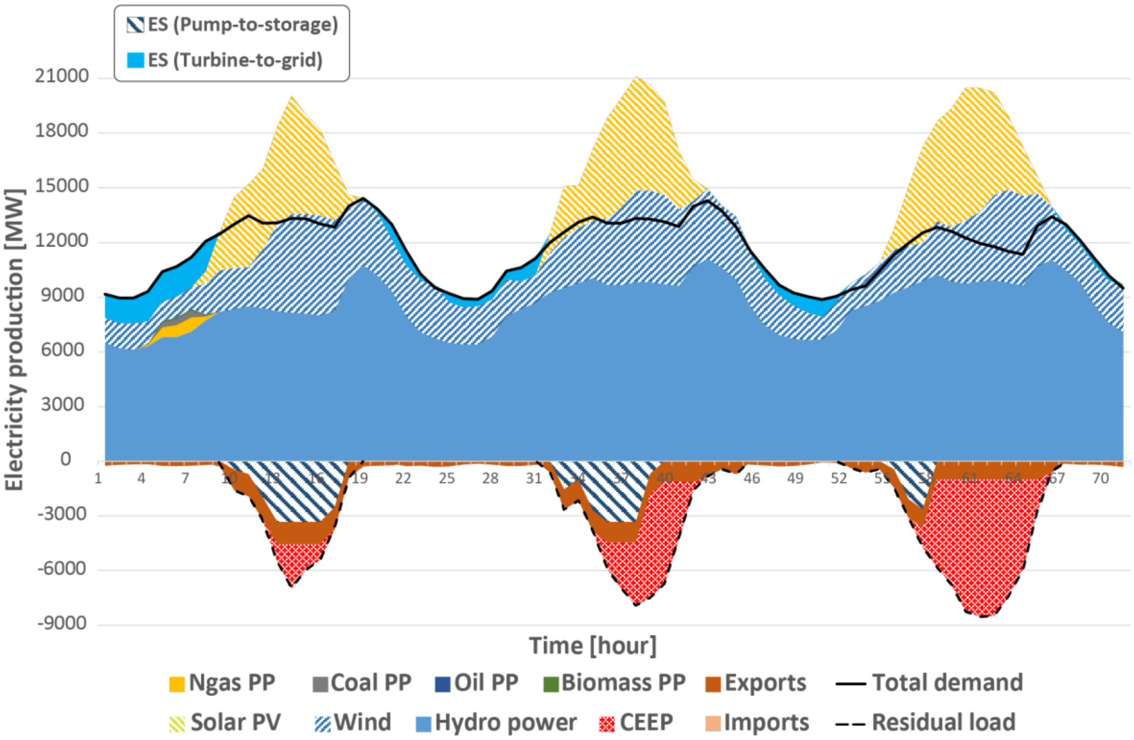

Figure 7.16. Hourly distribution of supply and demand for optimal reference configuration during ENSO La Nina.

In the presence of ENSO La Niña (Figure 7.16), renewable generation accounts for approximately 98% of the total annual electricity production. In this scenario, the synergy between variable generation and flexibility options, such as energy storage and cross-border interconnections, is evidenced. However, energy is wasted due to the high level of generation from these sources and the lack of demand for its use.

Figure 7.17 illustrates the electricity production and GHG emissions from some of the alternatives assessed in this chapter and Chapter 6. The optimal reference configuration clearly represents the best alternative under normal circumstances, and this is mainly because of the higher variable renewable penetration levels achieved after including electricity storage and higher external interconnection capacity into the system. A total RES penetration share of approximately 96.8% of the total generation could be achieved in this scenario, which represents a reduction of the sector's emissions of about 86.2%. Further, the emission factor of the power sector could be approximately 26.5 gCO_{2e}/kWh, and this is clearly below the target defined by the country during the COP21 by 2030 (156.7 gCO_{2e}/kWh).

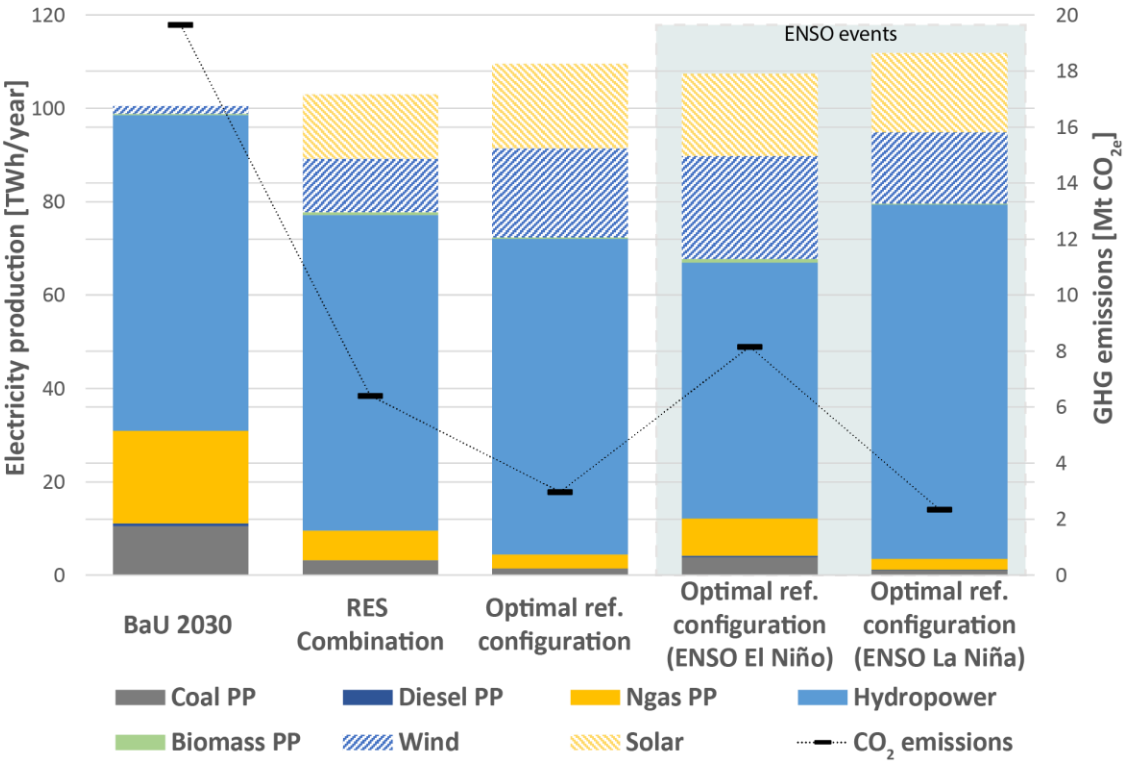

Figure 7.17. Electricity production and GHG emissions scenarios comparison.

7.5 Conclusions

In this chapter, the impacts of large-scale energy storage and cross-border interconnections on the future Colombian power system were analysed using the EnergyPLAN modelling tool. Initially, a parametric analysis using diverse scenarios was performed in order to study 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, which is clearly below 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 planners 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 a better exploitation of its energy potential.

In the following chapter the impact of the transport sector electrification in the Colombian energy system will be analysed using longer term scenarios (towards 2040).

Chapter 8 The role of electric vehicles and renewable energy towards low carbon energy systems

8.1 Introduction

The electrification of the transportation sector is considered a key aspect in the decarbonisation of national energy systems [43]. However, this represents a great challenge that requires significant changes in the transport demand structure. Transport sector still relies heavily on fossil fuels, with approximately 96% of its energy demand coming from petroleum-based products [42]. Electric vehicles (EV) could replace conventional vehicles in order to avoid tailpipe emissions and also assist in the reduction of variable RES curtailments [43].

In recent years, there has been an increasing interest in analysing the interactions between the power and transport sector, and what could be the impact on the national energy system. For instance, Nunes et al. [225] explored the synergies between solar PV and EV in the Portuguese power system in order to allow a 100% renewable electricity supply by 2050. Lund et al. [226] analysed the role of EV and V2G (Vehicle-to-grid) in the integration of higher levels of wind power in Denmark. Novosel et al. [227] build a demand profile of EV penetration in Croatia using the agent-based tool MATSim and studied its effect on the energy system using EnergyPLAN. They found that a 50% electrification of the road segment could reduce CO_2 emissions by 14.6% in the country. Similar studies using EneryPLAN have also been developed for Italy [48], [228], [229] and Germany [43]. In the case of Colombia, the research to date has tended to focus on the CO_2 mitigation potential of different transportation alternatives and their financial implications [230] rather than analysing the impacts of increasing levels of EV and variable RES in the power sector. Therefore, the aim of this chapter is to investigate to what extent the electrification of the transportation sector could be an effective solution for supporting the integration of higher shares of variable renewable sources into the power sector and the mitigation of GHG generation in the national energy system of Colombia. Further, this study aims to extend the existing literature by quantitatively defining the role of electricity storage, variable RES and EV to achieve the national CO_2 emissions reduction targets.

The main results are discussed in terms of key environmental and economic indicators such as CO_2 emissions, RES penetration, curtailments and system costs considering the current plans defined by the Colombian government for the future energy system. In addition, the outcomes of this chapter are expected to serve as a starting point for policy makers and energy analyst that could use them to define the most convenient path towards a sustainable and effective national energy strategy.

This chapter is organised in five sections. Section 8.2 provides a description of the transport sector in Colombia. Section 8.3 describes the methodology applied, including the main assumptions, the baseline and alternative future energy system scenarios. Section 8.4 discusses the results from the simulated scenarios and techno-economic optimisations, and the last section provides the conclusions and recommendations.

8.2 Transport sector in Colombia

The transport sector accounts for 4% of the national GDP and it is the largest consumer of energy in the country (35% of the total oil demand) [144]. As shown in Section 4.4, this sector is the major contributor to energy-related CO_2 emissions accounting for approximately 15% of the total net emissions in 2012 (28.2 $MtCO_{2e}$). The road segment was responsible for 90.5% of the sector’s emissions, followed by aviation, waterborne and rail segments that contributed with 7%, 2% and 0.5%, respectively [150].

The number of vehicles increased from 7.1 million in 2010 to 13.8 million in 2018 (see Figure 8.1), mainly driven by the increase in the demand of private vehicles [231]. The increasing number of vehicles serves as an important source of air pollution due to the lack of emissions control technologies over the ageing public service fleet, freight vehicles and motorcycles that characterise the sector [230], [232].

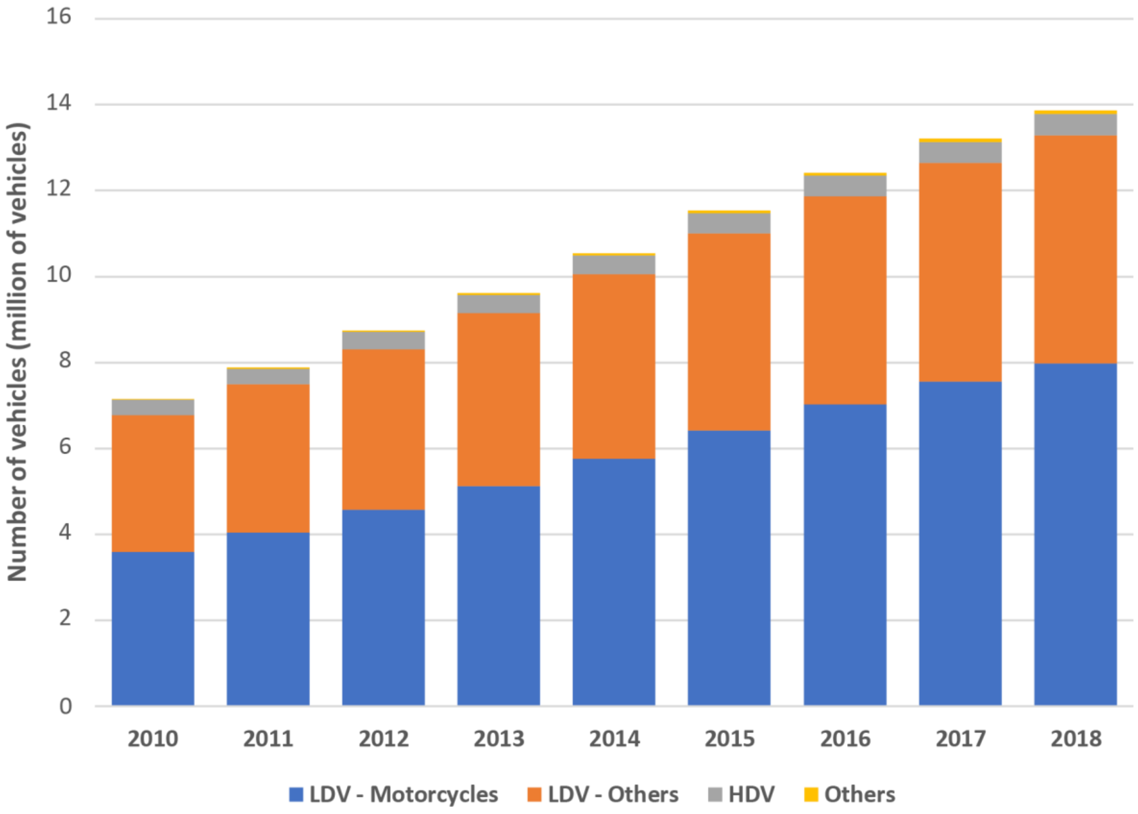

Figure 8.1. Historical fleet composition in Colombia.

8.2.1 Urban transport

Public transport and non-motorized modes are the main alternatives for daily commuting within the cities. Public transport is dominated by conventional buses and, in the case of the eight largest cities in the country, bus rapid transit (BRT) systems are in place [230]. In recent years, a transition from public to private modes of transport has been observed. This trend is characteristic of many developing countries [233], and similarly, the number of motorcycles (two and three wheelers) has experienced a sharp growth in the country [231]. In 2018, two and three wheelers accounted for about 58% of the total number of vehicles. The use of taxis complements the other modes; however, its fleet is controlled by local regulations [230].

The high share of public transport use and non-motorized trips are more related to low-income levels than to aspects such as environmental consciousness [234]. Some indices, such as the ratio of transport expenses to households income and the number of daily trips per capita, show that many people in the country still report transport poverty [235].

These factors are the main cause of the small carbon emissions per capita regarding the urban transport.

8.2.2 Freight transport

More than 95% of goods in Colombia are transported by lorries [231]. Some heavy fuels, such as oil and coal (both for exporting), have their own transportation infrastructure: oil pipelines and railways. Elevated costs resulting from a poor logistic system have been reported, however, a number of projects have been proposed in order to improve the sector's efficiency, reduce the size of the fleet and withdraw ageing vehicles from service [230].

In terms of energy use, passenger transport is the segment that consumes the most energy, accounting for approximately 72% of all the energy demanded by road transportation in 2018 [133]. The great majority of light-duty vehicles (LDV) are petrol-powered, whereas heavy-duty vehicles (HDV), including buses and lorries, run on diesel. The share of other energy carriers such as natural gas and electricity is small, representing only by 4.3% of the final energy use in 2018. Diesel is mixed with biodiesel (8–10%) and petrol is blended with ethanol (8–10%) [134].

8.3 Methodology

This section presents a description of the methodology used in order to assess the effects of EV and RES penetration into the Colombian energy system. The main data sources, assumptions and defined scenarios are outlined.

8.3.1 Baseline scenario

As discussed in Chapter 6, the analysis of the transport sector electrification requires the study of longer-term scenarios considering the country's poor infrastructure and high capital costs required to shift to this technology. In this case, and following the same approach used in the previous chapters, a baseline scenario and three different alternatives have been built towards 2040. The baseline or business as usual (BaU) scenario includes a series of inputs where no changes in policies, economics and technology will be considered in the country future roadmap. Therefore, it is expected that supply and demand energy trends remain unaffected in the future energy system. This scenario is used for comparing the effectiveness of the alternatives proposed in Section 8.3.3 regarding the GHG emissions, RES penetration and total system costs.

This scenario is based on the outlook developed by the Colombian government in its national energy plan towards 2050 [236]. From the demand side, the total electricity demand and the loads used for heating and cooling can be seen in Table 8.1. The load for space heating and hot water was modelled assuming that by 2040 the residential, commercial and public service segments will be electrified, and thus replacing the traditional use of biomass and natural gas for this purpose. The cooling energy demand is assessed considering the same share of annual electricity consumption used by the reference scenario (see Section 5.4) [176], and a constant load throughout the year is assumed. The electricity exchange with neighbouring countries is considered to keep the same trend as in previous years.

Table 8.1. Electricity load in BaU 2040 [TWh]

Load	**Consumption**
Electric cooling	11.28
Electric heating (Individual)	5.29
Net export	1.59
Total Demand	127.8

The fuel consumption by industries and other sectors (agriculture, mining, building and non-specified areas) for the scenario are shown in Table 8.2.

Table 8.2. Industry and various fuel demand [TWh].

Fuel	**Industry**	**Various**
Coal	26.59	5.06
Oil products	17.6	36.79
Natural gas	67.34	64.98
Biomass and waste	19.3	28.23

The estimated fuel and electricity consumption by the transport sector in the scenario is listed in Table 8.3.

Table 8.3. Transport sector fuel demand [TWh].

Fuel	Demand
JP (Jet Fuel)	27.39
Diesel	97.6
of which Biodiesel	5.14
Petrol	108.9
of which bioethanol	7.57
Natural gas	9.51
Electricity	0.18

The BaU scenario is conservative regarding the inclusion of new technologies and fuel shifting. The fuel share continues to be constant and equivalent to that in the reference year, as illustrated in Table 8.4, throughout the scope of the analysis. Due to its high contribution to the net energy demand and transport-related CO_2 emissions, the road segment is the focus of this chapter, and thus, is modelled in greater detail. This segment is divided according to the type of service (passengers and freight) and scale (urban and interurban).

Table 8.4. Fuel share in the BaU 2040 road segment.

Service type	Scale	Type of vehicles	Fuel share		
			Diesel	Petrol	Natural gas
Passenger	Urban	Light-duty vehicles (LDV)	18%	58%	25%
		Motorcycles	0%	100%	0%
		Taxis	0%	60%	40%
		BRT and conventional buses	80%	10%	10%
	Interurban	Buses	100%	0%	0%
Freight	Urban	Light-duty lorries	39%	55%	6%
		Medium-duty lorries	39%	55%	6%
		Heavy-duty lorries	100%	0%	0%
	Interurban	Light-duty lorries	89%	10%	1%
		Medium-duty lorries	89%	10%	1%
		Heavy-duty lorries	100%	0%	0%

Regarding the electricity production, this scenario considers that past trends in increasing conventional power generation and hydropower capacity remain the same. The variable RES capacity used in this case is equal to the current installed capacity in the power system (see Section 4.3) [185].

8.3.2 Electric vehicles penetration

The number of EV in the Colombian fleet in 2019 was used in order to estimate the amount of electricity consumed by this sector in future scenarios. The Battery electric vehicle (BEV) and Plug-in hybrid electric vehicle (PHEV) technical specifications and total sales for the period 2014 - 2019 are show in tables 8.5, 8.6 and 8.7. These data were collected from statistics from the National Unique Transit Registry (RUNT) [237] and the Sustainable Mobility National Association (ANDEMOS) [238]. The main vehicles operating parameters include the battery storage capacity (usually in kWh) and the estimated driving range at full capacity.

Table 8.5. BEV sales and technical specifications (Motorcycles not included).

Vehicle model	2014	2015	2016	2017	2018	2019	Total 2019	Capacity [kWh]	Range [km]
Mitsubishi iMiev	1	3	4	4	3	203	218	16	160
Renault Kangoo	0	0	16	9	0	0	25	33	200
BYD E5	0	0	0	1	0	0	1	60	300
TAYLOR DUNN ET-3000	0	0	1	0	0	0	1	12	48.3
Renault Zoe	0	0	0	0	17	5	22	22	210
Nissan Leaf	1	4	10	0	21	119	155	24	199
Bmw i3	2	26	13	54	122	278	495	22	190
Rariro GMDL05	0	2	3	2	0	0	7	7.2	100
KIA Soul EV SX	0	1	0	10	3	1	15	30.5	150
Renault Twizy	11	149	154	44	203	318	879	6.1	90
Tesla Model S	0	0	0	0	0	6	6	60	390
BYD E6	2	6	0	19	22	86	135	61	300
Total BEV Sales	**2031**	**2206**	**2217**	**2160**	**2409**	**3035**	**1959**		

Table 8.6. Electric motorcycles sales and technical specifications.

Vehicle model	2016	2017	2018	2019	Total 2019	Capacity [kWh]	Range [km]
Starker Avanti	23	89	1021	2049	3182	2.30	80
NIU	0	0	2	78	80	2.00	100
AIMA Kuwan	6	1	1	56	64	1.89	75
Electrika	0	0	77	15	92	2.00	60
Energy motion emax	82	54	20	41	197	2.16	50
Dayun	72	0	9	0	81	0.60	48.2
Green Thor	13	0	0	0	13	0.78	55
Luyuan MB5	8	1	0	0	9	1.44	60
Sunra Hawk	5	0	5	4	14	1.44	65
ELEKTROMOTORES M3	0	5	20	10	35	2.50	70
Total motorcycles sales	**2225**	**2167**	**3173**	**4272**	**3767**		

Table 8.7. PHEV sales and technical specifications.

Vehicle model	2014	2015	2016	2017	2018	2019	Total 2019	Capacity [kWh]	Range [km]
Volvo B215RH	0	0	50	3	27	43	123	20.1	51
BMW X5 xDrive40e	0	0	3	27	0	0	30	9.0	31
MINI Cooper S E ALL4	0	0	0	1	52	92	145	10.0	41.8
Mercedes-Benz GLC 300	0	0	0	0	11	86	97	13.5	46.7
Porsche Cayenne	6	0	3	2	10	13	34	9.4	32
Mitsubishi outlander	0	3	19	7	8	10	47	9.8	52.8
Audi A3 e-tron	0	0	0	0	0	17	17	8.8	50
Bmw330e	0	0	0	9	163	179	351	7.6	25
Volvo XC90 PHEV	0	0	0	3	0	0	3	9.0	40
Total PHEV Sales	**2020**	**2018**	**2091**	**2069**	**2289**	**2459**	**847**		

Following the same approach developed by Bellocchi et al. in [48], electric vehicles were categorized according to their battery storage capacity: small (capacities under 18 kWh), medium (18–28 kWh) and large vehicles (greater than 28 kWh). Further, PHEV were considered as medium capacity vehicles. This categorisation is necessary for the system modelling because each of the EV group will replace its equivalent conventional vehicle category in the future scenarios. The annual electricity consumption of each category is estimated using the equation (8.1), and this includes the battery storage capacity and driving range weighted averages, the average commuting distance (36.5 km/day as the mean value between conventional modes of transport [231]) and an EV average charging efficiency of 90% [238]. The estimated total EV annual electricity consumption was approximately 8.25 GWh, as shown in Table 8.8. This amount of energy is negligible considering the total energy demanded by the same road passenger segment in 2018 (43.67 TWh) [133].

$$EV\ annual\ consumption_j = \frac{\frac{\bar{X}_{SC}}{\bar{X}_{DR}} d_c n_{EV}}{\eta_{C,EV}} \tag{8.1}$$

where, $\bar{X}_{SC}$ is the weighted average for the battery capacity of the *j* category,

$\bar{X}_{DR}$ is the driving range weighted average of the *j* category,

d_c is the annual average commuting distance of the *j* category,

n_{EV} is the number of EV of the *j* category,

$\eta_{C,EV}$ is the average EV charging efficiency.

Table 8.8. EV annual electricity consumption in 2019.

Type	Category	Number of vehicles	Share	$\bar{X}_{SC}$ [kWh]	$\bar{X}_{DR}$ [km]	Annual consumption [GWh]
BEV	Small	1105	56.4%	8.07	103.84	1.27
	Medium	672	34.3%	22.46	192.73	1.16
	Large	182	9.3%	54.60	276.87	0.53
	Motorcycles	3767	-	2.23	77.32	1.61
Total BEV		**5726**				**4.57**
PHEV		847	-	10.77	36.73	3.68
Total EV		**6573**				**8.25**

In order to estimate the impact of EV penetration, the annual transport energy demand in the baseline scenario (Table 8.3) was further disaggregated to identify the effect of passenger transportation in the entire sector. Petrol, diesel and natural gas vehicles were divided into different categories according to their vehicle type (Table 8.9), and the annual fuel consumption was estimated based on the average fuel economy value using the equation (8.2). The UPME estimates that in 2040 the total number of vehicles in the country will be of approximately 27 million, of which about 24.5 million will be in the LDV category [236]. The rest of the fleet is in the HDV category, and it is still not clear yet if electrification is a real option for these vehicles [53]. The average annual travelled distance was reported as 10,120 km/year for petrol-fuelled vehicles and 16,500 km/year for diesel and natural gas-fuelled vehicles [48].

$$Annual\ fuel\ consumption = n_{CV} FE d_T HV \tag{8.2}$$

where, n_{CV} is the total number of vehicles by type,

FE is the fuel economy (L/100 km),

d_T is the average distance travelled per year,

HV is the fuel heating value.

In order to define the different penetration scenarios for the simulations, the number of vehicles in each category (petrol, diesel and natural gas) was estimated assuming a linear decrease along with a progressive replacement by EV until a complete substitution is achieved while the total number of vehicles in 2040 remains the same. For instance, Tables 8.10 and 8.11 illustrate the total energy consumption by the road segment when a replacement of 50% of the conventional fleet by EV is achieved. A complete list of the fuel and electricity consumption in all the EV penetration scenarios can be seen in Appendix D.

Table 8.9. Conventional vehicles annual fuel consumption in 2040.

Category	**Share**	n_{CV} **[thousand]**	**Fuel economy [L/100 km]**	**Fuel consumption [TWh/year]**
Petrol				
Motorcycles	57.6%	15547.9	3.31	48.42
Small (sedan/wagon)	13.1%	3530.9	5.1	16.94
Taxis	1.0%	261.2	5.1	1.25
Medium (Pick up, SUV, Vans)	7.8%	2117.5	6.0	11.95
Large (Shuttles and buses)	0.1%	38.0	7.7	0.28
Total		**21495.5**		**78.85**
Diesel				
Small (sedan/wagon)	3.8%	1034.9	4.2	7.09
Medium (Pick up, SUV, Vans)	2.3%	620.6	4.9	4.96
Large (Shuttles and buses)	1.1%	304.1	6.4	3.17
Total		**1959.7**		**15.22**
Natural Gas			**Fuel economy [m^3/km]**	
Small (sedan/wagon)	0.0%	-	-	0.00
Taxis	0.6%	174.1	0.045	1.29
Medium (Pick up, SUV, Vans)	3.4%	912.7	0.050	7.45
Large (Shuttles and buses)	0.1%	38.0	0.120	0.74
Total		**1124.9**		**9.48**

Following a similar approach as the one outlined in Chapter 7, different penetration levels of EV and RES were simulated using the baseline scenario in order to assess their impact on CEEP, CO_2 emissions and costs. For each EV level, the Smart Charging Strategy defined in [43] was applied, and the EV transport demand profile for a week can be observed in Figure 8.2. Using this strategy, the charging process is aimed at avoiding the grid overloading by charging the EV during the low demand hours while matching the drivers' load requirements.

In the case of PHEV, these types of vehicles are assumed to work in full electric mode for short journeys, such as daily commuting. However, for longer trips, such as in the case of holidays, the mixed-mode fuel demand was estimated using an average consumption of 1.9 L/100 km and a journey distance of 1000 km, which is the mean distance travelled by Colombians on vacations [231].

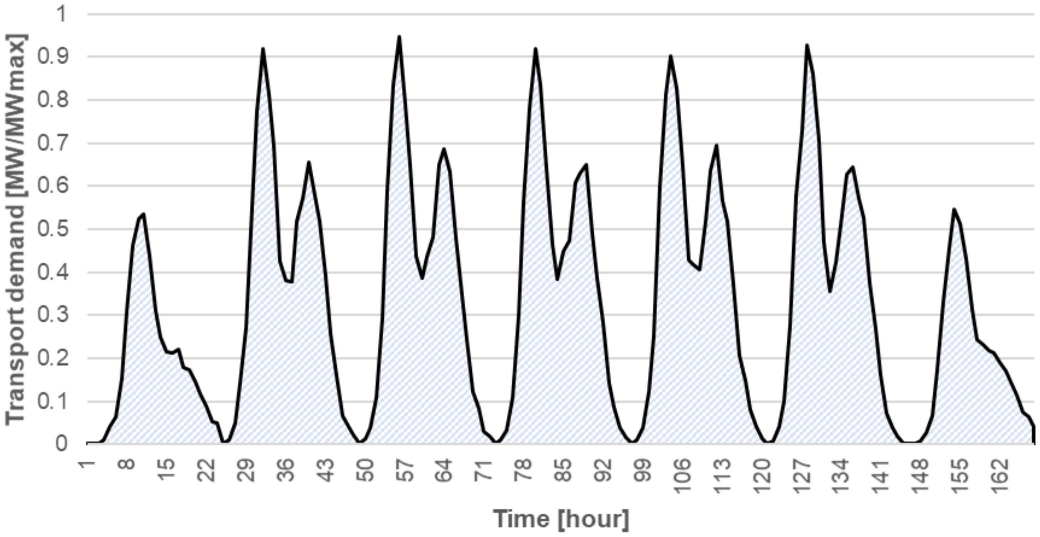

Figure 8.2. Weekly EV transport demand with the Smart Charge Strategy (Sunday to Saturday) [43]**.**

Table 8.10. Conventional vehicles annual fuel consumption with 50% EV penetration.

Category	Share	n_{CV} [thousand]	Fuel economy [L/100 km]	Fuel consumption [TWh/year]
Petrol				
Motorcycles	57.6%	7773.9	3.3	24.21
Small (sedan/wagon)	13.1%	1765.5	5.1	8.47
Taxis	1.0%	130.6	5.1	0.63
Medium (Pick up, SUV, Vans)	7.8%	1058.7	6.0	5.98
Large (Shuttles and buses)	0.1%	19.0	7.7	0.14
Total		**10747.7**		**39.43**
Diesel				
Small (sedan/wagon)	3.8%	517.5	4.2	3.54
Medium (Pick up, SUV, Vans)	2.3%	310.3	4.9	2.48
Large (Shuttles and buses)	1.1%	152.1	6.4	1.59
Total		**979.8**		**7.61**
Natural Gas			**Fuel economy [m^3/km]**	
Small (sedan/wagon)	0.0%	-	-	0.00
Taxis	0.6%	87.1	0.045	0.65
Medium (Pick up, SUV, Vans)	3.4%	456.4	0.050	3.72
Large (Shuttles and buses)	0.1%	19.0	0.120	0.37
Total		**562.4**		**4.74**

Table 8.11. EV annual electricity consumption with 50% penetration.

Category	**Share**	n_{CV} **[thousand]**	**Battery capacity [kWh]**	**Range [km]**	**Electricity consumption [TWh/year]**	**Battery storage [GWh]**
Motorcycles	63.3%	7773.9	2.23	77.32	4.11	17.31
Small	20.3%	2500.6	8.07	103.84	3.56	20.17
Medium	14.9%	1825.4	22.46	192.73	3.90	41.00
Large	1.5%	190.1	54.60	276.87	0.69	10.38
Total		**12290**			**12.26**	**88.86**

8.3.3 Alternative scenarios (optimal configurations)

After analysing the technical impacts of different shares of EV and RES in the energy system, four alternative scenarios were proposed for the year 2040 (see Table 8.12). The inputs for these alternatives are the result of the techno-economic optimisation for each scenario. They were developed assuming a significant growth in the RES capacity, energy storage and EV penetration, based on the characteristics of the Colombian system, the inputs from the previous Chapters and recent studies on smart energy systems [43], [48], [239]. These scenarios were defined as follows:

1. COL 2040: This scenario is built from the results of a techno-economic optimisation on the baseline scenario, including large penetration of RES and energy storage in the power sector. In order to obtain the inputs for the simulation, the MOEA Eplan app was used as the optimisation tool and the same methodology described in Section 7.3.4 was applied. The inputs can be seen in Table 8.12 and further details are presented in Section 8.4.2.

2. COL 50EV: This scenario is built from the optimisation results on the baseline scenario assuming that the EV replace the passenger segment fleet by 50%. The smart charge option is selected, assuming that the EV are charged during low demand hours in order to avoid grid overloading and reduce the energy curtailment.

3. COL 100EV: The inputs of this alternative are also developed from the techno-economic optimisation on the baseline scenario. However, in this case the EV are assumed to replace completely the conventional fleet of the passenger segment.

4. COL2040 Ideal: This scenario is derived from the COL 100EV alternative, and similar to the RES combination alternative defined in Section 6.2, it includes further development in the bioenergy sector of the country [240]. It targets a combined deployment of biomethane production, biomass-powered generation and increasing participation of biofuels in the HDV segment of the transport sector. The list of actions set for this scenario is presented in more detail in Table 8.13.

Table 8.12. Input data for baseline and alternative scenarios towards 2040.

	BaU 2040	**COL 2040**	**COL 50EV**	**COL 100EV**	**COL 2040 Ideal**
Electricity Demand					
Total electricity demand (TWh/year)	127.8	127.8	140.06	152.31	152.31
EV demand (TWh/year)	0.18	0.18	12.26	24.51	24.51
Electricity Supply					
Hydropower (MW)	18900	18900	18900	18900	18900
Thermal power plants (MW)	7821	7821	7821	7821	7821
Biomass (MW)	128	128	128	128	800
Wind power (MW)	24.8	9018	13407	13897	12855
Solar PV power (MW)	20	12772	14517	15866	15347
Electricity storage					
PHES pump power (MW)	0	5660	6193	5950	3946
PHES turbine power (MW)	0	2740	4690	6300	4082
Storage capacity (GWh)	0	70	73	73.5	52.6
Transport demand					
Biodiesel (TWh/year)	5.14	5.14	4.53	3.92	17.5
Bioethanol (TWh/year)	7.57	7.57	4.41	1.26	7.52
Fossil fuels (TWh/year)	243.4	243.4	195.39	147.37	127.53
Industry demand (TWh/year)	130.83	130.83	130.83	130.83	120.17
Other sectors demand (TWh/year)	135.06	135.06	135.06	135.06	135.06
Cross-border transmission capacity (MW)	571	1000	1000	1000	3000

Table 8.13. COL 2040 Ideal 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 power generation to 10%. Wind power capacity: 12.855 GW. Solar PV capacity: 15.347 GW.
Transport	Biodiesel (palm oil-based): increase diesel-biodiesel blend to B20 by 2040. Bioethanol (sugar cane-based): increase petrol-bioethanol blend to E20 by 2040.

8.3.4 Cost structure

As described in Chapter 7, the cost data used for the economic analysis are based on the future projection by the IRENA [51], the EnergyPLAN database [183] and ETRI from the European Commission [214]. Road vehicle costs were estimated considering a weighted average price for each category and technology, as shown in Table 8.14. Medium and large EV prices were evaluated assuming that the total number of vehicles consisted of 80% EV and 20% PHEV. The vehicles life cycle associated cost are not included, therefore, only the purchase and charging infrastructure costs are considered in the analysis. The interest rate was set to 10% (average rate in the Colombian private vehicle market) and the investment period to 5 years for both conventional and EV [238]. Based on the UK Department of Energy and Climate Change (DEEC) projections for 2040 [241], a CO_2 price of 150 €/tCO_{2e} was defined into the model.

Table 8.14. Forecasted EV charging infrastructure, conventional and electric vehicles prices in 2040.

Category	Average cost [€]
Electric	
Motorcycles	3,000
Small (sedan/wagon)	18,100
Medium (Pick up, SUV, Vans)	34,800
Large (Shuttles and buses)	155,000
Workplace EV charger	3,433
Public level 2 charger	4,814
DC fast charger	72,405
Conventional	
Motorcycles	6,000
Small (sedan/wagon)	20,600
Medium (Pick up, SUV, Vans)	43,100
Large (Shuttles and buses)	177,200

8.4 Results and discussions

This section presents the results obtained after the analysis of the different scenarios defined in Section 8.3. Following the same approach described in the previous chapters, these scenarios were compared in terms of annual CO_2 emissions, energy curtailments (CEEP) and total annual costs.

8.4.1 RES and EV positive interactions

Figure 8.3 illustrates the effects of increasing the intermittent RES capacity and EV penetration over the CO_2 emissions of the energy system. As expected, for scenarios with increasing shares of EV penetration, the emissions of the system decrease. The level of CO_2 reductions is even higher when combined with rising shares of intermittent RES generation. However, in the absence of ES and cross-border interconnections capacity, significant levels of energy surplus (CEEP) are produced (see Figure 8.4). Similar to the behaviour shown in Chapters 6 and 7, energy curtailed levels grow almost linearly with increasing shares of RES capacity, while as shown in Figure 8.3, CO_2 emissions decrease steeply when initial levels of variable RES are added to the system and then evidences lower rates of reduction with higher RES shares. Therefore, the lack of flexibility options, such as ES and international electricity exchanges, lead the emissions reduction potential to quickly achieve its saturation level. This behaviour has been reported in similar studies [43], [48], and this results in increasing levels of energy curtailments rather than fossil fuel displacement and emissions reduction.

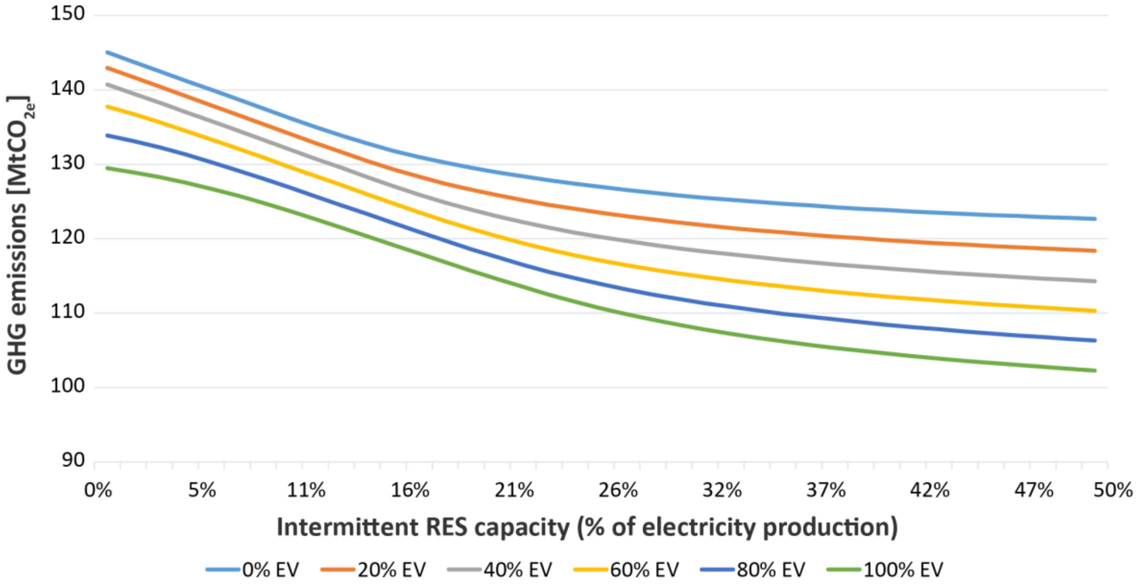

Figure 8.3. CO$_2$ emissions for increasing intermittent RES capacity and EV penetration.

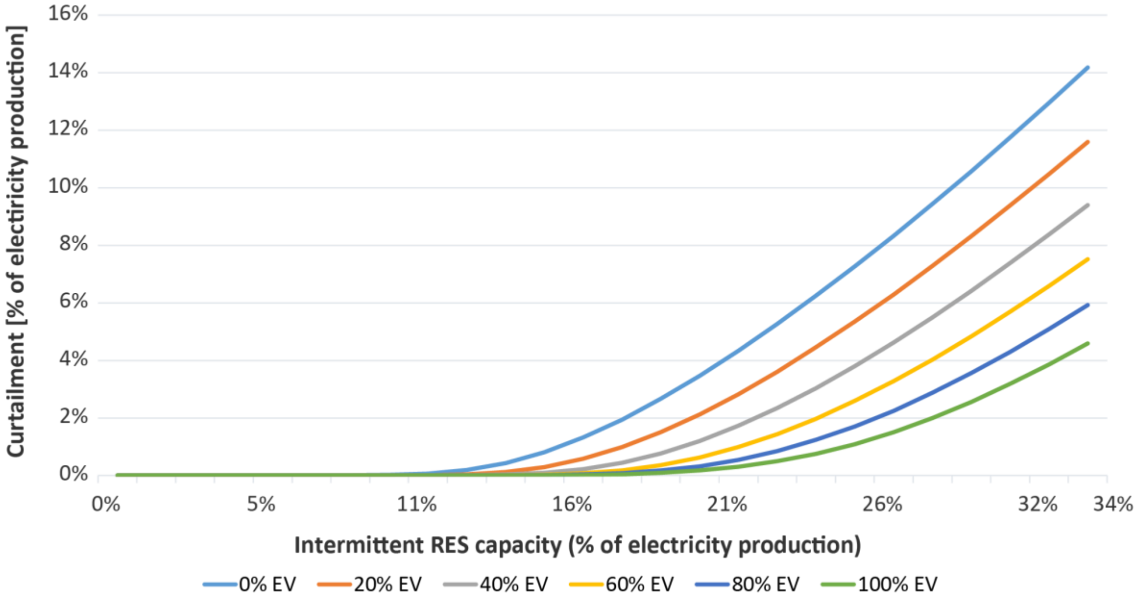

Figure 8.4. Energy curtailment (CEEP) for increasing intermittent RES capacity and EV penetration.

Table 8.15 shows the variation in CO$_2$ emissions, CEEP and the maximum technical RES levels compared to the baseline scenario. Considering the charging strategy used in this study (smart charge), the GHG emissions could be reduced by approximately 25.25% without a significant change in the amount of electricity curtailed (2.6% of the total production). Another advantage of increasing levels of EV is that the combined (wind and solar PV) technical feasible penetration could increase from about 17.1% to 28.9%

of the total electricity production. This represents the installed wind and solar capacities of 7.7 GW and 11.2 GW, respectively. It should be noted that these scenarios do not include either the large-scale energy storage or international electricity exchanges, this aspect is included in the alternative scenarios discussed in detail in Section 8.4.2.

Table 8.15. Change of CO_2 emissions, CEEP and RES share at maximum technical RES levels.

EV penetration	**CO_2 emissions change**	**CEEP (% of total production)**	**Variable RES share**
0%	-10.21%	1.9%	17.1%
20%	-13.24%	2.1%	19.7%
40%	-16.24%	2.3%	22.3%
60%	-19.28%	2.6%	24.9%
80%	-22.43%	2.9%	27.6%
100%	-25.25%	2.6%	28.9%

For the economic analysis, and following a similar structured as presented in Chapter 7, the costs were disaggregated in fuel, CO_2, investment and other (fixed and variable O&M) costs as shown in Figure 8.5. The annual investment costs account for the largest share of the total annual system cost in all cases, and this is mainly because they include the transport fleet and the new power generation units’ costs. When the EV penetration level into the system increases from 0 to 100%, the total investment and fuel costs decrease by 19.8% and 27.4%, respectively, compared to the baseline scenario. This is mainly because by 2040 the EV purchase price is estimated to be 20% cheaper than conventional fossil-fuelled vehicles [239]. When EV replace entirely the LDV segment and the RES share is set to its maximum feasible levels, a reduction of about 25% of the CO_2 associated costs are avoided.

It should be noted that a large EV adoption contributes to the emission reductions of the system, but it is also reported [242], [243] that this strategy could help in the improvement of the air quality, which is a relevant problem in the largest cities in the country. This study only focuses on the techno-economic side, however, further analysis should be dedicated to analyse the wider socio-economic perspective.

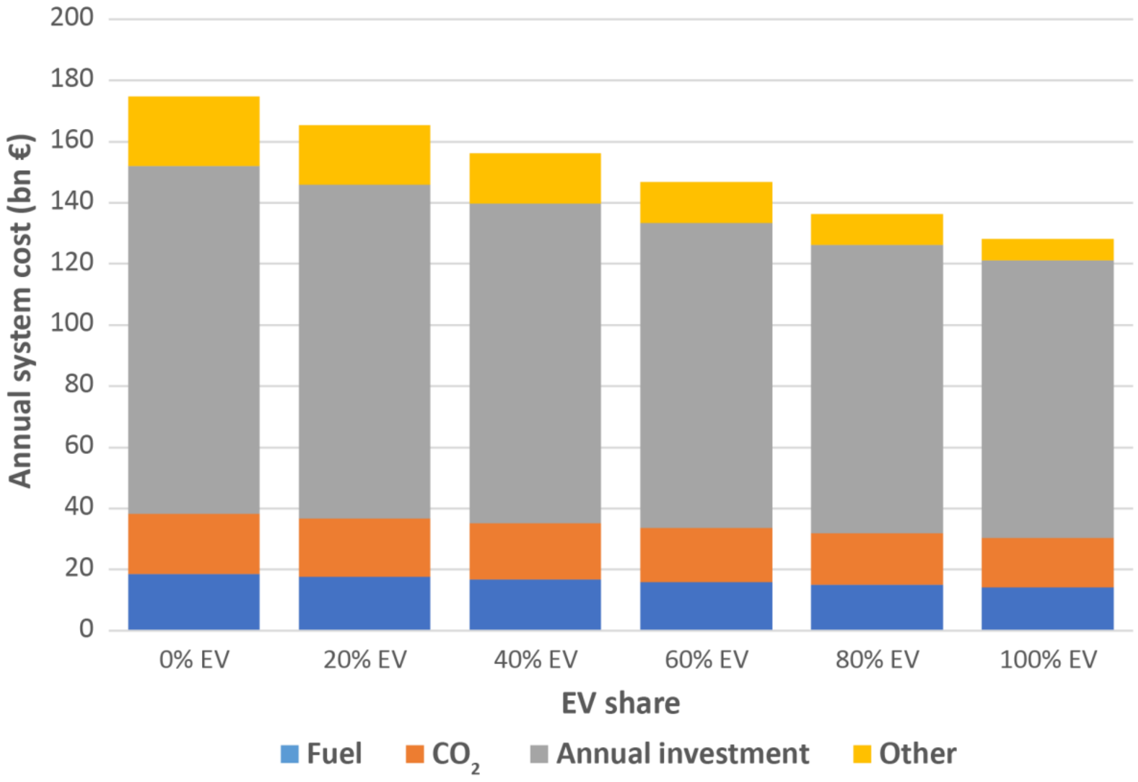

Figure 8.5. Cost variation for increasing EV shares at maximum technical RES levels.

8.4.2 Scenario results

In this section, the outputs of each of the scenarios described previously in Section 8.3 are discussed. All the scenarios were compared using different indicators, such as the annual GHG emissions, fuel consumption and RES share. Each of the alternative scenarios contributes to a reduction in both the total energy demand of the system and the CO_2 emissions, and this is mainly because of the high shares of variable RES and the flexibility measures proposed. The resulting Pareto fronts for the techno-economic optimisation performed on each alternative are shown in the Appendix E. Following the same approach discussed in Section 7.4.4, an optimal reference configuration was selected for each alternative. Figure 8.6 illustrates the differences in fuel consumption and CO_2 emissions for the baseline scenario and the different alternatives. The total system energy consumption in the baseline scenario is expected to be of approximately 730.6 TWh, and the annual GHG emissions could reach about 144.9 $MtCO_{2e.}$ These results agree with the estimations reported by the Colombian government on its report to the UNFCC [144], in which an increase in the energy-related emissions to approximately 150 $MtCO_{2e}$ by 2040 is expected.

The COL 2040 scenario, which is the only alternative that does not include transport electrification, evidences a reduction of approximately 6.4% and 16.3% in the fuel consumption and GHG emissions, respectively, compared to the baseline scenario. This is because of the changes made in the power sector, in which large shares of variable RES and electricity storage were added to the system.

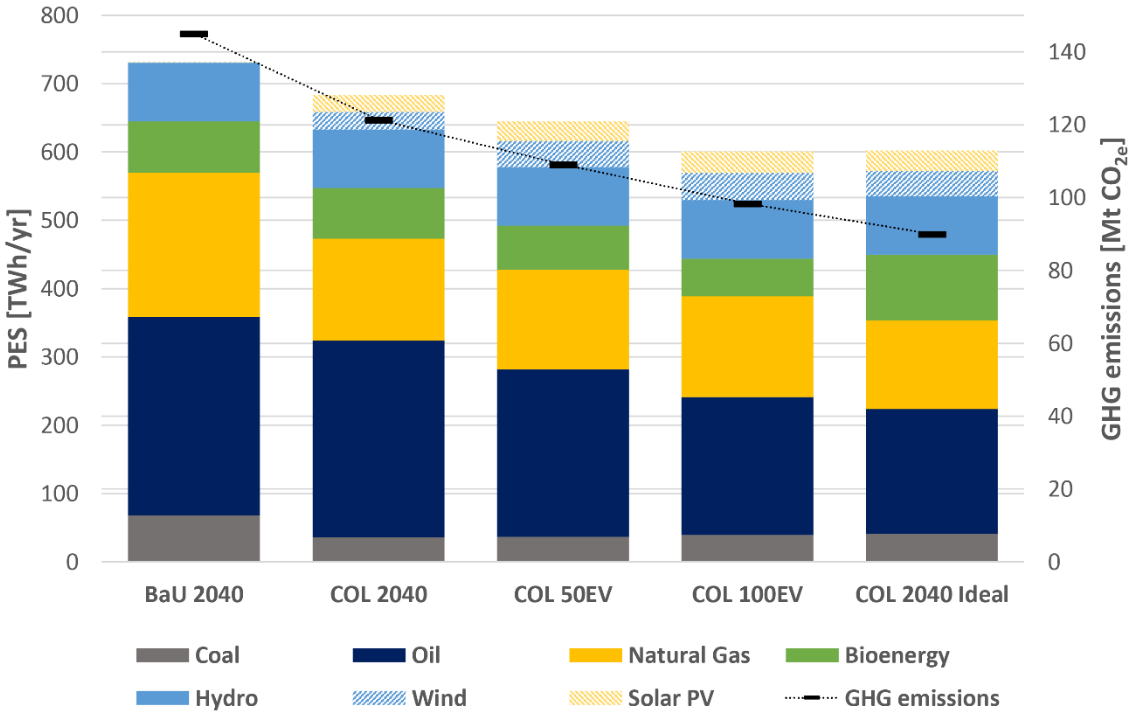

Figure 8.6. PES and CO_2 emissions for the 2040 scenarios.

The alternatives COL 50EV and COL 100EV represent two scenarios characterised by significant levels of transportation electrification over an optimised power sector, as described in Section 8.3.3. It is clear that the replacement of the LDV fleet by EV carries important benefits for the energy system. Both have lower fuel consumption and GHG emissions than the baseline scenario (644.6 TWh and 109.2 $MtCO_2e$, respectively for scenario COL 50EV; 600.58 TWh and 98.34 $MtCO_2e$ for scenario COL 100EV).

The COL 2040 Ideal alternative produces the lowest annual GHG emissions, and one of the lowest annual energy consumptions of all the alternatives, with approximately 90 $MtCO_2e$ and 602.4 TWh, respectively. Compared to the baseline scenario, the mitigation effect is about 38%, and this is a consequence of including strategies that tackle the emissions of the transportation sector, which is the main contributor to energy-related emissions. Extending the share of bioenergy in the system by increasing the biofuel blend regulations represents an effective option when combined with the electrification of the LDV segment. However, further levels of decarbonisation of the energy system could be achieved if policy makers define a roadmap that also includes energy efficiency for the other sectors and additional sustainable mobility alternatives.

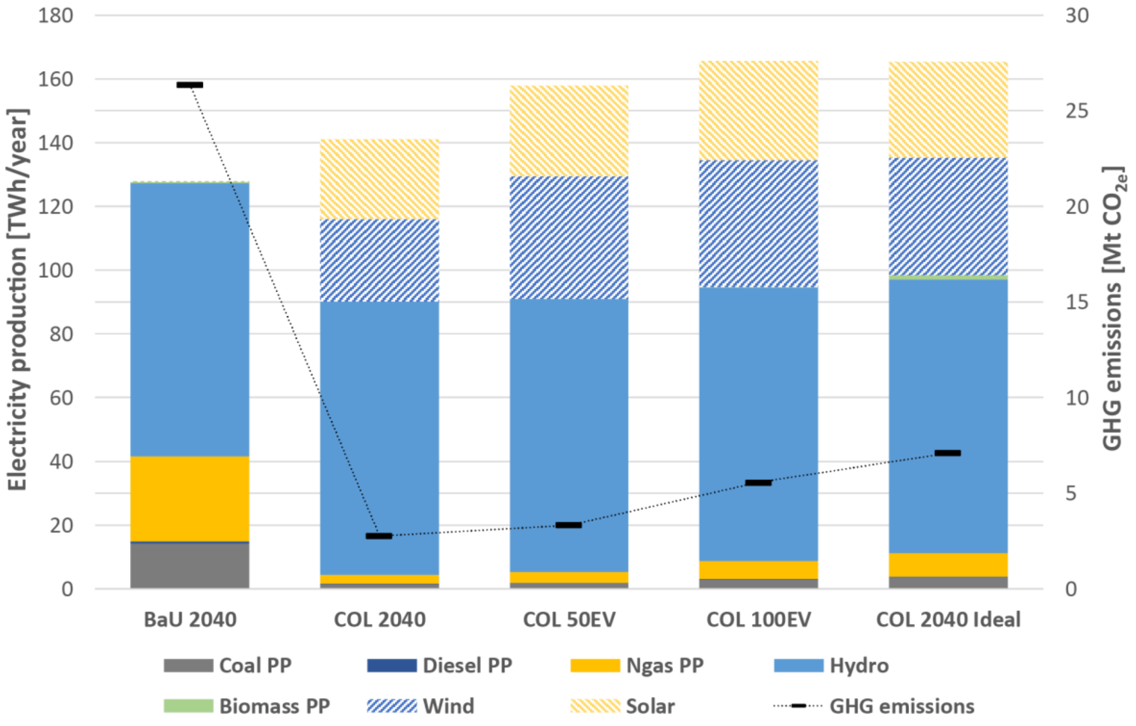

Figure 8.7. Electricity and CO_2 emissions for the 2040 scenarios.

Even though the total GHG emissions of the energy system are further reduced in the alternatives that include higher shares of EV in their system, the power sector experiences a different behaviour. As shown in Figure 8.7, higher levels of electrification of transportation require additional load that increases the total system demand. This effect causes a growth in the electricity generated by thermal plants that results in higher emissions of the sector. In the COL 2040 alternative approximately 93.2% of the total electricity is produced by RES and the annual GHG production is about 7.1 $MtCO_2e$. This represents an emission reduction of 73% compared to the baseline scenario.

Figure 8.8 shows the hourly electricity supply and demand for two typical working days and a weekend day. The total demand includes the EV load and the other sectors demand. Similar to the system behaviour shown in Chapter 7, wind and solar PV substitute most of the fossil-fuel based electricity generation. ES plays an important role in balancing the system during low variable RES generation hours, and this could assist in the reduction of sharper thermal power plants ramps. Further, additional cross-border interconnection capacity allows a better integration of variable RES by exporting the electricity surplus and reducing the total amount of energy curtailed.

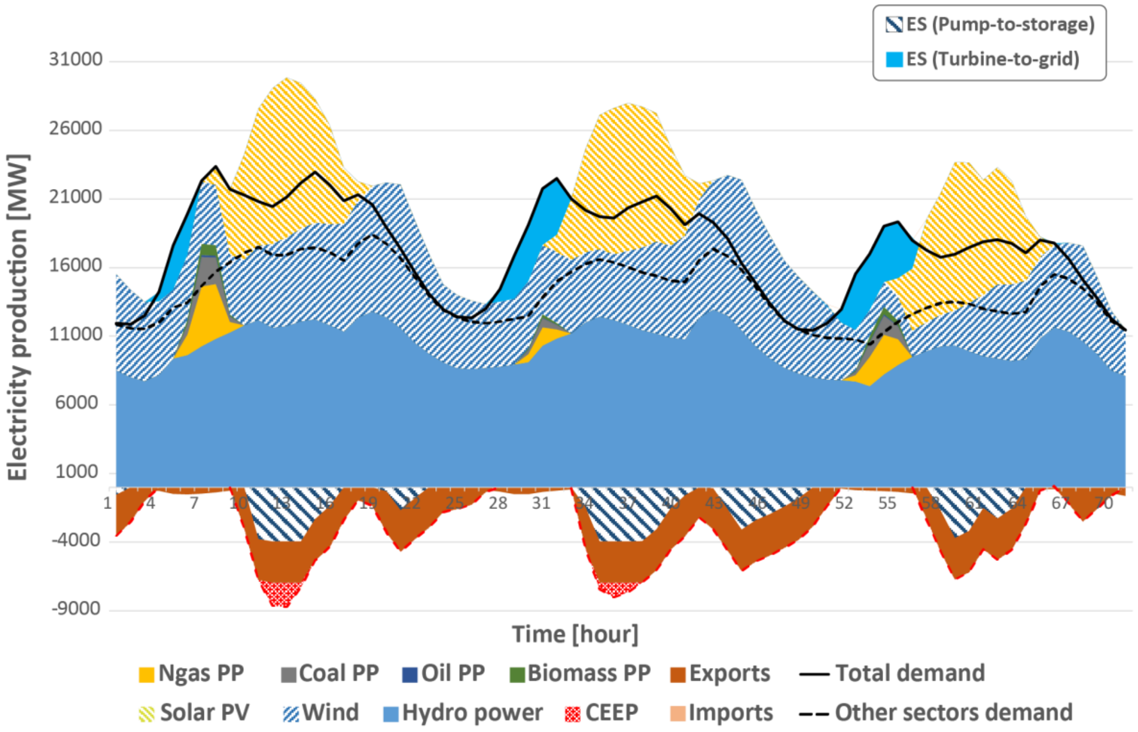

Figure 8.8. Hourly distribution of supply and demand for scenario COL 2040 Ideal.

It should be noted that the electrification of the LDV fleet shifts the total demand curve and peak demand times. This aspect is highly dependent on the charging strategy used, and in the case of Colombia, EV regulations should be focused on taking advantage of the great solar resources in order to charge the vehicles during daytime and reduce the amount of electricity curtailed.

8.5 Conclusions

The aim of this chapter was to evaluate the techno-economic effects of different levels of transport electrification into an energy system with increasing shares of renewable energy. A smart charging strategy was used in order to estimate the demand requirements of EV and to estimate the total system costs and GHG emissions.

In the best-case alternative (COL 2040 ideal), GHG emissions can be reduced by approximately 38% compared to the baseline scenario. This scenario evidences the importance of a more integrated alternative that includes all the different sectors of the energy system. The total annual system cost can also be reduced with the electrification of the transport sector. In particular, when the EV share in the LDV segment replaces completely the conventional fleet, the total investment and fuel costs decrease by 19.8% and 27.4%, respectively.

Overall, the integration of large shares of variable RES requires the shifting to a smarter energy system that includes the electrification of different sectors (such as heat and transportation), further participation of the bioenergy segment, suitable electricity storage systems and expansion of the international energy exchange capacity.

Finally, in the next chapter a summary of the key findings and contributions of this research will be discussed.

Chapter 9 Conclusions and future work

Shifting towards a more secure, affordable and sustainable energy systems represents one of the great challenges of our generation, and therefore, a comprehensive analysis of the impacts of integrating intermittent sources of energy generation into the current system is required.

This chapter provides an overview of the key findings, contributions and recommendations of this research. Section 9.1 summarises the key findings of this research and how the aim and the three research questions, described in Chapter one, were addressed. Section 9.2 highlights the originality of this study and its contributions to the field. Section 9.3 identifies the methodological limitations and areas for further research, and finally, Section 9.4 provides the concluding remarks and policy recommendations.

9.1 Summary of the research findings and contributions

This research contributes to the field of renewable energy integration into energy systems, and its geographical scope was on the Colombian energy system. The overall aim was to assess the integration of variable renewable technologies and flexibility options into national energy systems, considering scenarios that could allow a successful transition towards a low-carbon and more efficient system. Based on the literature reviewed and the research gaps identified, three research question were formulated in order to achieve the research aim.

The *first research question (RQ1)* addressed the technical impacts of increasing the variable renewable energy shares into national energy systems dominated by elevated hydro energy production. In order to answer this and the other two research questions, an energy system modelling tool that represented the Colombian system was required. The assessment of different tools reported in the literature and the selection criteria were explained in detail in Chapters 3 and 5. EnergyPLAN was the modelling tool selected for building the Colombian energy system model and it addresses all three of the research questions. This tool has proved its suitability for energy system analysis because it includes all energy sectors, considers a large set of technologies and allows the representation of high temporal resolution power systems. This latter is a very important aspect when analysing the integration of high shares of intermittent renewable sources in future energy system scenarios.

In Chapter 5, the methodology for building the Colombian energy system model was described. The model was validated considering 2014 as the reference year and then five different scenarios towards the year 2030 were built and simulated. In Chapter 6, the results and analysis of the scenarios are presented. These results 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 power sector. Its high flexibility represents an advantage for the integration of intermittent sources of generation. The maximum technical penetration levels in these scenarios for wind and solar power were estimated to be of approximately 22% and 11%, respectively. Higher levels of penetration could result in over-generation that might limit the feasibility of the system. In the power sector, the results from the best-case scenario showed that an emission intensity of 70.44 gCO_{2e}/kWh could be achieved by 2030 if the suggested levels of wind, solar and bioenergy described in Chapter 6 are implemented. The general results presented in the chapter agree with those from earlier studies generated for Colombia [131], [174], [197] and other countries with similar electricity mix [19], [184].

In the presence of weather anomalies, such as ENSO, the power system could be less vulnerable to power outages because of the variable sources of generation (wind and solar). The results from the sensitivity analysis showed that these sources could compensate the reduction of hydro generation during dry years, and therefore, contribute to the mitigation of negative technical and environmental impacts caused by additional thermal power production.

The *second research question (RQ2)* is related to the techno-economic benefits of integrating large-scale energy storage and cross-border interconnections into power systems with increasing levels of intermittent renewable energy penetration. In order to assess the effects of these two flexibility options into the system, this part of the study focussed on the power sector only. EnergyPLAN is able to generate hourly outputs for a complete year, and this represents a significant advantage compared to other traditional long-term energy planning tools. This feature allows the modeller to analyse more precisely the likely implications of load demand seasonal patterns and the impacts of electricity storage and international exchanges.

The economic assessment is an important part of every renewable integration analysis, and therefore, it is included in this part of the research. Due to the topography of the country and the characteristics of the power system infrastructure, PHES was found to be the most cost-effective storage alternative between the alternatives evaluated. Further, the PHES capital cost could be further reduced if the current dam reservoirs of large-scale hydro power plants are adapted to be part of the storage system. The CO_2 price evidenced to have a significant impact on the economic analysis, and if the CO_2 price is set below 26 €/tCO_{2e} all the alternatives result in higher total annual costs than the baseline scenario. This highlights the importance that the policies defined by national governments have in supporting the future feasibility of these technologies.

The results discussed in Chapter 7 evidenced that energy storage and international interconnections have a significant role in enabling larger levels of intermittent RES into the power system. In the case of Colombia, optimal configurations could allow a generation from renewable sources of approximately 96.8% of the total electricity production and reduce about 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, which is clearly below the target defined by the country during the COP21 by 2030. Further, a South American integrated electricity system, similar to the case of the European system, could provide additional benefits in terms of renewable integration and reduction of energy curtailments that could be used by a neighbouring country. The hydrological complementarities reported for these countries could be highly beneficial for achieving a more resilient power sector. In Colombia, this could also assist in overcoming the internal transmission constraints between the different sources of generation and allow a better exploitation of their energy potential.

The *third research question (RQ3)* considers the importance of transport electrification for the integration of higher shares of variable renewable penetration and the mitigation of GHG generation in national energy systems. This question is addressed in Chapter 8 by analysing longer-term scenarios (towards 2040) in the Colombian energy system. This is necessary because significant levels of electrification of the transport sector are not included in the government plans towards 2030, and this is mainly due to the lack of infrastructure and the high capital costs required to shift to these systems [176]. Further, transport systems in developing countries are characterised by obsolete technologies and elevated participation of two and three wheelers in the total fleet.

The impacts of the transport electrification in the Colombian system were assessed in two parts: firstly, different penetration levels of EV and RES were simulated and compared with conventional alternatives by evaluating their impact on CEEP, CO_2 emissions and costs; and secondly, based on the inputs of the previous chapters, alternatives scenarios were optimised for finding the trade-offs between GHG emissions and total annual costs. The results showed that a total replacement of the conventional LDV fleet by EV could allow higher variable RES penetration and significant savings in the total system costs by 2040. This is mainly because by 2040 the EV purchase price is estimated to be 20% cheaper than conventional fossil-fuelled vehicles [239]. Further, total electrification of the LDV segment and maximum feasible levels of variable RES shares could represent a reduction of about 25% in the CO_2 associated costs.

The best of the alternatives analysed (COL 2040 Ideal) achieved a reduction of approximately 38% of the annual GHG emissions compared to the baseline scenario, and this represents a generation of about 90 $MtCO_2e$ each year. This is clearly an effect of including strategies that tackle the emissions of the transportation sector, which is the main contributor to the total energy-related emissions. Extending the share of bioenergy in the system by increasing the biofuel blend regulations represents an effective option when combined with the electrification of the LDV. However, further levels of decarbonisation of the energy system could be achieved if policy makers define a roadmap that also includes energy efficiency for the other sectors and additional sustainable mobility alternatives.

9.2 Original contributions to knowledge

This research has contributed to the growing body of literature on renewable energy integration into national energy systems. The models and analysis are mainly focused on the Colombian energy system, but the outcomes are also relevant to systems in other countries with similar characteristics.

There has been little quantitative analysis on the integration of renewable energy in developing countries, and in the case of Colombia, a limited number of studies have been able to represent the entire energy system (including the heat, electricity, and transport sectors) in great detail. The existing studies reported in the literature use long time-step simulations (yearly simulations) models, and these models do not usually include the intermittency and variability of renewables such as wind and solar. Therefore, in this research a reference model of the Colombian energy system was developed and validated. This is a high temporal resolution model that includes all the major sectors of the energy segment and could be used for the building and analysis of future energy scenarios. Its high temporality allows the assessment of the behaviour of variable RES in the power system and their synergies with the other sectors. Further, maximum feasible penetration levels of wind and solar power into the Colombia electricity system were estimated by analysing some possible future scenarios. These results were published in the author’s paper titled “Large scale integration of renewable energy sources (RES) in the future Colombian energy system” [176].

The present study confirms previous findings and contributes additional evidence that suggests that large-scale energy storage and cross-border interconnections have an important role in enabling greater levels of wind and solar penetration into the electricity system. Further, they add flexibility to the system, reduce its carbon intensity and assist in the total fuel and costs savings. In particular, this research provides some suggested levels of energy storage, international transmission, wind and solar capacities that could bring significant techno-economic and environmental benefits to the Colombian energy system.

Building energy system models oriented to facilitate sustainable energy planning strategies and understand the technical challenges associated with the integration of renewable energy sources require detailed and large amount of data as inputs. As a result of this research, several datasets were produced and made freely available for the scientific community. The methodology for building these datasets is explained in the author’s paper titled “Renewable energy production and demand dataset for the energy system of Colombia” [177], and the data can be accessed in the Mendeley repository [244]. These datasets can be used by researchers and policymakers in order to analyse the technical challenges of renewable energy integration into electricity systems. In addition, the complementarity of the different renewable sources and their variability during periods of weather abnormalities, such as ENSO, can be further analysed.

This research will serve as a base for future studies of transport sector electrification in developing countries. This is the first work that simulates different levels of LDV electrification into the Colombian energy system and then analyses its effect on the variable RES penetration. Further, the results from the optimisation of future scenarios evidence the benefits of this strategy in terms of GHG emissions, annual costs and reduction of RES curtailments.

Finally, a MATLAB app, called *MOEA Eplan*, was developed in this study, and it can be accessed freely from the open access repository Zenodo in [220]. This app integrates the EnergyPLAN modelling tool with the Multi-objective evolutionary algorithm (MOEA) used by the MATLAB optimisation toolbox in order to provide a framework for energy scenario analysis and design. *MOEA Eplan* offers a user-friendly interface where the optimisation parameters can be set easily, and no previous knowledge of coding is required for its execution. In addition, energy planners and policymakers could benefit from the tool for generating multiple Pareto-optimal solutions. This will allow them to select from different scenarios depending on the specific constraints of each case and on the analysis of the trade-offs between their economic and environmental targets.

9.3 Limitations and future work

This research includes significant aspects that contribute to the field of renewable energy integration into national energy systems. However, developing energy models is based on many inputs and assumptions, and it is important to acknowledge the limitations of the research and some potential areas that require further investigation. These points are summarised as follows:

Heating and cooling demand profiles in Colombia

Hourly heating and cooling datasets are important for understanding load variations and potential impacts in the power grid. As explained in Chapter 5, there is no existing demand profile available for any of these two variables in Colombia, and therefore their consumption was assumed constant throughout the year in the reference model. Further work is needed that is oriented to collect detailed statistics in the country that allow the building heating and cooling demand profiles.

Offshore wind energy potential

Offshore wind is estimated to play a major role in the future power sector. However, it is not included in this study due to the lack of statistical data for its analysis. Further research is needed to calculate the offshore wind potential in Colombia. Further, some offshore meteorological dataset would be very useful in future sustainability analysis.

Impacts on thermal power plants operation

In the power sector, this research focuses on the techno-economic and environmental effects of increasing renewable energy production into the power system. However, it is also necessary to further analyse the impacts on the conventional thermal plants. These plants could be decommissioned during the transition towards cleaner generation if they are not able to generate enough profits. Considering their role as ancillary services and the availability of resources, such as coal in the country, further investigations are required to generate some insights in the future role and operation of conventional power plant in the Colombian power system.

Diversification of energy storage technologies

PHES was selected in this study as the most cost-effective technology for the power system of Colombia. However, the diversification of these technologies is important for addressing all the challenges associated with the variability of renewable sources. EnergyPLAN only allows the simulation of one technology at a time. Therefore, another possible area of future research would be to investigate the impact of combined types of energy storage technologies into the power system.

In addition, a further study could assess the potential cost reduction of the PHES capital costs by using part of the current hydro infrastructure in the country, as described in more detail in Chapter 7.

Transmission system constraints

The national power grid in EnergyPLAN is modelled as a copperplate, and therefore, the internal transmission constraints are not considered in the analysis. This is not realistic because energy producers and load centres are distributed across the space and connected to the national transmission system. Thus, the effects of fast fluctuations in energy production caused by intermittent renewables are not reflected in the results. A further study could assess the impacts of internal transmission constraints in a power system with increasing shares of variable renewable sources. In addition, international networks should be included in the analysis considering the benefits of integrated systems reported in Chapter 7.

Other flexibility options

The current study has only examined two of the options for improving the flexibility of the energy system described in Chapter 2. However, additional options such as Demand-side management and Smart grids could accelerate the transition towards more sustainable energy system. Further research should focus on developing additional energy scenarios that include these options.

EV transport demand profiles in Colombia

An EV smart charging strategy was used in this research for simulating the penetration of different levels of LDV into the energy system. This strategy is aimed at avoiding the grid overloading by charging the EV during low demand hours while matching the drivers' load requirements. However, this profile was taken from the available literature, and it is used in developed countries. Therefore, it is uncertain if the behaviour of the Colombian transport demand would behave similarly. Further research is needed in order to build different transport load profiles that accurately represents the behaviour of the sector in the country.

Socio-economic benefits

The impacts of renewable energy integration and flexibility options on rural communities' development, improvements in trade balances, job creations and improvement in the air quality have been considered out of the scope of this research. This study has focussed on the techno-economic aspects, however, further analysis should be dedicated to analyse the wider socio-economic perspective.

Energy efficiency scenarios

It is important to highlight that energy efficiency scenarios were not examined in this research as it was assumed that the future energy demands would remain the same as estimated by the Colombian government. However, given the significant economic and environmental benefits that energy efficiency could bring to the energy system, future works should develop new scenarios that combine energy efficiency alternatives with the insights produced in this study.

9.4 Concluding remarks and policy recommendations

In conclusion, this research has addressed three relevant questions aimed to assess the integration of variable renewable technologies and flexibility options in the transition towards a low-carbon and more efficient energy system in Colombia.

The findings of this work should be interpreted with caution. The intention of the author 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.

Finally, the energy transition in every country must be supported by dedicated policies and measures. As a result of this research, the following policy recommendations are outlined:

- A more inclusive and ambitious national renewable energy plan should be formulated. Existing policies focuses primarily on the power sector, while support for sustainable alternatives in the heating, cooling and transport sectors lags behind. Specific targets for each of the energy sectors are key in order to achieve a clean energy transition.

- Fiscal and financial incentives are required for accelerating the adoption of the alternatives proposed in this work, and these include subsidies, grants and carbon taxes. Financial incentives are also important for supporting research and development of new alternatives, such as advanced biofuels, power-to-X and CCS.

- A national bioenergy roadmap should be developed. Bioenergy holds a great potential in Colombia for the development of the power and transport sector. In particular, an increase in the biofuel blends mandates, such as the proposed in this work, could represent important benefits in decarbonising the transport sector.

- The COVID-19 crisis is expected to have a significant negative impact on the global economy in the following years. However, it also represents an important opportunity for national governments to boost a green recovery by shifting the fiscal recovery packages towards sustainable development options. These options could include investments in clean infrastructure (grid modernisation and expansion, large-scale energy storage and CCS), improvements in building efficiency and an additional support for clean energy research and development projects.

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Appendix A. Energy storage technologies summary [22], [214], [245]–[247].

	PHES	**CAES**	**L/A battery**	**High-powered Flywheels**	**Li-ion battery**	**VRB flow battery**	**NaS battery**	**SMES**	**Super capacitors**
Energy storage capacity (kWh)	≥ 150	≥ 10	≤ 100	1-25	≤ 10	20-50	≤ 100	≤ 10	≤ 10
Typical power output (MW)	250-1000	100-300	1-100	0.01-10	1-100	0.01-10	5	0.1-10	0.1-10
Discharge duration	Several hours	Hours	Hours	Seconds-minutes	Minutes-hours	2-8 hours	Hours	Hours	Seconds
Charge duration	Several hours	Hours	Hours	15 min	Minutes-hours	2-8 hours	Hours	Seconds	Seconds
Response time	Seconds-minutes	Minutes	Seconds	Seconds	Seconds	Seconds	Miliseconds	Miliseconds	Seconds
Lifetime (years)	25+	20+	3-10	20	10-15	5-20+	15	5-20	5-20
Roundtrip efficiency (%)	80-90%	45-60%	70-90%	85-95%	85-95%	70-85%	80-90%	> 90%	90%
Technology maturity	Mature	Commercial	Commercial	Commercial	Demonstration	Demonstration	Commercial	Demonstration	Developed
Advantages	Large storage capacity - Fast response time - Very low self-discharge - Good roundtrip efficiency - Long life and storage periods- Low storage costs - Good start/Stop flexibility	Fast response time - Relative low-costs (readily accesible gas cavern)	Low cost - High recycled material - High reliability and roundtrip efficiency - Abundant manufacturing and operational experience	Fast response time - Low maintenance - High cycles - High power density - Fast charge capabilities - Long lifecycle - No capacity degradation	High efficiency - High energy density	Higher discharge depth - High cycling tolerance - Relative high energy efficiency - Long lifetime - High discharge rate - Fast response time	High energy density - Quick response - Efficient cycles	High efficiency	Excessively high costs
Disadvantages	Geographic constraints - Low energy density - High initial investment - Long construction period - Environmental concerns	Low-efficiency - Geographic constraints - Limited projects in operation	Low energy density - Large footprint - Limited discharge depth - Low cycling times - Periodic water replacement	Excessively high costs - Tensile strength limitations - Low energy density (relatively) - High self-discharge rates	Excessively high costs - Limited discharge depth	Low energy density - Low efficiency - High cost of vanadium and membrane designs	Safety issues	Excessively high costs - Low energy density	Excessively high costs - Low energy density

Appendix B. List of assessed energy modelling tools

No	Model (Developer)	Perspective on the future	Specific purpose	Geographical coverage	Sectoral coverage	Time horizon	Renewable technologies	Storage technology?	Transport sector included?
1	DECC 2050 calculator (DECC)	Forecasting	Energy supply, environmental emissions target	UK	Energy sector	Medium, long term, 2010-2050	Solar PV, Solar thermal, Geothermal, hydroelectric	Wind, Wave, Tidal, Biomass	Storage, demand shifting and interconnection, international aviation, international shipping
2	DECC DDM (DECC, developed by LCP)	Exploring	Energy demand, Energy supply, matching demand and supply, environmental impacts.	UK	Electricity sector	Medium, long term, 2010-2050	Solar PV, Wind, Biomass	Pumped storage	Not included
3	DSIM (Imperial college London)	Exploring	Energy demand, Energy supply, specifically designed to model storage and variable generation	Multi-regional	Electric power system	Short term	Wind, solar, hydro, geothermal	Electricity storage, heat storage, pumped hydro	Not included
4	DynEMo (UCL)	Exploring	Energy demand, supply, with renewable energy integration.	UK and France	Energy sector	Short, medium, long term. 4 seasons, peak days, weekends, weekdays	Wind, solar, tidal flow, wave	Electric vehicles, synthetic liquids, district heat, pumped storage	Cars, rail, aviation
5	E3MG (Cambridge Econometrics)	Exploring	Simulation model of the global energy environment-economy system	Global (20 world regions)	E3 (energy-environment-economy) system	Up to 2100	Solar PV, marine, bio-waste, wind, hydro	Storage and CCS included	-
6	EnergyPLAN* (Aalborg University)	Exploring, forecasting	Energy supply and demand, with focus on future options	National, state, regional	Electricity, heat and transport	1 year	Wind, solar PV, wave power, river hydro	Electricity storage unit, electrolysers	Fuel inputs, hydrogen vehicles, battery electric vehicles
7	ESME (ETI)	Exploring	Energy supply and demand, environmental impacts	UK	Energy sector	Short, medium term	Solar, tidal, hydro, wave, wind, recoverable heat, geothermal, biomass	CCS, pumped hydro	Not included
8	LEAP (Stockholm environmental institute Boston, USA)	Exploring, forecasting	Demand, supply, environmental impacts. Integrated approach.	Global, national, regional, local	All sectors	Medium, long term	All technologies	All technologies	Road, rail, air, water
9	MARKAL (IEA/ETSAP)	Exploring	Energy supply with constraints	National, local	Energy sector	Medium, long term	Hydro, solar, wind, biomass, geothermal	Only night-day storage, storage plants, pumped storage	Cars, buses, light trucks, commercial trucks, medium trucks. International aviation, domestic aviation, rail transportation, navigation.

No	Model (Developer)	Perspective on the future	Specific purpose	Geographical coverage	Sectoral coverage	Time horizon	Renewable technologies	Storage technology?	Transport sector included?
10	MARKAL-MACRO (Brookhaven National Lab, USA)	Exploring	Demand, supply, environmental impacts. Integrated approach.	National, local	All sectors	Medium, long term	Hydro, solar, wind, biomass, geothermal	Only night-day storage, storage plants, pumped storage	Cars, buses, light trucks, commercial trucks, medium trucks. International aviation, domestic aviation, rail transportation, navigation.
11	MDM-E3 (Cambridge econometrics)	Forecasting	A framework for generating forecasts and alternative scenarios.	UK	E3 (energy-environment-economy) system	Up to 2030	Nuclear electricity, hydro, biomass, wind, solar PV, solar thermal, marine, geothermal	Storage integrated	Not included
12	MESSAGE-III (International Institute for Applied System Analysis, IIASA, Austria)	Exploring	Energy demand and supply, environmental impacts	National, local	Energy sector	Long, medium and short term	User-defined. Technologies are defined by their inputs and outputs, their efficiency and their variability if more than one input or output exists	Storage and conversion technologies can be simulated in MESSAGE as well as carbon sequestration	Included - no information known
13	NEMS (US Energy Information Administration, EIA)	Exploring	Balances generation and consumption along with prices	US	Energy sector	Medium term (25 years)	Wind, geothermal, solar thermal, solar PV, biomass, hydro	Not known	6 car sizes, 6 light truck sizes, 63 conventional fuel-saving technologies, for light-duly vehicles, Gasoline, diesel and 14 alternative-fuel vehicle technologies for light-duty vehicles 20, vintages for light-duty vehicles, Regional, narrow and wide-body aircraft, 6 advanced aircraft technologies, Light, medium and heavy freight trucks 37 advanced freight truck technologies
14	OSeMOSYS (Open source research community incl. UCL)	Exploring	Energy supply and demand with constraints	Flexible?	Energy sector	Medium, long term (2010 - 2050). 3 seasons, 2 intraday.	Flexible due to modular design	Flexible due to modular design	Flexible due to modular design
15	POLES (European comission)	Forecasting	Detailed econometric, long term global energy outlooks with demand supply and price projections by main regions.	Global (split into 47 regions)	15 energy demand sectors	Up to 2050	Combined heat and power, biomass, solar PV, solar thermal, small hydro, wind, biofuels for transport, fuel cell, stationary fuel cell	CCS	Road, rail, air transport

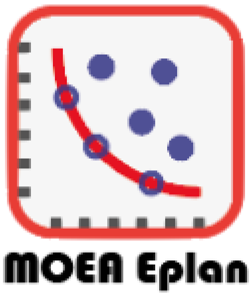
No	Model (Developer)	Perspective on the future	Specific purpose	Geographical coverage	Sectoral coverage	Time horizon	Renewable technologies	Storage technology?	Transport sector included?
16	PRIMES (National Technical University of Athens, NTUA)	Exploring	Projections of energy demand, supply prices and investment to the future.	EU28 member-states and Western Balkans countries	Energy sector	Medium to long term	Thermal solar, geothermal, biomass and waste, solar PV, solar thermal, wind, hydro, tidal, wave energy	Several electricity storage technologies including hydro with reservoir, hydro pumping, compressed air storage and hydrogen-based storage	Passenger and goods transport
17	RETscreen (CEDRL/Natural Resources Canada)	Exploring	Energy supply, specially for renewable energy technologies	National, local	Energy sector	Long-term (up to 50 years)	Comprehensive technology database	Only battery energy storage (not hydrogen)	Not included
18	SAGE (ETSAP)	Exploring	Energy system and energy trading	Global	Energy sector	Medium, long term	Hydro, solar, wind, biomass, geothermal	Only night-day storage, storage plants, pumped storage	Cars, buses, light trucks, commercial trucks, medium trucks. International aviation, domestic aviation, rail transportation, navigation.
19	TIAM (ETSAP)	Exploring	Decarbonisation pathways, technology assessment, global policy.	Global multi-region	E3 (energy-environment-economy) system	Medium to long term	Hydro, solar, wind, biomass, geothermal	CO2 capture and underground storage, biological carbon sequestration	Cars, buses, light trucks, commercial trucks, medium trucks. International aviation, domestic aviation, rail transportation, navigation.
20	TIMES (ETSAP)	Exploring	Decarbonisation pathways, technology assessment, global policy.	Global, national, regional, local	Energy sector	Medium, long term	Hydro, solar, wind, biomass, geothermal	Flexible. Storage processes "consume" commodities at one time-slice and release them at other	Cars, buses, light trucks, commercial trucks, medium trucks. International aviation, domestic aviation, rail transportation, navigation.
21	UKENVI (University of Glasgow, University of Strathclyde)	Forecasting	Environmental assessment of macro-economic policy	Regional, national	Energy sector	Medium to long term	Hydro, wind	Not included	Included - no information known
22	WASP (International Atomic Energy Agency, IAEA)	Forecasting	Pathways analysis, comprehensive planning tool for electric power system expansion analysis.	National, regional	Power sector	Medium to long term (up to 30 years)	Wind, wave, tidal, hydro, biomass	Pumped hydro	Not included
23	AEOLIUS (Institute for Industrial Production, Universitat Karlsruhe)	Exploring	Effects of intermittent renewable energy on conventional generation	National, state, regional	Energy sector	Yearly	Wind, solar PV, geothermal	Pumped hydro, Compressed air	Not included
24	BALMOREL (Project Driven with a users network and forum around it)	Exploring	Energy demand, supply, with renewable energy integration.	International	Electricity sector	Max 50 years	Hydro, wind, solar	Hydrogen storage, pumped hydroelectric	Not included

No	Model (Developer)	Perspective on the future	Specific purpose	Geographical coverage	Sectoral coverage	Time horizon	Renewable technologies	Storage technology?	Transport sector included?
25	BCHP Screening tool (Oak Ridge National Laboratory)	Exploring	Assessment of saving potential of combined cooling, heating and power systems.	Single-project investigation	Energy sector	Yearly	Not included	Not included	Not included
26	COMPOSE (Aalborg University)	Exploring	Assessment how the system van support intermittency, while offering a realistic evaluation of the distribution of costs and benefits under uncertainty.	Single-project investigation	Energy sector	No limit		Included - no information known	Included - no information known
27	E4cast (Australian Bureau of Agricultural and Resource Economics)	Forecasting	Project Australia's long-term energy production, consumption, and trade.	National/state/regional	Energy sector	Max 50 years	Hydro, biomass, biogas, wind, and solar		Conventional vehicles and rail
28	EMCAS (Argonne National Laboratory)	Exploring, forecasting	Simulate the opertation of the power system	National/state/regional	Energy sector	No limit	Included, no details	Included expect hydrogen and electric vehicles	Partly included
29	EMINENT (Instituto Superior Técnico, Technical University of Lisbon)	Exploring	Help introducing new energy technologies and new energy solutions into the market in a faster way.	National/state/regional	Energy sector	Yearly	Included, no details	Included, no details	Not included
30	EMPS (Stiftelsen for Industriell og Teknisk Forskning)	Exploring	Simulation and optimisation of the operation of power systems with a certain share of hydropower	International	Electricity sector	25 years	Wind	Pumped hydroelectric	Not included
31	energyPRO (Energi-Og Mijødata (EMD) International A/S)	Exploring	Modelling software for combined techno-economic design, analysis and optimisation of both fossil and bio-fuelled cogeneration and trigeneration projects.	Single-project investigation	Energy sector	Max 40 years	All technologies	All technologies	Not included
32	ENEP-BALANCE (Argonne National Laboratory)	Exploring, forecasting	Matches the demand for energy with available resources and technologies	International	Energy sector	25 years	All technologies	Only hydrogen	Included - no information known
33	GTMax (Argonne National Laboratory)	Exploring, forecasting	Simulates the dispatch of electric generating units and the economic trade of energy among utility companies	National/state/regional	Energy sector	No limit	All technologies	All technologies except hydrogen	Not included
34	H2RES (Instituto Superior Técnico and the University of Zagreb)	Exploring	Increase the integration of renewable sources and hydrogen into island energy-systems which operate as stand-alone systems.	Island	Energy sector	No limit	All technologies except tidal	All technologies except compressed-air energy storage	Partly included
35	HOMER (National Renewable Energy Laboratory and HOMER Energy LLC)	Exploring	Simulates and optimises stand-alone and grid-connected power systems	Local/community	Energy sector	Yearly	All technologies	All technologies	Not included

No	Model (Developer)	Perspective on the future	Specific purpose	Geographical coverage	Sectoral coverage	Time horizon	Renewable technologies	Storage technology?	Transport sector included?
36	HYDROGEMS (Institutt for energiteknikk)	Exploring	Simulate integrated hydrogen energy-systems, particularly renewable energy based stand-alone power systems	Single-project investigation	Electricity sector	Yearly	Wind, solar PV, water electrolysis	Metal hydride hydrogen storage, hydrogen compressor, batteries	Not included
37	IKARUS (Research Centre Jülich, Institute of Energy Research)	Exploring, forecasting	Linear cost-optimisation tool for national energy systems	National/state/regional	Energy sector	Max 50 years	All technologies	All technologies	Included - no information known
38	INFORSE (The International Network for Sustainable Energy)	Exploring, forecasting	Energy balancing tool for national energy-systems	National/state/regional	Energy sector	50+ years	All technologies except tidal	All technologies	Included - no information known
39	Invert (Energy Economics Group, Vienna University of Technology)	Exploring	Support the design of efficient promotion schemes for renewable and efficient energy technologies	National/state/regional	Energy sector	Max 50 years	All technologies except tidal an wave	Not included	Partly included
40	Mesap PlaNet (seven2one)	Exploring	Analyse and simulate energy supply, demand, costs and environmental impacts for local, regional and global energy systems.	National/state/regional	Energy sector	No limit	All technologies	All technologies	Included - no information known
41	MiniCAM (Pacific Northwest National Laboratory)	Exploring, forecasting	Examine long-term, large-scale changes in global and regional energy and agriculture systems	Global and regional	Energy sector	50+ years	All technologies except CHP plants, wave, and tidal	Not included	Included - no information known
42	ORCED (Office of Integrated Analysis and Forecasting, Energy Information Administration)	Exploring, forecasting	Dispatches the power plant to meet the electricity demand for any given year up to 2030	National/state/regional	Electricity sector	Yearly	All technologies except wave and tidal	Pumped-hydro	Partly included
43	PERSEUS (Institute for Industrial Production, Universität Karlsruhe)	Forecasting	Tool family with several different applications. Commonly used in energy utility companies	International	Electricity sector	Max 50 years	All technologies	All technologies	Electric vehicles only
44	ProdRisk (Stiftelsen for Industriell og Teknisk Forskning (SINTEF))	Exploring	Optimisation and simulation of hydro-thermal systems	National/state/regional	Electricity sector	Multiple years	Wind, hydro	Pumped hydroelectric	Not included
45	RAMSES (Danish Energy Agency)	Exploring	Analyse the Nordic electricity market	International	Electricity sector	30 years	Wind, hydro, solar PV	Pumped hydroelectric, compressed air and batterie	Not included
46	SimREN (Institute of Sustainable Solutions and Innovations)	Exploring	Design models of energy supply and demand	National/state/regional	Electricity sector	No limit	All technologies except wave and tidal	Pumped hydroelectric, battery and hydrogen	Partly included
47	SIVAEL (Energinet.dk)	Exploring	Simulate the electricity sector and district-heating systems	National/state/regional	Electricity sector	Yearly	Wind	Batteries	Not included

No	Model (Developer)	Perspective on the future	Specific purpose	Geographical coverage	Sectoral coverage	Time horizon	Renewable technologies	Storage technology?	Transport sector included?
48	STREAM (Ea Energy Analyses)	Forecasting	Scenario building tool that produces results for decision making in nationa energy systems	National/state/regional	Energy sector	Yearly	All technologies included	Pumped hydroelectric	Conventional vehicles, battery electric-vehicles, rail, and aviation
49	TRNSYS16 (The University of Wisconsin Madison)	Exploring, forecasting	Analysing single-project, local community, or island energy systems	Local/community	Energy sector	Multiple years	Wind, solar PV, solar thermal. NOT hydro, wave, tidal.	Batteries	Not included
50	UniSyD3.0 (Unitec New Zealand)	Forecasting	Multi-regional partial-equilibrium too for national energy and economic systems	National/state/regional	Energy sector	Max 50 years	All technologies except wave and tidal	Not included	Incorporate four separate vehicle technologies: conventional vehicles, hydrogen internal-combustion, hydrogen fuel-cell, and battery electric vehicles.
51	WILMAR Planning Tool (Risø DTU National Laboratory for Sustainable Energy)	Exploring	Analyse the optimal operation of a power system	International	Power sector	Yearly	All technologies except solar thermal and geothermal	Pumped-hydroelectric, battery, compressed air	Partly included
52	PLEXOS (Energy exemplar)	Exploring, forecasting	Modelling tool for electricity maket	International	Power sector	Hours to 40 years	Wind and hydro	Pumped-hydroelectric	Not included

Appendix C. MOEA Eplan user's guide



User's guide

Contents

1 Introduction

MOEA Eplan (Multi-objective evolutionary algorithm optimisation for EnergyPLAN) is a MATLAB app that allows the user to perform a multi-objective optimisation for energy system models developed in the EnergyPLAN modelling tool [1]. The optimisation algorithm applied is an elitist and controlled variant of the Non-Dominated Sorting Genetic Algorithm (NSGA-II) used by the Global Optimisation Toolbox in MATLAB [2].

MATLAB and EnergyPLAN are linked using the scripts built by Cabrera [3] in his toolbox.

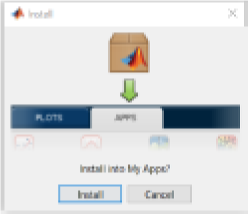
The MOEA Eplan app was developed by Oscar Pupo-Roncallo, MSc (orpuporoncallo1@sheffield.ac.uk). Energy 2050, The University of Sheffield, Sheffield, UK, S3 7RD.

2 Installation

After downloading both the EnergyPLAN modelling tool from https://www.energyplan.eu/ and the MOEA Eplan installer, follow the next steps to install the app in MATLAB:

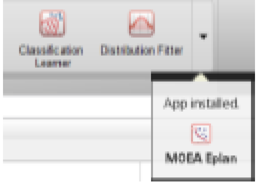
1. Open the MATLAB software.
2. In the apps tab, push the *Install App* button.

3. Select the file "MOEA Eplan.mltbx" and open it.
4. A confirmation windows will pop up, please select Install.



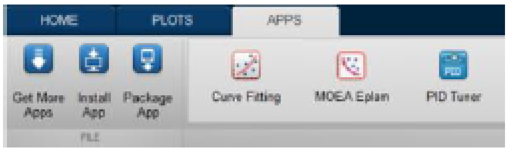
Install into My Apps?

5. A message will pop up from MATLAB confirming the installation.



App installed.

6. Finally, the app is installed and available from the apps tab in MATLAB.



2.1 Requirements

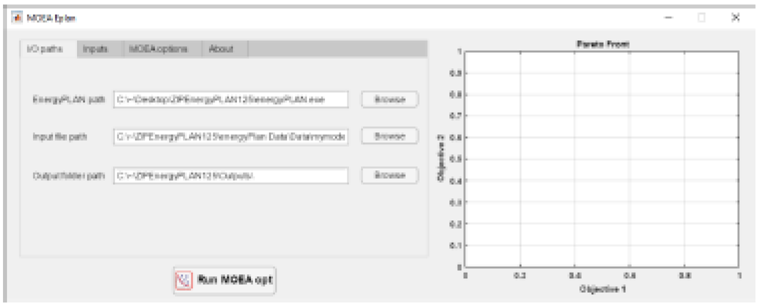
The app requires EnergyPLAN version 12.5, MATLAB version 9.2.0.556344 (R2017a) or newer and its Global Optimisation Tool.

3 Running MOEA Eplan

MOEA Eplan technology inputs include up to four different renewable energy sources (RES) and energy storage (charging/discharging power and energy capacity). The optimisation objective variables include the two most common options: the CO_2 emissions and total annual cost (CO2 - Cost); and the Primary Energy Supply and the Critical Excess of Electricity Production (PES - CEEP). Further, the MOEA options allow the user to set the population size, number of generations, function tolerance, Pareto fraction and crossover fraction[1].

3.1 Inputs configuration

The app is organised in two sections: the input tabs and the Pareto front section, where the resulting Pareto front is displayed.



The input tabs include I/O paths, Inputs and the MOEA options. These are described as follows:

3.1.1 I/O paths

Running the EnergyPLAN modelling tool in MATLAB requires the definition of three paths [3]:

- The EnergyPLAN executable file, usually *energyPLAN.exe* that can be found in the same folder downloaded from the software website.
- The energy system model to simulate, saved as a .txt file and located inside the energyPLAN data folder (...\ZIPEnergyPLAN125\energyPlan Data\Data).

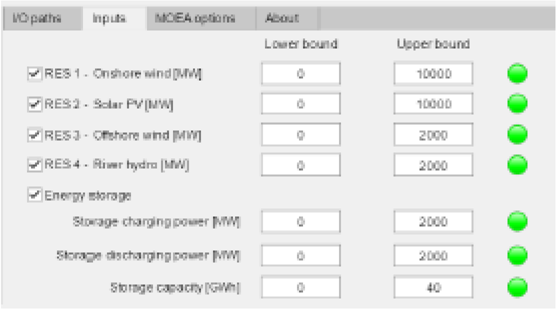
---

[1] For more details on these inputs, consult the MATLAB documentation [2].

- The folder where the output file with the final configuration simulated will be stored.

3.1.2 Inputs

In this tab, the number of decision variables to be optimised and their lower and upper bounds are set by the user. Up to four different RES technologies and energy storage can be included in the simulation.



	Lower bound	Upper bound	
☑ RES 1 - Onshore wind [MW]	0	10000	●
☑ RES 2 - Solar PV [MW]	0	10000	●
☑ RES 3 - Offshore wind [MW]	0	2000	●
☑ RES 4 - River hydro [MW]	0	2000	●
☑ Energy storage			
Storage charging power [MW]	0	2000	●
Storage discharging power [MW]	0	2000	●
Storage capacity [GWh]	0	40	●

3.1.3 MOEA options

This tab allows the configuration of the MOEA optimisation options. The following parameters can be defined:

- Population size
- Number of generations
- Pareto fraction
- Function tolerance
- Crossover fraction

More information about these options can be found in the Global optimization toolbox documentation [2].

Population size 10

Function tolerance 0.01

Number of generations 5

Crossover fraction 0.8

Pareto fraction 0.8

☐ Plot running Pareto front

Objective variables CO2 Cost

The two pairs of objective variables in the app are the followings:

- CO_2 emissions and total annual cost (CO2 - Cost)
- Primary Energy Supply and the Critical Excess of Electricity Production (PES - CEEP).

If the checkbox *Plot running Pareto front* is activated, the resulting Pareto front at each generation will be displayed.

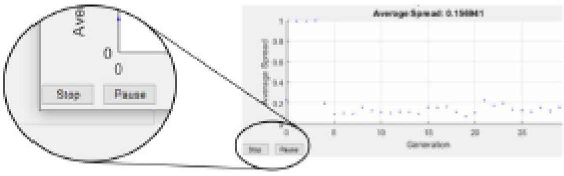
3.2 Running and stopping the optimisation

After setting up all the inputs required, push the *Run MOEA opt* button to start the optimisation.

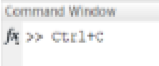
You will notice that the EnergyPLAN modelling tool starts opening and closing while simulating each one of the individuals. This modelling tool is fast, and each simulation takes approximately 3 seconds in a common workstation with a single-core processor. However, depending on the population size and number of generations defined by the user the total optimisation time could last for a few hours. As a reference, running a MOEA optimisation considering 5 inputs, with a population of 50 individuals and 30 generations could take approximately 3 hours to generate the Pareto front.

There are two options to *stop* the optimisation process:

- Using the plot windows, the user can push the *Stop* or *Pause* button that is located on the left-bottom corner. This window will pop up after the first set of individuals is assessed.



- By pressing *Ctrl+C* in the command windows.

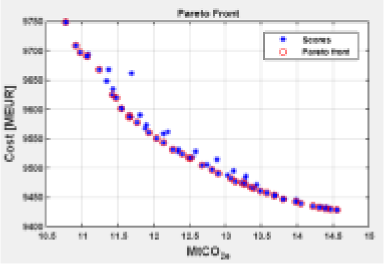


```
>> Ctrl+C
```

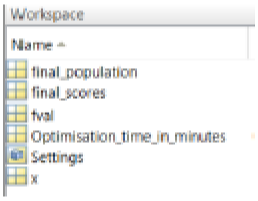
3.3 Optimisation outputs

Once the optimisation process is completed, the following outputs are generated:

- Pareto front graph.

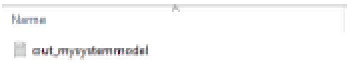


- In the MATLAB workspace: the final population and scores, the Pareto front points (x) and its associated fitness function values (fval), the total optimisation time (in minutes) and the *gamultiobj* solver settings.



final_population
final_scores
fval
Optimisation_time_in_minutes
Settings
x

- In the output folder directory, defined in the I/O paths, an output text (.txt) file with the final configuration simulated can be found.



Name

out_mysystemmodel

4 References

[1] H. Lund, "EnergyPLAN - Advanced energy systems analysis computer model." [Online]. Available: https://www.energyplan.eu/. [Accessed: 27-Jul-2018].

[2] The MathWorks Inc, *MATLAB Global Optimization Toolbox User's Guide*. Natick, MA: The MathWorks Inc., 2017.

[3] P. Cabrera, H. Lund, J. Z. Thellufsen, and P. Sorknæs, "The MATLAB Toolbox for EnergyPLAN: A tool to extend energy planning studies," *Sci. Comput. Program.*, vol. 191, p. 102405, 2020.

Appendix D. Annual energy consumption at different EV penetration levels

Table D.1. Conventional vehicles (ICE) annual fuel consumption with 0% EV penetration.

Category	**Share**	**Number [thousand]**	**Fuel economy [L/100 km]**	**Fuel consumption [TWh/year]**
Petrol				
Motorcycles	57.6%	15547.9	3.3	48.4
Small (sedan/wagon)	13.1%	3530.9	5.1	16.9
Taxis	1.0%	261.2	5.1	1.3
Medium (Pick up, SUV, Vans)	7.8%	2117.5	6.0	12.0
Large (Shuttles and buses)	0.1%	38.0	7.7	0.3
Total		**21495.5**		**78.85**
Diesel				
Small (sedan/wagon)	3.8%	1034.9	4.2	7.06
Medium (Pick up, SUV, Vans)	2.3%	620.6	4.9	4.95
Large (Shuttles and buses)	1.1%	304.1	6.4	3.17
Total		**1959.7**		**15.22**
Natural Gas			**Fuel economy [m^3/km]**	
Small (sedan/wagon)	0.0%	-	-	0.00
Taxis	0.6%	174.1	0.045	1.292
Medium (Pick up, SUV, Vans)	3.4%	912.7	0.050	7.448
Large (Shuttles and buses)	0.1%	38.0	0.120	0.745
Total		**1124.9**		**9.48**

Table D.2. Conventional vehicles (ICE) annual fuel consumption with 20% EV penetration.

Category	Share	Number [thousand]	Fuel economy [L/100 km]	Fuel consumption [TWh/year]
Petrol				
Motorcycles	57.6%	12438.3	3.3	38.74
Small (sedan/wagon)	13.1%	2824.7	5.1	13.56
Taxis	1.0%	209.0	5.1	1.00
Medium (Pick up, SUV, Vans)	7.8%	1694.0	6.0	9.56
Large (Shuttles and buses)	0.1%	30.4	7.7	0.22
Total		**17196.4**		**63.08**
Diesel				
Small (sedan/wagon)	3.8%	827.9	4.2	5.67
Medium (Pick up, SUV, Vans)	2.3%	496.5	4.9	3.97
Large (Shuttles and buses)	1.1%	243.3	6.4	2.54
Total		**1567.7**		**12.18**
Natural Gas			**Fuel economy [m^3/km]**	
Small (sedan/wagon)	0.0%	-	-	0.00
Taxis	0.6%	139.3	0.045	1.03
Medium (Pick up, SUV, Vans)	3.4%	730.2	0.050	5.96
Large (Shuttles and buses)	0.1%	30.4	0.120	0.60
Total		**899.9**		**7.59**

Table D.3. EV annual electricity consumption with 20% penetration.

Category	Share	Number [thousand]	Battery capacity [kWh]	Range [km]	Electricity Consumption [TWh/year]	Battery storage [GWh]
Motorcycles	63.3%	3109.6	2.23	77.32	1.64	6.92
Small	20.3%	1000.2	8.07	103.84	1.42	8.07
Medium	14.9%	730.2	22.46	192.73	1.56	16.40
Large	1.5%	76.0	54.60	276.87	0.27	4.15
Total		**4916**			**4.90**	**35.54**

Table D.4. Conventional vehicles (ICE) annual fuel consumption with 40% EV penetration.

Category	Share	Number [thousand]	Fuel economy [L/100 km]	Fuel consumption [TWh/year]
Petrol				
Motorcycles	57.6%	9328.7	3.3	29.05
Small (sedan/wagon)	13.1%	2118.5	5.1	10.17
Taxis	1.0%	156.7	5.1	0.75
Medium (Pick up, SUV, Vans)	7.8%	1270.5	6.0	7.17
Large (Shuttles and buses)	0.1%	22.8	7.7	0.17
Total		**12897.3**		**47.31**
Diesel				
Small (sedan/wagon)	3.8%	621.0	4.2	4.25
Medium (Pick up, SUV, Vans)	2.3%	372.4	4.9	2.98
Large (Shuttles and buses)	1.1%	182.5	6.4	1.90
Total		**1175.8**		**9.13**
Natural Gas			**Fuel economy [m³/km]**	
Small (sedan/wagon)	0.0%	-	-	0.000
Taxis	0.6%	104.5	0.045	0.775
Medium (Pick up, SUV, Vans)	3.4%	547.6	0.050	4.469
Large (Shuttles and buses)	0.1%	22.8	0.120	0.447
Total		**674.9**		**5.69**

Table D.5. EV annual electricity consumption with 40% penetration.

Category	Share	Number [thousand]	Battery capacity [kWh]	Range [km]	Electricity Consumption [TWh/year]	Battery storage [GWh]
Motorcycles	63.3%	6219.2	2.23	77.32	3.28	13.85
Small	20.3%	2000.5	8.07	103.84	2.85	16.13
Medium	14.9%	1460.3	22.46	192.73	3.12	32.80
Large	1.5%	152.1	54.60	276.87	0.55	8.30
Total		**9832**			**9.81**	**71.09**

Table D.6. Conventional vehicles (ICE) annual fuel consumption with 60% EV penetration.

Category	Share	Number [thousand]	Fuel economy [L/100 km]	Fuel consumption [TWh/year]
Petrol				
Motorcycles	57.6%	6219.2	3.3	19.37
Small (sedan/wagon)	13.1%	1412.4	5.1	6.78
Taxis	1.0%	104.5	5.1	0.50
Medium (Pick up, SUV, Vans)	7.8%	847.0	6.0	4.78
Large (Shuttles and buses)	0.1%	15.2	7.7	0.11
Total		**8598.2**		**31.54**
Diesel				
Small (sedan/wagon)	3.8%	414.0	4.2	2.84
Medium (Pick up, SUV, Vans)	2.3%	248.3	4.9	1.98
Large (Shuttles and buses)	1.1%	121.6	6.4	1.27
Total		**783.9**		**6.09**
Natural Gas			**Fuel economy [m^3/km]**	
Small (sedan/wagon)	0.0%	-	-	0.00
Taxis	0.6%	69.7	0.045	0.517
Medium (Pick up, SUV, Vans)	3.4%	365.1	0.050	2.979
Large (Shuttles and buses)	0.1%	15.2	0.120	0.298
Total		**449.9**		**3.79**

Table D.7. EV annual electricity consumption with 60% penetration.

Category	Share	Number [thousand]	Battery capacity [kWh]	Range [km]	Electricity Consumption [TWh/year]	Battery storage [GWh]
Motorcycles	63.3%	9328.7	2.23	77.32	4.93	20.77
Small	20.3%	3000.7	8.07	103.84	4.27	24.20
Medium	14.9%	2190.5	22.46	192.73	4.68	49.20
Large	1.5%	228.1	54.60	276.87	0.82	12.45
Total		**14748**			**14.71**	**106.63**

Table D.8. Conventional vehicles (ICE) annual fuel consumption with 80% EV penetration.

Category	Share	Number [thousand]	Fuel economy [L/100 km]	Fuel consumption [TWh/year]
Petrol				
Motorcycles	57.6%	3109.6	3.3	9.68
Small (sedan/wagon)	13.1%	706.2	5.1	3.39
Taxis	1.0%	52.2	5.1	0.25
Medium (Pick up, SUV, Vans)	7.8%	423.5	6.0	2.39
Large (Shuttles and buses)	0.1%	7.6	7.7	0.06
Total		**4299.1**		**15.77**
Diesel				
Small (sedan/wagon)	3.8%	207.0	4.2	1.42
Medium (Pick up, SUV, Vans)	2.3%	124.1	4.9	0.99
Large (Shuttles and buses)	1.1%	60.8	6.4	0.63
Total		**391.9**		**3.04**
Natural Gas			**Fuel economy [m^3/km]**	
Small (sedan/wagon)	0.0%	-	-	0.00
Taxis	0.6%	34.8	0.045	0.258
Medium (Pick up, SUV, Vans)	3.4%	182.5	0.050	1.490
Large (Shuttles and buses)	0.1%	7.6	0.120	0.149
Total		**225.0**		**1.90**

Table D.9. EV annual electricity consumption with 80% penetration.

Category	Share	Number [thousand]	Battery capacity [kWh]	Range [km]	Electricity Consumption [TWh/year]	Battery storage [GWh]
Motorcycles	63.3%	12438.3	2.23	77.32	6.57	27.70
Small	20.3%	4000.9	8.07	103.84	5.70	32.27
Medium	14.9%	2920.7	22.46	192.73	6.24	65.60
Large	1.5%	304.1	54.60	276.87	1.10	16.60
Total		**19664**			**19.61**	**142.17**

Table D.10. EV annual electricity consumption with 100% penetration.

Category	Share	Number [thousand]	Battery capacity [kWh]	Range [km]	Electricity Consumption [TWh/year]	Battery storage [GWh]
Motorcycles	63.3%	15547.9	2.23	77.32	8.21	34.62
Small	20.3%	5001.2	8.07	103.84	7.12	40.34
Medium	14.9%	3650.8	22.46	192.73	7.80	82.00
Large	1.5%	380.1	54.60	276.87	1.37	20.76
Total		**24580**			**24.51**	**177.72**

Appendix E. Pareto fronts for the alternative scenarios of Chapter 8

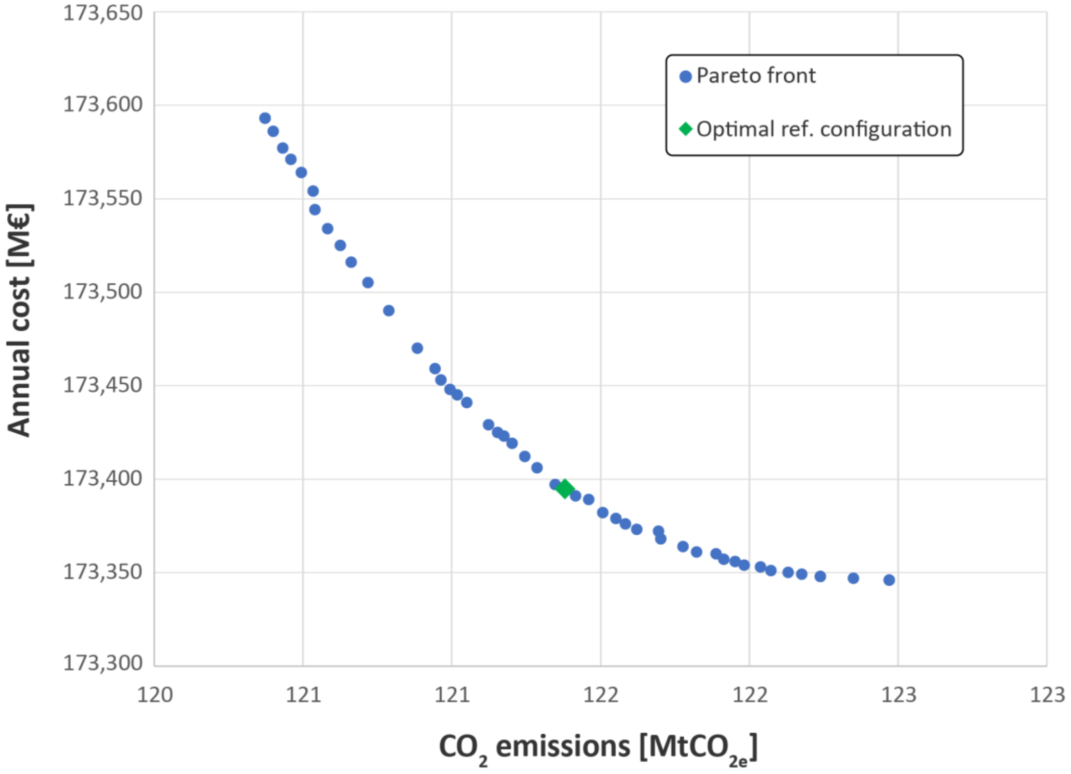


Figure E.1. Pareto front for scenario COL 2040.

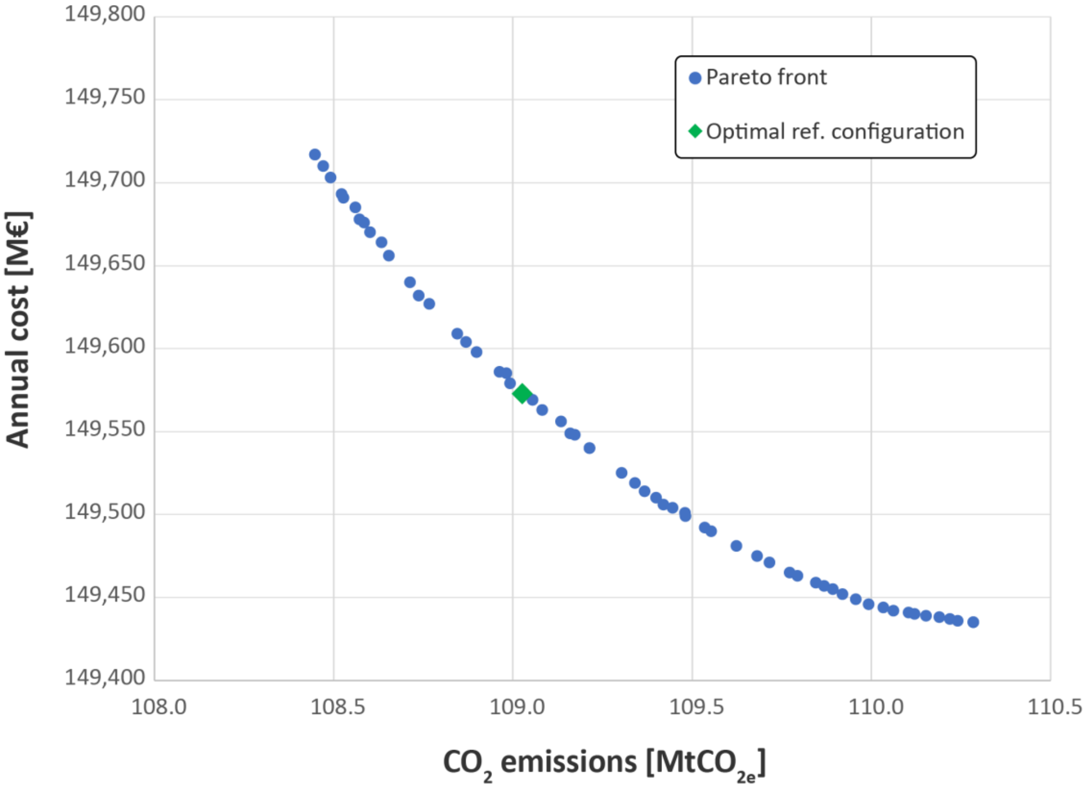


Figure E.2. Pareto front for scenario COL 50EV.

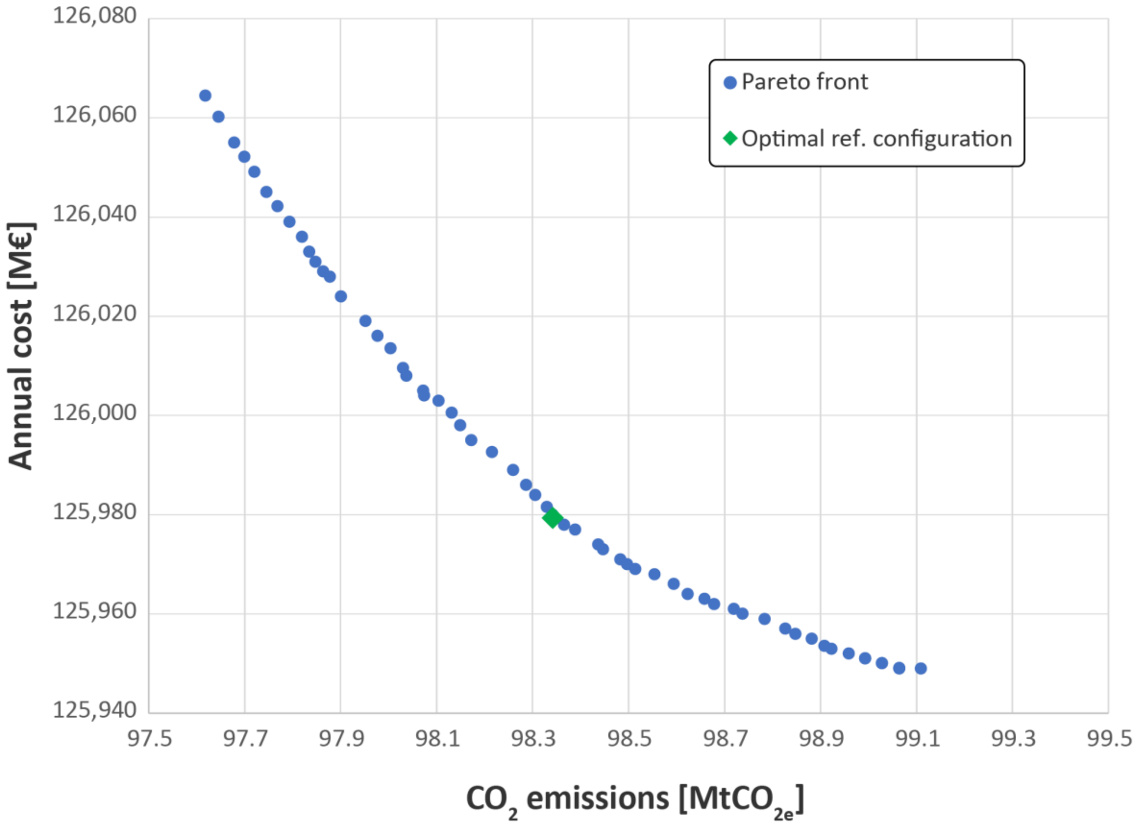


Figure E.3. Pareto front for scenario COL 100EV.

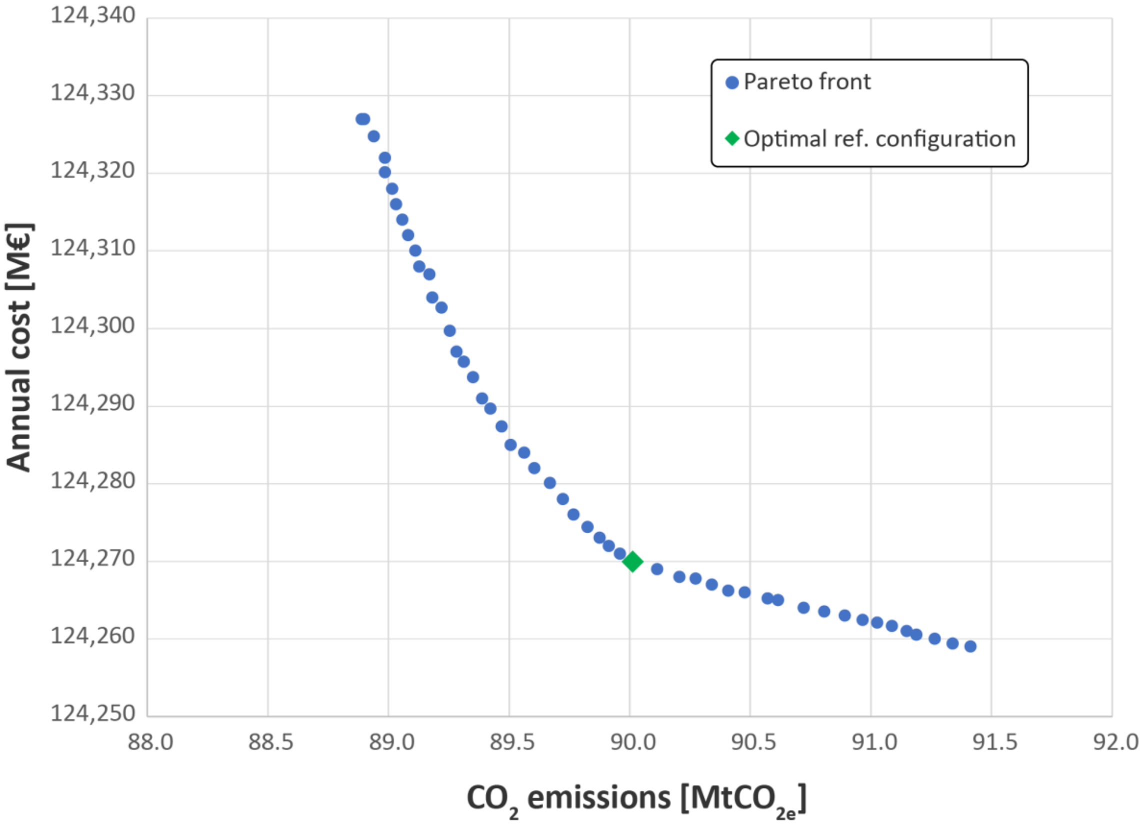


Figure E.4. Pareto front for scenario COL IDEAL.