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ELECTRIC INTEGRATION AND DEVELOPMENT OF A RENEWABLE
ELECTRIC GRID IN LATINAMERICA

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LATIN AMERICA

One of the main challenges in the future development of electrical systems is the cost-effective incorporation of renewable resources. In that sense, Latin America presents a high potential in their application; nevertheless, the target expected by each country of the region is still conservative. The hypothesis of this work is that an electric integration among the countries of the Latin American region can allow a higher share of renewable generation without increasing the total cost.

This study includes a review of other studies on electric integration conducted in Latin America, with the objective of including methodological approaches or elements used. Those works are also considered as references to define interconnection candidates. On the other hand, in order to have a better understanding of the Latin American reality, a review of the current electric system and projections for each country in the region is carried out. This revision is also used to fill the database of each country.

To validate the hypothesis presented, this work proposes a methodology of incremental scenarios where the total cost of each case can be compared. In all cases, is applied a model that minimize the investment cost in generation and transmission and the operational costs of the electric system for a time horizon of 15 years. For this purpose, preprocessing of input parameters, synthetic time series of inflows for hydro power and catchments systems, definition of new constraints, and validation framework for each country were developed and integrated in a commercial planning tool. The reference scenario considers a *business as usual* projection both without a major development of renewable energy and with the current and planned interconnections. The second scenario is intensive in renewable generation. It sets a target of renewable generation by the end of the horizon, but only the current and planned interconnections are considered. Finally, the third scenario is an integrated renewable case; in addition to the renewable target, the development of new interconnection candidates in the region is allowed. With these scenarios, it is possible to compare the total cost of investments and operation to conclude if the integrated renewable scenario allows a higher amount of renewable participation with a lower total cost for the region.

This work allows concluding, in the first place, that the methodology of incremental scenarios is appropriate to quantify the benefits of an integrated grid in order to achieve a high renewable electric matrix in Latin America. According to the results obtained, it is possible to ascertain that a scenario with a higher integration level can reach a high renewable participation without increasing the total cost.

This work is part of a project financed by the Inter-American Development Bank and developed by a partnership of four consultants: Energy Exemplar, AWS Truepower, Quantum America and the Energy Center of the University of Chile. The author of this document is the engineer in charge of developing the main tasks of this project as a member of the Energy Center. All comments presented in this document are exclusive responsibility of the author and do not necessarily represent the opinion of the institutions involved in the project.

INTEGRACIÓN ELÉCTRICA Y DESARROLLO DE UNA MATRIZ RENOVABLE EN AMÉRICA LATINA

Uno de los principales desafíos en el desarrollo futuro de los sistemas eléctricos es la incorporación costo efectiva de recursos renovables. En ese sentido, Latinoamérica cuenta con un alto potencial renovable; sin embargo, las metas esperadas por cada uno de los países de la región son aún conservadoras. La hipótesis de este trabajo es que la integración eléctrica entre los países de la región Latinoamericana puede permitir una mayor participación de generación renovable sin incrementar los costos totales.

Este estudio incluye una revisión de otros estudios enfocados en Latinoamérica en relación con la integración eléctrica, con el objetivo de incluir enfoques metodológicos o elementos utilizados. Estos trabajos han sido también considerados como referencias para definir candidatos de interconexión. Por otro lado, para tener una mejor comprensión de la realidad en Latinoamérica, se ha llevado a cabo una revisión de los sistemas eléctricos actuales y proyecciones para cada país de la región. Adicionalmente, esta revisión es utilizada para completar la base de datos de cada país.

Para validar la hipótesis planteada, este trabajo propone una metodología de escenarios incrementales donde puede ser comparado el costo total de cada caso. En todos los casos, es aplicado un modelo que minimiza el costo de inversión en generación y transmisión y el costo de operación del sistema eléctrico en un horizonte de 15 años. Para este propósito, se llevó a cabo el procesamiento de parámetros de entrada, la confección de series sintéticas de caudales hidráulicos y definición de su topología hidrográfica, definiciones de nuevas restricciones, y un marco de validación para cada país; los que fueron integrados a la herramienta de planificación. El escenario de referencia considera una proyección *business as usual*, sin un mayor desarrollo en energías renovables y considerando las interconexiones actuales y planificadas. El segundo escenario es intensivo en generación renovable. Se establece una meta de generación renovable a cumplir para el final del horizonte, pero sólo las interconexiones actuales y planificadas son consideradas. Finalmente, el tercer escenario es un caso renovable integrado, donde, además de la meta renovable, se permite el desarrollo de nuevos candidatos de interconexión en la región. Con estos escenarios, es posible comparar el costo total de inversión y operación para concluir si el escenario renovable integrado permite una mayor participación renovable con un menor costo total para la región.

Este trabajo permite concluir, en primer lugar, que la metodología de escenarios incrementales es apropiada para cuantificar los beneficios de una red integrada para alcanzar una matriz eléctrica altamente renovable en Latinoamérica. De acuerdo con los resultados obtenidos, es posible afirmar que un escenario con alta integración puede alcanzar una alta participación renovable sin incrementar el costo total.

Este trabajo es parte de un proyecto financiado por el Banco Interamericano del Desarrollo, y desarrollado por un consorcio de cuatro consultoras: Energy Exemplar, AWS Truepower, Quantum America y el Centro de Energía de la Universidad de Chile. El autor de este documento es el ingeniero que desarrolló las principales tareas del proyecto como miembro del Centro de Energía. Todos los comentarios presentados en este documento son exclusiva responsabilidad del autor, y no representan necesariamente la opinión de las instituciones involucradas en este proyecto.

"...like the philosopher Jagger once said, 'You can't always get what you want.'"

Gregory House

"And, in the end, the love you take is equal to the love you make"

John Lennon, Paul McCartney

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I'd like to dedicate this work to my family: to my mother Veronica, because you have been my main backbone my entire life, and I owe you all my accomplishments. To my father Juan José, the biggest responsible for my interest in this career. To my step-father Francisco, thank you for your infinite confidence and faith in me. To my brother Ignacio and my sister Magdalena, I'll be always extremely proud of you. To the rest of my big family that always have been encouraging me to be better every day.

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1. INTRODUCTION

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1.1. HYPOTHESIS

The hypothesis of this work is that an electric integration among the countries of the Latin American region can allow a higher share of renewable generation without increasing the total cost.

1.2. MOTIVATION

The Latin-American region counts with enough renewable resources to supply its entire electric demand of the continent. Nevertheless, the renewable targets set by each country are still conservative in comparison to the potential available [1]. This can be explained by the current reality of the Latin-American countries, where there is an ongoing learning process in the access to new technologies.

On the other hand, one of the main concerns regarding a high participation of generation based on variable resources —such as wind and solar energy— is the technical feasibility to dispatch these resources without compromising the reliability of the grid.

A limiting factor in the renewable generation growth in Latin America is the reduction of the analysis only into the resource and electric grid of each country, without considering an integration of this electric system with each other. In Latin America, studies advocating for the integration of regional systems have been led by the Regional Energy Integration Commission (CIER) [2].

Over the last years, several Latin American authorities have expressed their intention for a higher electrical integration among the countries in the region, considering the current existence of 22 major interconnections with capacities ranging from 50 [MW] to 3200 [MW]. With a higher integration level, a set of challenges and opportunities arises, especially in the development of renewable resources. First, if it seems reasonable to assume that the energy resources for an electric grid will be developed in a cost-effective way—for example, by installing solar generation in places where the solar resource is better— the same criteria can be applied for the entire region. Additionally, with the inclusion of different areas in the Latin American region, it is possible to exploit the time and space complementarity among variable resources.

Another opportunity concerning the regional integration is the security of the electric grid, since a bigger electric grid allows for a robust system with a higher inertia and the possibility of sharing operating reserves, among other services related to the network flexibility. These factors are crucial to increase the participation of variable resources.

1.3. OBJECTIVES

1.3.1. General Objective

The main objective of this work is to quantify the economic benefit of developing an integrated grid in Latin America, in order to achieve a high renewable participation in electric generation.

1.3.2. Specific Objectives

The previous analyses about interconnections in Latin America have considered specific projects among countries, instead of a centralized vision of development. One of the relevant objectives of this work is to apply an optimization model to solve the expansion of generation and transmission in the entire region with a centralized approach, considering both technical and economic constraints.

To ensure the solvency of the results in this work, a relevant objective is to define the proper assumptions regarding the constraints and forecast values of the variables needed to define each electric system in the region.

Another specific objective of this work is to establish the location of the main generation resources that should be developed in the Latin American region. In the same way, the study aims at determining which interconnections can promote the development of these generation resources along the continent.

Finally, as a complement of the main objective, a quantification is proposed of the installed capacity of each technology to reach a high renewable participation, as well as the outcoming emissions of these results.

1.4. SCOPE

In this work, an optimization model will be applied to define the expansion of generation and transmission for Latin America. This model involves assumptions and scopes as follows:

- The transmission network will be simplified for each country according to the topology of the grid. The objective is to have a zonal representation of the main generation and consumption centers, as well as quantify the transmission capacity among them.
- The hydraulic topology will be simplified according to the characteristics of each country, representing the main basins and reservoirs of each system.
- All the model variables will be integrated with a deterministic approach, including the cost projections. The only endogenous stochastic variable included in the model will be the natural inflows for each basin, where a probabilistic time series scenario will be proposed.

- The time resolution in the model will consider a dispatch in non-chronological energy blocks per month, where each block will be built from the load duration curve for the entire region.

1.5. DOCUMENT STRUCTURE

This document is divided into five chapters including the present Introduction, where the motivation, objectives and scope of the work are described.

Chapter 2 contains a revision of the state of the art on generation and transmission expansion planning, as well as integration studies in Latin America. Also, a description is presented of the current reality of electric generation in each country, as well as the operative and future interconnections in the region.

Chapter 3 is focused on the definition of the methodological approach of this work. This description includes the characteristics of the mathematical model, its constraints, and the set of indicators that will be analyzed from the results. In chapter 4, the application of the methodology is described, including the detail of the assumptions, the simulated scenarios and results.

Finally, chapter 5 is dedicated to the findings and conclusions of the work, with special focus on the results of the model used. Additionally, this section proposes future projections in this work field.

2. STATE OF THE ART

This chapter is divided in three sections displaying preliminary information for the study. The first section is dedicated to previous studies related to generation and transmission expansion planning. The second section addresses previous studies related to integration in Latin America. The third is a revision of the current reality of the electric systems in the continent, including their development in the last years and expectations for the future.

2.1. GENERATION AND TRANSMISSION EXPANSION PLANNING

Methods to solve a co-optimization problem of generation and transmission expansion have been developed for some time now. As is recognized in [3], the transmission expansion planning of an electric power system is a large-scale, complex and nonlinear problem, and its nature is mixed integer. Within this complexity, a transmission expansion planning could be classified into two categories: a static (single-stage) planning, where the decision must be about the transmission solution to be built; and a dynamic (multi-stage) planning, where in addition to the transmission solution, the time when this solution must be installed also is figured out.

In [4] is presented a method to obtain a transmission network solution with a “two-steps” methodology: a first step of linear flow estimation, and a second step of new circuit selection. This works offers a transportation model, that later will be analyzed and improved in [5]. This transportation model allows the usage of linear programming to solve the transmission network problem as is proposed in [6].

For generation expansion planning, considering that there are uncertainties that affects the expansion of the generation, a stochastic programming is proposed to internalize a set of future scenarios with its probability of occurrence. In [7] is proposed a stochastic mixed-integer programming to include the hydrological uncertainty in the generation capacity expansion planning, while in [8] is applied to consider the demand uncertainty.

In application cases, the Westerns Electricity Coordinating Council performs an Interconnection-wide Transmission Plan, which in its 20-years studies uses a Long Term Planning Tool. As is described in [9], this tool iterates between a generation expansion and operational decision and a transmission expansion decision, as is presented in Figure 2-1. In this case, the transmission expansion planning is modeled as a mixed-integer linear optimization, since feasible transmission alternatives are considered for a particular system condition. In addition, in the cost minimization are considered environmental, policy, economic and reliability factors.

In the case of ENTSO-E analysis, the Ten-year Network Development Plan is achieved through a combined cost-benefit and multi-criteria assessment described in [10], which exceeds the technical and economic analysis, but includes the categories presented in Figure 2-2. This reference suggests the relevance of includes other matters than the conventional constraints of the optimization models used for generation and transmission planning.

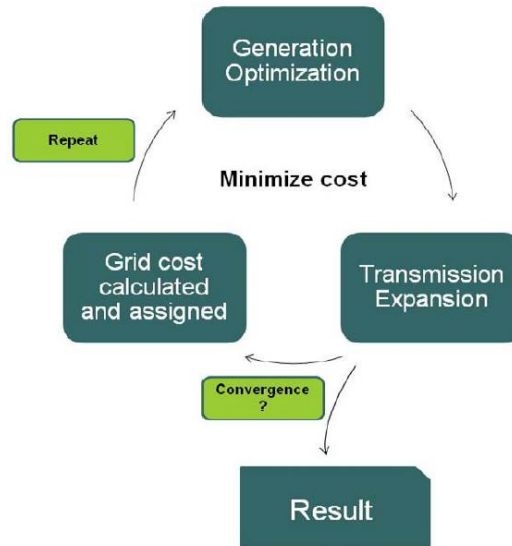


Figure 2-1 LTPT iterative process. Source [9]

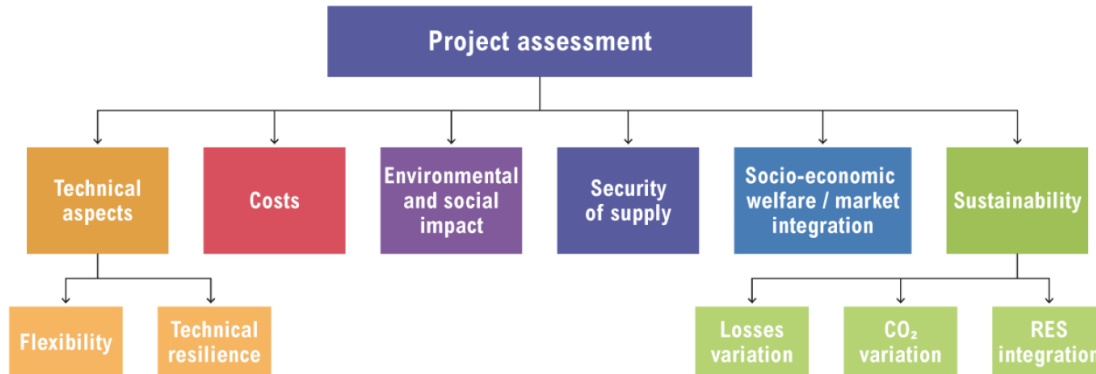


Figure 2-2 Main categories of the Project assessment methodology. Source [10]

Another approach for transmission planning is the integration of future generation uncertainty into the optimization model, considering different development scenarios for generation, as is applied in [11]. This is especially relevant in Latin American countries that need to define the transmission program without certainty of the generation development, in cases where this last one is a private decision.

According to [12], the operation and planning of power system is influenced by resilient requirements and the increasing of renewable energy resources. Considering the future uncertainties and the objective of minimize the operational and investment cost of the system subjected to technical constraints, this work proposes that the next generation transmission expansion planning follows the process presented in Figure 2-3. This proposal also agrees with the concept of a transmission expansion planning subjected to generation planning uncertainties.

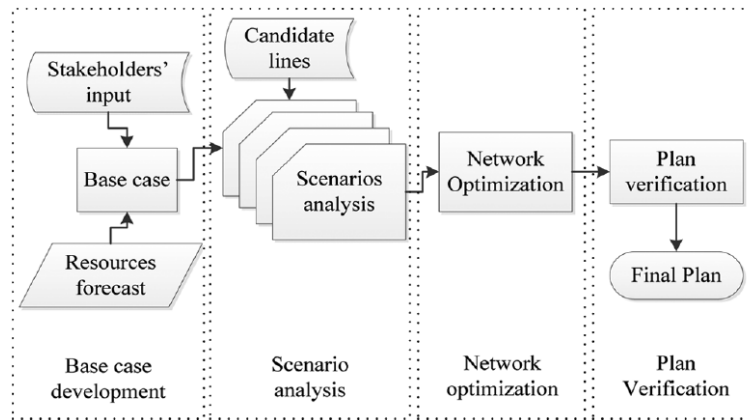


Figure 2-3 Next generation expansion planning process. Source: [12]

One of the major challenges of a generation and transmission expansion planning model is the properly representation of the short-term operational effects. With a higher share of variable generation, it is necessary to have flexible generation to complement that variability. This flexibility is restricted to the technical characteristics of the installed capacity, especially regarding minimum output capacity, ramping capacity, minimum operation and shut-down times, among others. In that sense, conventional models usually don't represent properly these short-term requirements, since these requirements need a chronological approach of the time steps modeled.

Some examples of the public-sector models are: The National Energy Modeling System (NEMS), designed and implemented by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) [13], and the TIMES (The Integrated MARKAL-EFOM System), based on the Market Allocation Model (MARKAL) [14]. These models don't consider chronological time step, but an approximation of three to four periods to represent the day, which does not allow a representation of the operational constraints.

The National Renewable Energy Laboratory has developed an integrated tool that includes planning and dispatch constraint, in the model named Resource Planning Model (RPM) [15]. However, the feasibility of apply a model with short-term constraint is the simulation time required to solve a large-scale model, especially in cases with a high share of hydrological resource with storage capacity.

Regarding the consideration of Kirchhoff's Voltage Law in expansion planning models, [16] concludes that disregarding this constraint could distort the optimal network solution, in particular could generates new loops in the transmission grids that will increase congestions not identified in a simplified model with transmission based on transportation.

2.2. INTEGRATION STUDIES IN LATIN AMERICA

To define a proper methodology to reach the objectives of this work, it is important to make a review of methodologies used in previous studies, with the aim of keeping those methodological

aspects that can be applied to this study. Since this is the first analysis including the entire Latin American region, the amount of information involved will be higher in contrast with other studies.

In this subsection, two studies employed to define the proposed methodology are described. Nevertheless, other documents have been revised and used as references to define specific interconnection candidates. The first aims at an increase in the interchange of electricity between Mexico, Guatemala and Central America [17]. It conducts a review of the current capacity and analyzes if an increase of the interconnections is technically allowed and economically justified by the price projections between the markets.

Another study considered for the input database of this work is the analysis of scenarios for the electric integration of Belize with its neighbor countries [18]. Similarly, the “Arco Norte” project, defined and studied in [19], is included in the database.

A review of the integration development in different regions of the world is presented in [20]. It includes not only the Latin American, but also the European, North American, Asian and African cases, with the objective of presenting the challenges and opportunities to carry an integrated electric process in Latin America. Finally, a similar analysis of the North American and Latin America experience is presented in [21], with the purpose of presenting lessons learned to move forward in further integration processes.

2.2.1. CIERT 15 Project, Phase II [22]

This study is titled “Estudio CIER: Transacciones de energía entre los sistemas de la comunidad Andina, America Central y Cono Sur – Factibilidad de su Integración”. It is also known as the CIER 15 Project. Its objective illustrates that it is possible to raise interconnection schemas and comply with the internal policies of each country.

The study involves three areas of Latin America: Central America, including Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama (the current interconnection between Guatemala and Mexico is also considered, but the analysis does not include further development with Mexico); The Andean Community, including Bolivia, Colombia, Ecuador and Peru; and the Mercosur area, which involves Argentina, Brazil, Chile, Uruguay and Paraguay.

The Phase II has been divided into two modules. The first one has the objective of determining the energetic resources available in the region. Meanwhile, the second module is relevant to review methodologically, since its goal is to analyze the economic feasibility of interconnection projects.

Figure 2-4 presents the methodological schema used in this project. It is relevant to notice that this methodology presents a comparative analysis between a scenario without interconnections and one with interconnections. In the first place, the database is fixed for all scenarios in terms of the internal capacity of generation and transmission of each country. Then, the scenarios compared are a reference case –which does not involve interconnection projects among countries— and an interconnected case considering a determined group of interconnections previously defined.

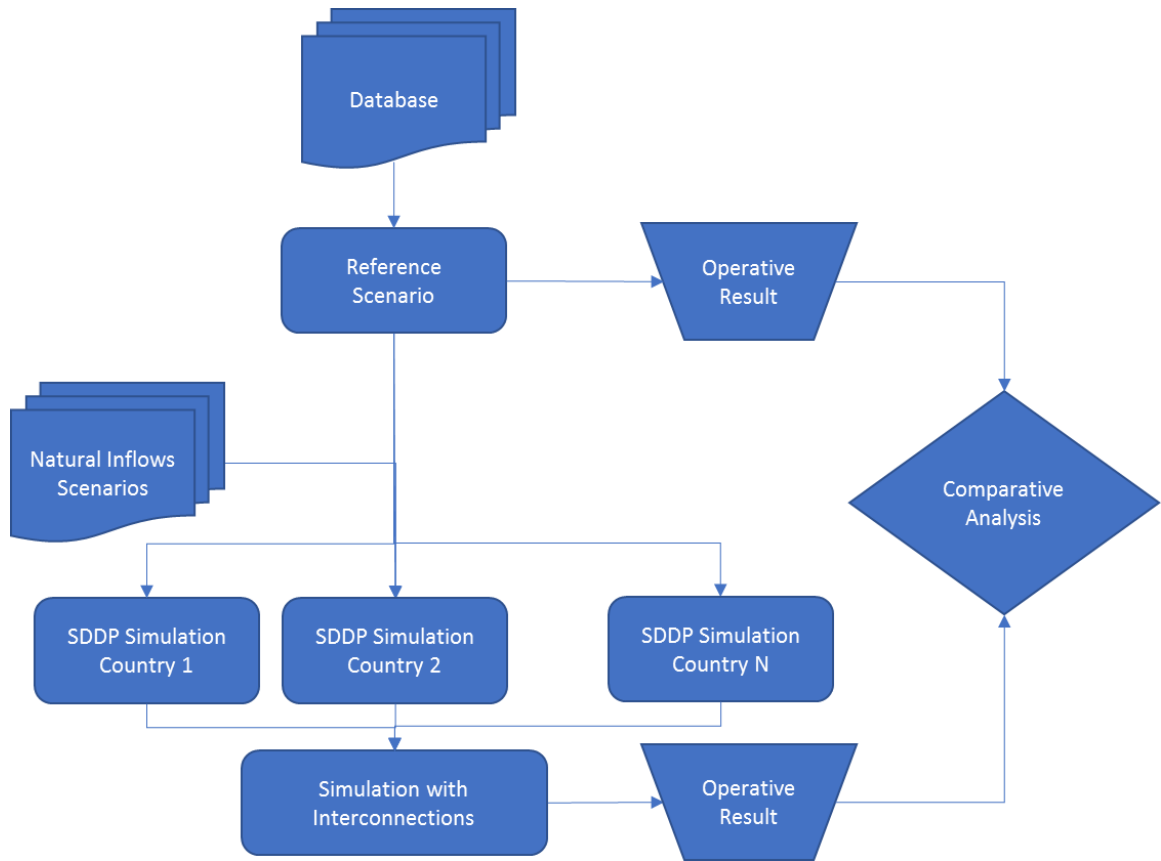


Figure 2-4 Methodology used in CIER 15 Phase II

Then, a Cost-Benefit Index is employed to conclude the benefit of each project, calculated as the ratio of annual reduction in the operational cost of both countries involved in one interconnection, as well as the annualized investment cost of the line. Additionally, a Cost-Benefit and Environmental Index is used, in which the annual benefit also includes a valuation of the CO_2 reduction.

An interesting aspect of this work is that the approach includes the comparative analysis of the operation of a scenario without interconnections and a scenario with interconnections. Additionally, it is pertinent to incorporate the natural inflow scenarios, considering that hydropower constitutes one of the main resources in the region.

2.2.2. Technical and Economical Prefeasibility Analysis of Interconnections [23] [24]

The objective of this study is to identify sustainable and feasible alternatives of electricity exchange among Bolivia, Chile, Colombia, Ecuador and Peru. This work considers a methodology of incremental scenarios, where all of them have a fixed generation capacity plan along the horizon.

Figure 2-5 presents the methodological schema of the study. It can be observed that this work defines the design of interconnections by establishing a comparison between a base scenario, considering the current interconnections, and a scenario without interchange limits. Then, over this design, four scenarios are presented, each one including an additional interconnection in the region. For all scenarios, the following results are calculated: operational generation margin, energy load at marginal price, operational cost minus annualized investment and operational cost of interconnections, valuation of CO_2 emissions and a contingency analysis. From those results, the comparison between the reduction in the operational cost and the annualized cost of the interconnection is the most relevant indicator to conclude the economic feasibility of each interconnection project.

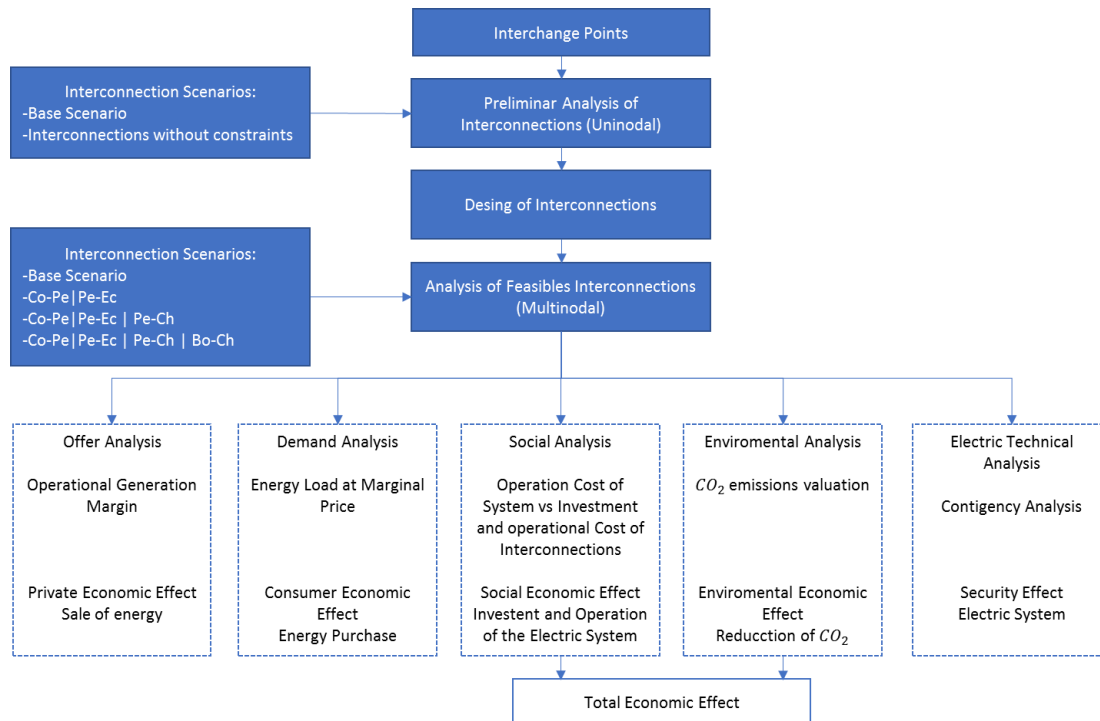


Figure 2-5 Methodology used in PNUD Study

On the other hand, this work presents a different approach in terms of the definition of the interconnection design. It does not use only fixed candidates, but also optimizes those needed. Furthermore, it is important to notice that the relevant results are similar to other studies, where the reduction of the operational cost of the system should compensate for the cost of the interconnection.

2.2.3. Central America Electric Integration (SIEPAC) [25]

The SIEPAC project is a Regional Electric Transmission System in Central America, developed from 2010 to 2014 with support of the Inter-American Development Bank. The system has a mean capacity of 300 MW in 230 kV, with 1800 km of lines from Guatemala to Panama. This integration includes a common Regional Electric Market (MER), where any agent can trade electricity

regardless of their location or their country. In operational terms, there is a Regional Operator Entity (EPR) that acts as the operator of the integrated system, where both the operation and the expansion of the system are executed with a centralized perspective.

The feasibility study of this project included a financial evaluation with different integration levels, both in the expansion planning and the operation of the grid. The conclusion of this study is that, with a low integration in the planning and operation processes, the economic benefit does not compensate the investment cost. On the other hand, a higher integration allows an increase in the benefit, eventually exceeding the investment cost.

For future scenarios, study [25] based on [26] estimates that a high integration in the electric market can allow a reduction in 5% to 20% in the price of electricity. The same study estimates that this integration can increase the GDP of each country between 0.1% and 0.5%, as a result of the price reduction and the growth of investment.

The net revenue of the transactions in the Regional Electric Market has been quantified in 132 million US\$ in the period 2013-2015. This project is a clear example of the benefit that the electric integration can bring to the participating countries, not only in terms of the security and flexibility of the grid and the reduction of operational costs, but also in the impact on the economy as a result of lower electricity prices and the increase of investment in the electricity sector.

2.3. REVIEW OF ELECTRIC SYSTEMS IN LATIN AMERICA

Any approach of integration in Latin America must take into account the different realities of each country. It must also consider the proportion of energy consumed and generated in each country of the region. This is essential to understand the limits and opportunities regarding the current reality, resources and projections of these countries. Figure 2-6 illustrates the participation by each country in generation by 2012.

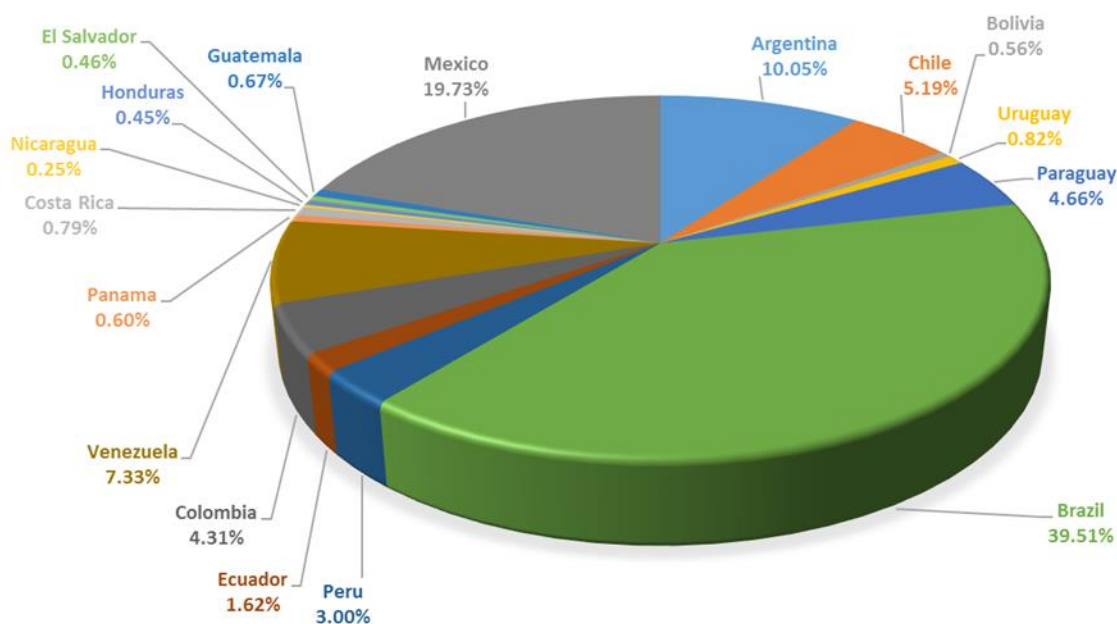


Figure 2-6 Generation Participation by each country in the Latin American region in 2012 [27]

One of the main challenges to achieve a reliable study in Latin America is the amount of information available for each country. For example, Figure 2-7 presents the available information in terms of installed generation capacity and expansion plan for each country. As observed, some countries not only have updated information for the current capacity, but also an extended expansion plan. On the other hand, some countries do not have information of expansion plans or previous data regarding the current capacity.

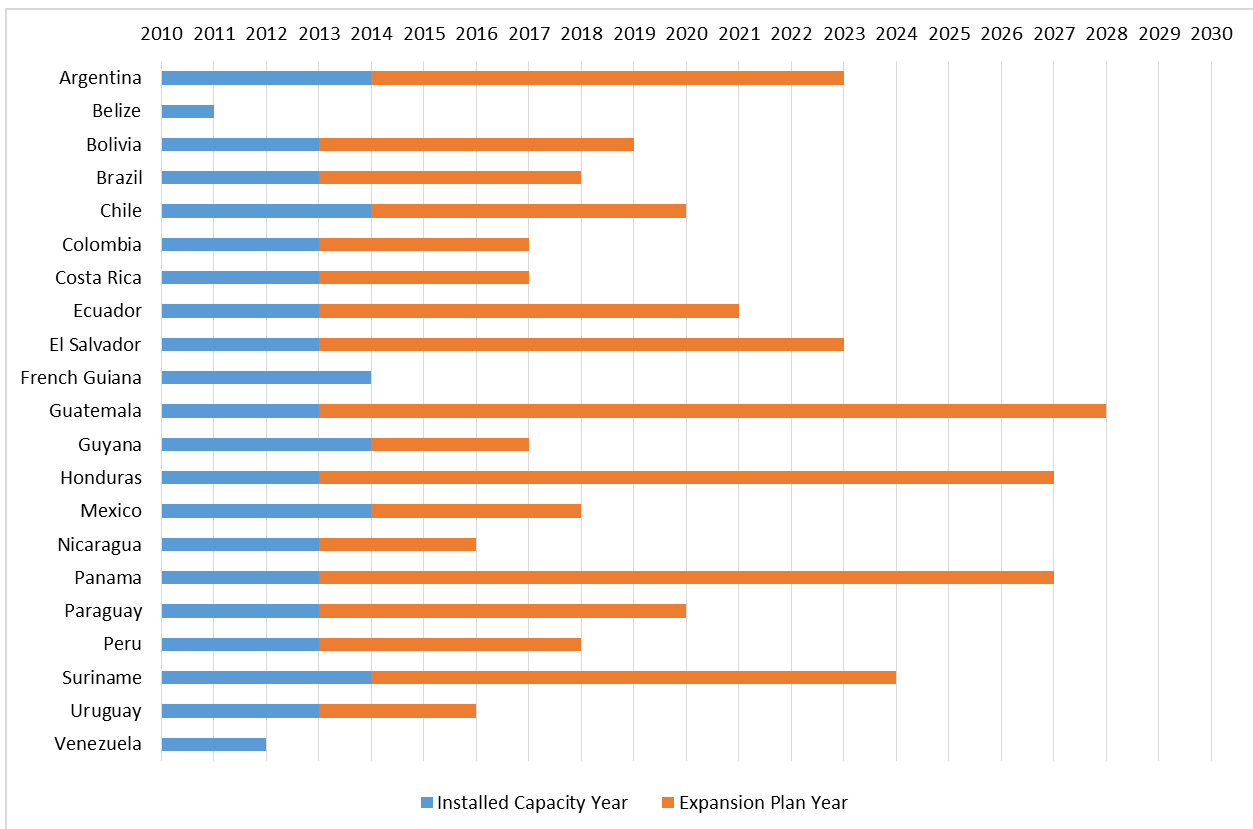


Figure 2-7 Installed Capacity and Expansion Plan Information

2.3.1. REVIEW OF RENEWABLE TECHNOLOGIES IN LATIN AMERICA

Considering the amount of information to describe the current reality of each country, an Appendix has been included in this report with the main statistics for all the countries involved in the study. This section will review the definition of renewable energy set by each country and the target expected in the future years in terms of renewable generation. Other relevant data, such as the renewable target, will be covered in further sections.

2.3.1.1. Definition of renewable energy per country

Although there is a common idea of what is defined as renewable energy, there are a few differences from country to country, especially regarding the concept of *non-conventional renewable energy*, which usually excludes large hydropower plants. Consequently, Table 2-1 defines the non-conventional renewable energy idea for each country, in order to have a clear idea of the similarities and differences within the region.

Considering that the definitions of non-conventional renewable energy can be quite different, especially in terms of the size of hydropower plants, the formal definition used will be applied to all renewable energy for the purposes of this study. This includes: Solar PV, Solar CSP, Biomass, Biogas, Wind, all Hydropower plants, Geothermal, Tidal and Wave.

Table 2-1 Definition of Non-Conventional Renewable Energy per Country

Country	Definition of Non-Conventional Renewable Energy
Argentina	Solar, Biomass, Wind, Geothermal, Tidal, Landfill Gas, Purification Treatment Plant Gas, Biogas, Hydro < 30 MW
Bolivia	Solar PV, Biomass, Wind, Hydro < 2 MW (Target includes complete Hydro)
Brazil	Solar, Biomass, Wind, Hydro < 30 MW
Chile	Solar, Biomass, Wind, Geothermal, Tidal, Hydro < 20 MW
Colombia	Solar, Biomass, Wind, Geothermal, Hydro < 10 MW
Ecuador	Solar PV, Biomass, Wind, Geothermal, Hydro < 50 MW
Paraguay	Solar, Biomass, Wind, Hydro < 2 MW
Peru	Solar, Biomass, Wind, Geothermal, Tidal, Hydro < 20 MW
Uruguay	Solar, Biomass, Wind, Geothermal, Tidal, Small Hydro
Venezuela	Does not have a legal definition.
Belize	Does not have a legal definition.
Costa Rica	Solar, Biomass, Wind, Geothermal, Hydro < 20 MW
El Salvador	Solar, Biomass, Wind, Geothermal, Hydro
Guatemala	Solar, Biomass, Wind, Geothermal, Tidal, Hydro
Honduras	Solar, Biomass, Wind, Geothermal, Wave, Tidal, Hydro
Nicaragua	Solar, Biomass, Wind, Geothermal, Hydro
Panama	Solar, Biomass, Wind, Geothermal, Hydro < 10 MW
Mexico	Solar, Biomass, Wind, Geothermal, Wave, Tidal, Hydro < 50 MW

2.3.1.2. Renewable Energy Targets per Country

A relevant input to understand the projection expected by each country is the renewable target set by authorities. As observed in the description column of Table 2-2, some of the targets have been defined in National Laws, while others are just pronounced initiatives.

Table 2-2 Renewable Energy Target for each Country

Country	Target 2015	Target 2020	Target 2025	Target 2030	Target Unit	Description
Argentina	8.0% by 2016	8.0%	8.0%	8.0%	Energy	Law 26.190 (2006) set an 8% target in the national electric

Country	Target 2015	Target 2020	Target 2025	Target 2030	Target Unit	Description
						consumption by 2016. Main incentive: value-added tax reduction to the investment.
Bolivia			70.0%	70.0%	Energy	Article 379 of the State Political Constitution: "development and promotion of alternative energies" sets a 70% alternative and hydraulic energies target by 2025.
Brazil			10.0%	10.0%	Energy	Law 10.762 (2003) 10% target of NCRE in the electricity matrix by 2025.
Chile	4.5%	9.0%	17.9%	18.6%	Energy	Law 20.698 (2013) set a 20% target of NCRE generation by 2025.
Colombia	3.5%	6.5%	6.5%	6.5%	Energy	Law 697 (2001) and Resolution 180.919 (2010) set a 6.5% of NCRE by 2020 for the interconnected system and a 30% of NCRE by 2020 for non-interconnected areas.
Ecuador		4.2 GW hydro by 2022 277 MW other than hydro by 2022			Installed Capacity	Does not have an NCRE target, but Regulation N° CONELEC - 004/11 guarantees preferential energy selling prices and preferential dispatch conditions to the NCRE generation units.
French Guiana						Does not have a publicly available official NCRE target or any promotional plan.
Guyana		20% (2017) 28% (2022)	47% (by 2027)			Does not have a publicly available official NCRE target or any promotional plan. Informed CARICOM target instead.
Paraguay						Does not have an NCRE target or any promotional plan.
Peru		6.0%				Does not have an NCRE target, but Legislative Decree 1002 (2010) guarantees a minimum 12% return to the NCRE electricity generation.
Suriname		20% (2017) 28% (2022)	47% (by 2027)			Does not have a publicly available official NCRE target or any promotional plan. Informed CARICOM target instead.

Country	Target 2015	Target 2020	Target 2025	Target 2030	Target Unit	Description
Uruguay	300 MW	300 MW	300 MW	300 MW	Installed Capacity	Decree N° 403/009 sets a target of 300 MW of wind generation units installed by 2015.
Venezuela		613 MW additional				Does not have an NCRE target or any promotional plan.
Belize				15 MW Hydro by 2033	Installed Capacity	Does not have a public NCRE target or any promotional plan.
Costa Rica		28.2%				Does not have a publicly available NCRE target. Tax law incentives to promote renewable energy decrees tax reductions for renewable projects.
El Salvador			652[W] (by 2026)			Does not have an NCRE target. Tax law incentives to promote renewable energy decrees tax reductions for renewable projects.
Guatemala			60% (including hydro by 2022)			Does not have an NCRE target, Decree N° 52 – 2007 sets tax reductions for renewable projects.
Honduras			60% (including hydro by 2022)	80% (including hydro by 2034)	Energy	Does not have an NCRE target, Decree N° 70 – 2007 sets preferential terms for renewable projects.
Nicaragua	51%	74%	74%	91%	Energy	Indicative plan of electric generation expansion sets a target of 91% renewable generation (including all hydroelectric generation) by 2027.
Panama			706 MW hydro (by 2023)			Does not have an NCRE target. Law N° 45 – 2004 sets preferential terms for renewable projects.
Mexico			35%	35%	Energy	Law on the Use of Renewable Energies and the Financing of the Energy Transition (2008) set a 35% target of electricity generation with renewable resources by 2024.

2.3.2. REVIEW OF INTERCONNECTIONS IN LATIN AMERICA

This work must consider the current interconnections installed in the region –operative or non-operative. In this sense, Table 2-3 presents a review of all the installed interconnections in the region, while Figure 2-8 illustrates these interconnections in a map. It is interesting to notice that most of the interconnections are concentrated in the northwest and southeast regions. In the latter, three binational hydropower plants have also been included (Salto Grande, Yacyretá and Itaipú). Considering the capacity of the binational power plants, the total amount of interchange capacity in Latin America is over 27 [GW], yet still presenting a high potential for new interconnections.

The future projects or candidates considered in the project will be presented in further sections of this document.

Table 2-3 Current Interconnections in Latin America

Name	ID	Transmission Capacity [MVA]	Nominal Voltage [KV]	Technology	Status
Chile-Argentina	ICx01	717.07	345	HVAC	Operative
Peru Ecuador	ICx02	332	230	HVAC	Operative
Ecuador Colombia	ICx03	332	230	HVAC	Operative
Colombia Venezuela	ICx04	100	230	HVAC	Operative
Paraguay-Brazil	ICx05	50	220	HVAC	Operative
Panama-Costa Rica	ICx06	300	230	HVAC	Operative
Costa Rica-Nicaragua	ICx07	300	230	HVAC	Operative
Nicaragua-Honduras	ICx08	300	230	HVAC	Operative
Honduras-El Salvador	ICx09	300	230	HVAC	Operative
El Salvador-Guatemala	ICx10	300	230	HVAC	Operative
Honduras-Guatemala	ICx11	300	230	HVAC	Operative
Guatemala-Mexico	ICx12	200	400	HVAC	Operative
Rincón de Santa María-Garabí	ICx13	2000/2200	500	HVDC	Operative
Yacyretá	ICx14	3200	500/220	HVAC	Operative
Salto Grande [AR]- Salto Grande [UR]	ICx15	1890	500	HVAC	Operative
Colonia Elia-San Javier	ICx16	1386	500	HVAC	Operative
Brasil(Itaipú)-Paraguay(Itaipú)	ICx17	14000	500/220	HVAC	Operative
Livramento-Rivera	ICx18	70	230/150	HVDC	Operative
Pte Médici-San Carlos	ICx19	500	500	HVDC	Official Expansion Plan
Colombia Venezuela (2)	ICx20	100	230	HVAC	Operative
Venezuela Brazil	ICx21	200	230	HVAC	Operative
Belize Mexico	ICx22	50	115	HVAC	Operative



Figure 2-8 Current Interconnections in Latin America

3. METHODOLOGY

As mentioned in this document, the approach proposed to understand the impact of an integrated electric grid in the development of renewable resources in Latin America will rely on a mathematical model, which will be used to define the optimal expansion in generation and transmission. This model assumes a centralized perspective of generation and transmission development in the entire region.

Such a centralized plan is a simplification of this methodology, considering that each country will make their own decisions about expansion and, in most cases, decisions on generation will be made by the private sector, often without a centralized objective. Fundamentally, this model will contribute to minimize the net present value of the investment and operational costs for the entire Latin American grid in a time horizon.

To properly define each country' model, it is necessary to define both specific and general criteria for constraints and forecast values of each variable in the model. This process must be validated with references from all countries, in order to ensure the quality of the results of the scenarios simulated. This validation is carried out through a benchmarking process considering the last available planning report of each country studied.

The methodology proposed for this work consists of an incremental sequence analysis. It allows to quantify the marginal benefit of each sensitivity under study. Figure 3-1 shows a methodological schema of the three incremental scenarios that will be used to conduct a comparative analysis. Each scenario is described as follows:

- **Base Scenario:** a business-as-usual-oriented scenario, in order to meet the projected demand until the end of the horizon. The objective of this scenario is to have a reference case without constraints related to renewable targets or interconnection development. In this case, there is no possibility of building new interconnections beyond those under construction or the planned projects.
- **Renewable Scenario:** this scenario considers the same description of the base one, but includes a renewable generation target that must be reached by the end of the horizon. Similarly, it does not allow the construction of new interconnection projects.
- **Integrated Renewable Scenario:** This case also includes the renewable generation target set in the Renewable Scenario, but allows the construction of new interconnections among countries by optimal decision of the model.

With this methodology, it is possible to quantify the cost for the application of each sensitivity. Additionally, the method proves useful to determine if the possibility of installing new interconnections among countries allows a higher participation of renewable resources with a lower total cost for the system.

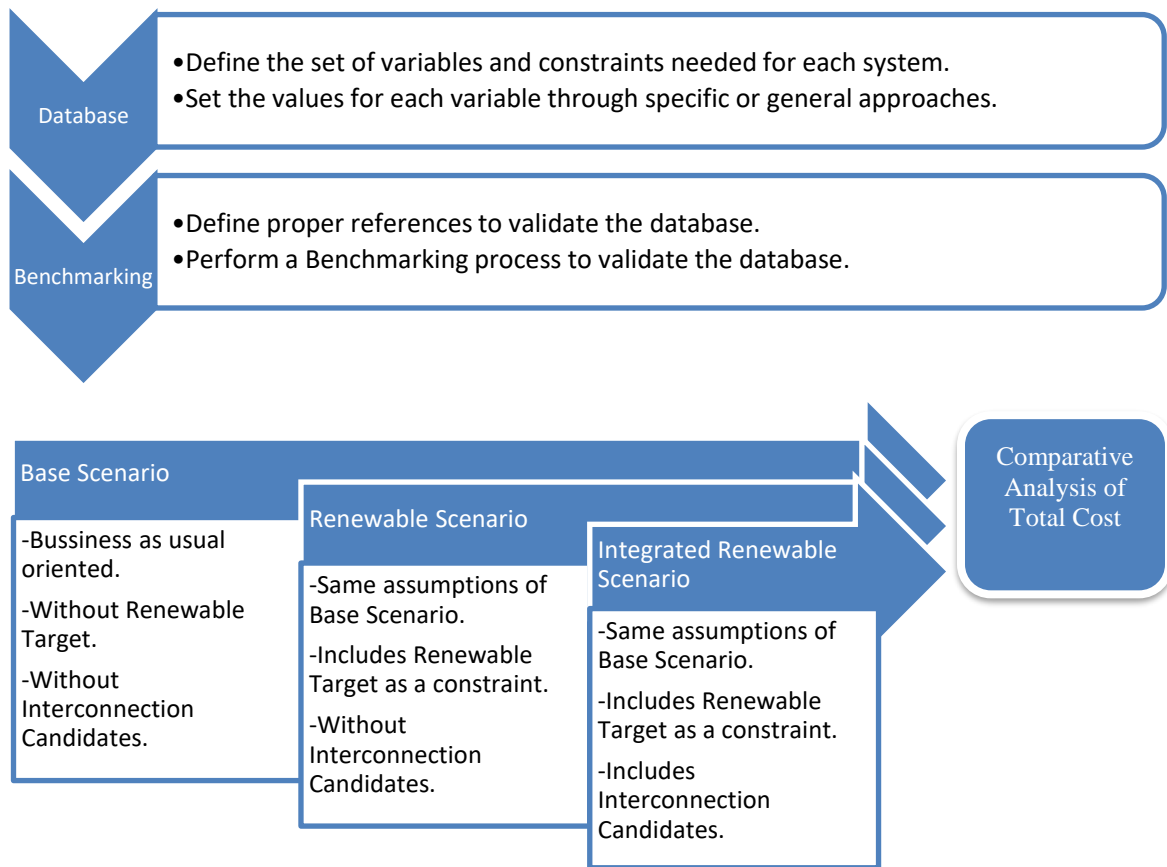


Figure 3-1 Methodology Schema

One of the keys of this work is to solve this optimization model with a centralized approach. For this reason, it is relevant to analyze the different results per country for each scenario. This will contribute to the goal of understanding which countries could be encouraged to build generation and transmission projects, and how a centralized integrated operation could affect the total cost for each country.

3.1. OPTIMIZATION MODEL DESCRIPTION

The model used in this work is a tool in a commercial software developed by the company Energy Exemplar, named PLEXOS ® Integrated Energy Model.¹ Specifically, the released version PLEXOS 7.3 R1 64bits has been employed. This software allows the resolution of an expansion problem using a linear programming technique and using CPLEX Optimizer² as a solver. In general, as showed in Figure 3-2, the model minimizes the net present value of the total cost of the system. It is calculated as the addition of the investment cost and the production cost over a defined

¹ Link: <http://energyexemplar.com/software/plexos-desktop-edition/>

² Link: <https://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/>

horizon. As a result, this minimization simultaneously solves the expansion of the generation and transmission capacity and the dispatch of each time block.

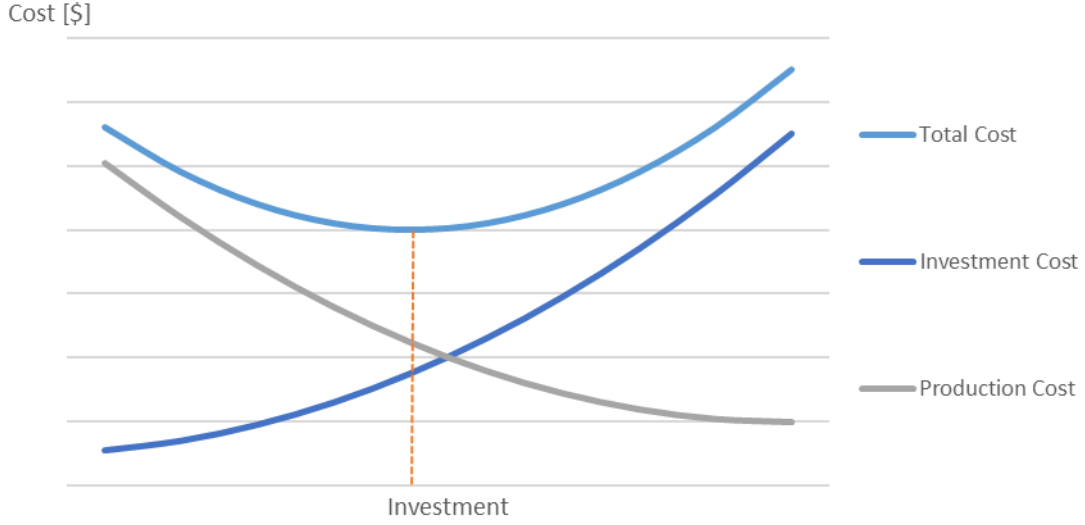


Figure 3-2 Total Cost Minimization

This minimization is a linear problem mainly represented in the following equations.

$$\min \sum_t^T \sum_g^G \sum_n^N ((Cap_T^g \cdot Cost_{Inv}^g + Cap_T^{n,m} \cdot Cost_{Inv}^{n,m}) + (Pgen_t^g \cdot VC_t^g + USE_Cost_t)) \quad (1)$$

$$\sum_g^G Pgen_t^{g,n} + \sum_{m \neq n}^N F_t^{n,m} = Load_t^n + USE_t^n, \forall t, n \quad (2)$$

$$Pgen_t^g \leq Cap^g, \forall t, g \quad (3)$$

$$F_t^{n,m} \leq Cap^{n,m}, \forall t, n, m \quad (4)$$

$$Cap_Reserve_t^n \geq Cap_Reserve_1^n, \forall t, n \quad (5)$$

Where, t is the time step index, g the generation index and n the node index. In the same way, T is the time horizon, G the total amount of Generators and N the total amount of nodes. Equation (1) represents the minimization of the Investment Cost for generation and transmission, the Operational Cost and the Unserved Energy Cost. Equation (2) defines the system balance of generation, load and unserved energy. This balance is applied for each node and time step according to the transmission constraints. Within this constraint, it is included the Kirchoff's Law of current (KCL). The time step considered for the balance is equivalent to the energy block. From (3) can be noticed that the generation for each unit is limited to the generation capacity. This capacity is modeled as a continuous variable subject to the candidate maximum potential, for example, in the case of solar and wind this potential is related to the energy resource. From (4) can be concluded that this model considers only a transfer capacity of the line, without considering the Kirchoff's

Law of voltage (KVL). This simplification is based on the concept of model only transfer capacity between zones and not necessarily real transmission lines. The transmission capacity is also modeled as a continuous variable subject to the candidate maximum potential. The investment decision is taken on annually basis by the model.

In (5) is specified a novel constraint related with each country adequacy policy. In this work is applied the assumption that each country will protect its own system from foreign electricity dependency, this assumption is included in the model as a minimum capacity margin as the ratio of the national installed capacity and the annual peak load. This margin should be at least the same or higher than the initial margin for each country over time. Considering that the investment decisions are annual, this constraint is also applied on that time basis.

Other specific constraints are included in the model depending on the country, like minimum or maximum capacity factor for hydropower generators, related with water use restrictions. In the same way, constraints of maximum energy for some thermal generator are included according to fuel limits or environmental constraints.

For reservoirs, the hydrological balance considers the minimum and maximum volumes as constraints, and a monthly balance of the total energy of the input/output water flow for each reservoir. In addition, in each system is modeled a simplified hydrological network, considering natural inflows, efficiency of each hydropower turbine, and the hydrological topology.

The only uncertainty included endogenously in the model is the natural inflow time series, where each hydrological scenario is considered with a relative weigh according with the probability of its occurrence. The stochastic model applied uses a two stages scenario-wise decomposition, illustrated in Figure 3-3, that, after taking a build decision, calculates the total cost considering the expected operational cost of each sample with its probability of occurrence, and iterates over the build decision to find the optimal solution.

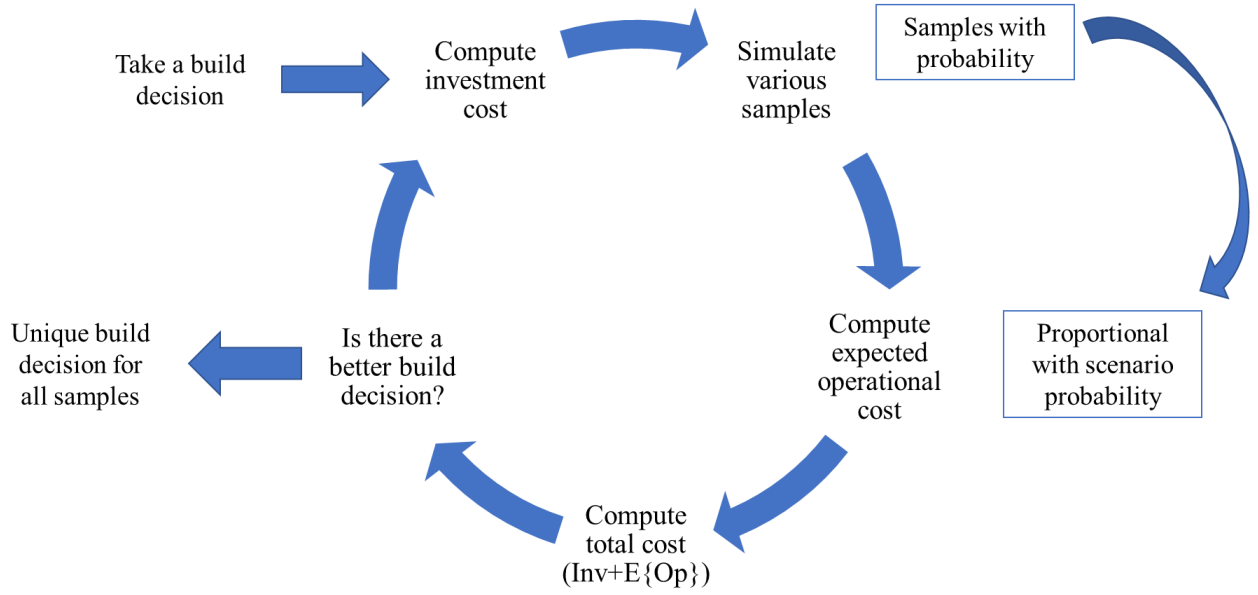


Figure 3-3 Two stages scenario-wise decomposition

In those scenarios where a renewable target is considered, the constraint included is presented in (6).

$$\sum_n^N \sum_g^G Pgen_t^{g,n} \geq Target \cdot \sum_n^N Load_t^n, \forall t \in 2030, \forall g \in \{Renewable\} \quad (6)$$

To apply this model, it is necessary to define the set of inputs regarding the energy offer, energy demand and transmission capacity. Each element of the input can be divided into three categories, as showed in Figure 3-4:

- Existing capacity: it includes the elements, power plants and transmission lines under operation by the beginning of the horizon.
- Under construction and planned capacity: those elements defined as under construction or planned by the authority. In this case, it is considered that such elements will certainly be part of the system.
- Future candidate's capacity: the elements in this category will be part of the solution grid only if the model decides to build them according to the optimization process. These candidates should be related to the availability of energy resources in each area, the investment cost trends, the fuel price trends, and any other constraint that can affect the development of new facilities.

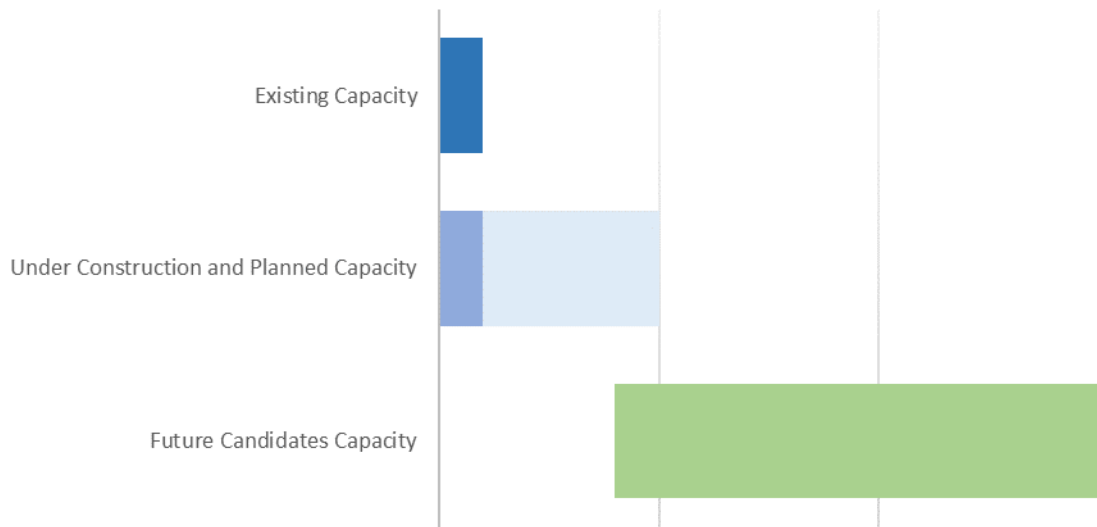


Figure 3-4 Power System Elements Categories

4. APPLICATION OF THE OPTIMIZATION MODEL

This section is dedicated to the application of the methodology proposed. It includes all the input information used in the database, the assumptions and constraints modeled in this work, the definition of scenarios according to the methodology proposed (and the study case in particular) and, finally, the results of this application for each scenario.

4.1. ASSUMPTIONS FOR THE OPTIMIZATION MODEL

The study case considers a horizon of 15 years, from 2016 until 2030. This horizon is extended in two years, in order to remove the end effects of large reservoirs from the results. These two years are subject to the same conditions as the last year of the horizon in terms of demand, fuel price, capital cost, among others. It is also relevant to point out that this model considers the perpetuity of the last year in the present net total cost of the simulation.

This work includes the 21 countries from continental Latin America: Argentina, Brazil, Belize, Bolivia, Chile, Colombia, Costa Rica, Ecuador, El Salvador, French Guiana, Guatemala, Guyana, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Uruguay and Venezuela. All the sources considered in this work were collected in 2015. However, some key assumptions have been changed in the last years, such as the capital cost of the renewable technologies. These changes may modify the result of the analysis.

The time resolution is set in 6 energy blocks per month. The investment decision is made yearly. In terms of generation capacity, all the power plants of the named countries have been included. This database has a total of 5062 generators and 718 hydraulic reservoirs.

4.1.1. Transmission Network

The electric grid has been defined to represent the main production and consumption zones of the region, as well as the transport capacity between those areas. Figure 4-1 shows the network proposed. For example, the definition of a node in the southern zone of Argentina is observable. Even though the current generation and load are not a large part of the total system, there is a relevant wind potential. On the other hand, there are nodes dedicated specially to main consumption regions, like *Sao Paulo* in Brazil and *Central* in Mexico, and others directed to main production regions, like *Itaipu* between Brazil and Paraguay. This electric topology includes 63 nodes, 107 existing lines that represent the transmission capacity between zones and 106 candidate lines, including internal lines and interconnections.

The transmission network does not intend to represent real electric transmission lines, but only the transmission capacity between zones. For this reason, it only considers the transfer capacity and not the reactance or resistance of each line. Transmission losses are represented as part of the demand of each node.



Figure 4-1 Transmission System

All the interconnection candidates have been taken from previously studied projects. Consequently, information is included in all cases in relation to the cost and the technical specification of the interconnection proposed.

In the Central America & Mexico area, presented in Figure 4-2, there is an elevated level of interconnection among the countries. Currently, six countries have a common operation in a unified market, the SIEPAC: Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica and Panama. This system has a mean transmission capacity of 250 MW. In the model proposed, a second and third line of the SIEPAC system can be built, each one with 300 MW of capacity.

Additionally, there is a current line of 100 MW between Belize and Mexico that supplies about 45% of the electricity demand in Belize. This connection can be reinforced with a second line of 100 MW. The current connection between Mexico and Guatemala has a 140 MW capacity and there are two candidates proposed to expand this connection. The first has a 200 MW capacity, while the second presents a 1000 MW capacity.

Finally, this area does not currently report a connection between Belize and Guatemala; however, there is a candidate of 100 MW capacity that can be built.

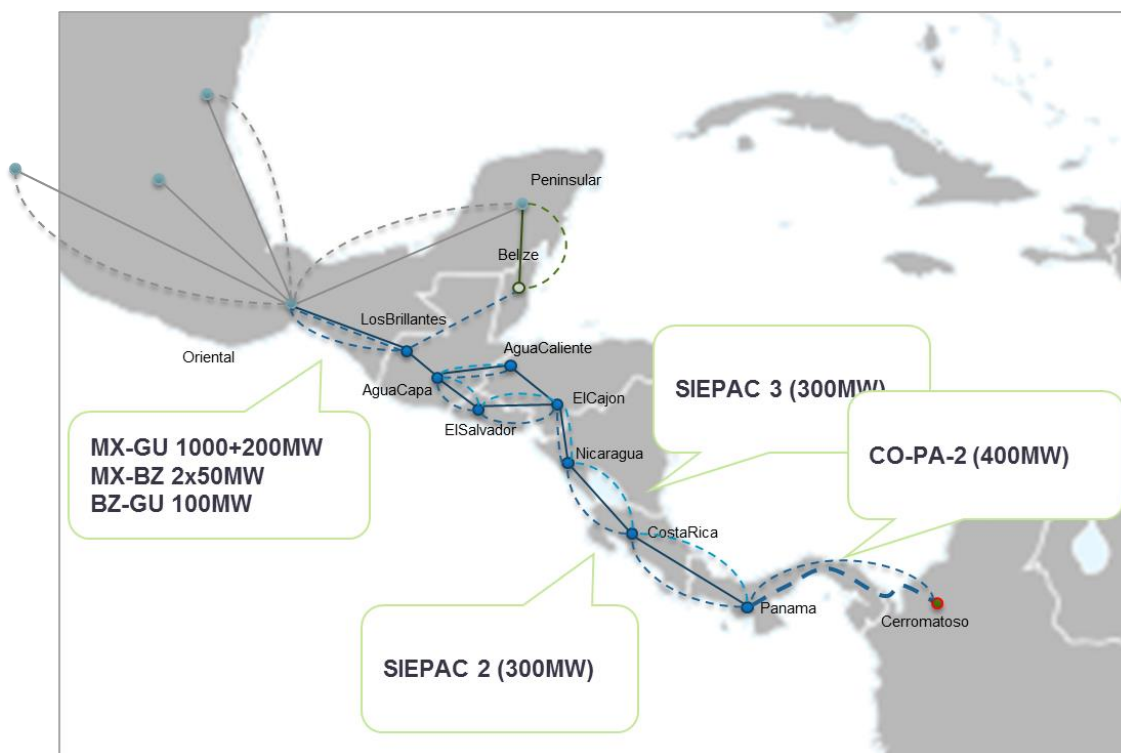


Figure 4-2 Interconnections in the Central America & Mexico area.

Between the Central America and South America regions, there is a project of interconnection for Panama and Colombia, with a capacity of 400 MW. This has been considered in the analysis as a firm project for 2020, but a second interconnection with the same capacity is proposed to be optimally built by the model.

In South America, presented in Figure 4-3, there are zones with a high exchange capacity, while others do not present interconnections developed so far. In Brazil, Paraguay, Uruguay and Argentina there are not only interconnections lines, but also binational power plants placed in the border of rivers between countries. In the case of Itaipu, a 14000 MW hydro power plant between Paraguay and Brazil, it has been modeled in the Itaipu node within the Brazilian system. A 2000 MW interconnection has been added between the Itaipu node and the Asuncion node in Paraguay. This interconnection can be reinforced with a second and a third line with the same capacity.

A second binational power plant, Yacyreta, a hydro power plant of 3200 MW of capacity in the border of Argentina and Paraguay, has a similar treatment than Itaipu. In this case, the power plant is included in the Yacyreta node within the Argentinian system. This node is interconnected with the Ayolas node in Paraguay, with a capacity of 3200 MW.

The last binational power plant is Salto Grande, in the border of Argentina and Uruguay, with a capacity of 1890 MW. It has been modeled with a generation factor of 50% for each country.

Additionally, a current interconnection of 1890 MW and a firm project of 1386 MW have been considered.

In this area, there is a current interconnection between Uruguay and Brazil, with a 500 MW capacity. Given the absence of future interconnection projects studied, this work has not considered further interconnection candidates between these countries.

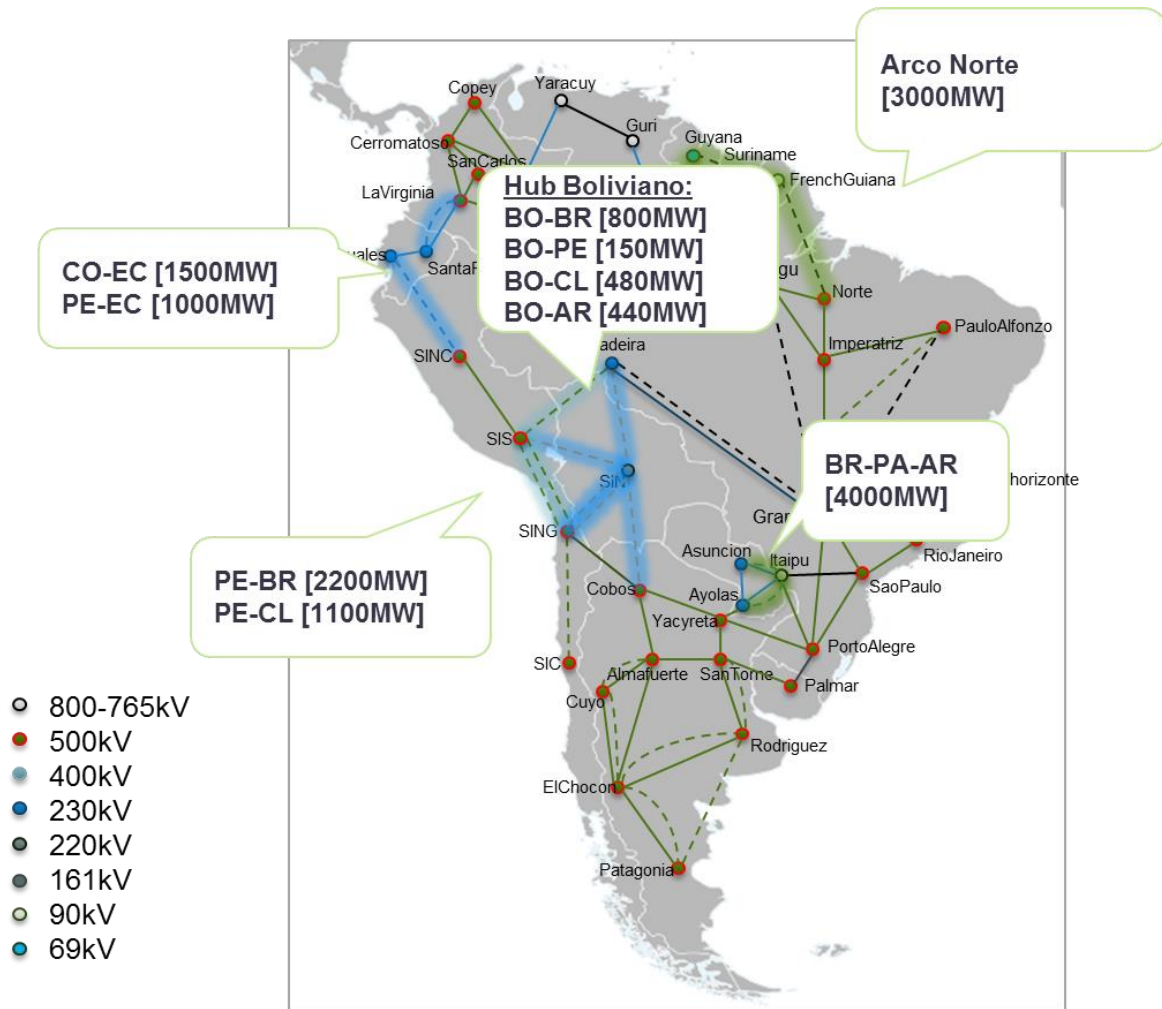


Figure 4-3 Interconnections in the South America area.

In the northern part of South America, there is an operative interconnection between Venezuela and Brazil to supply the north of the latter country –an isolated zone given the difficulties to develop internal lines through the Amazon area. This interconnection has a current capacity of 200 MW. There are also two interconnections between Venezuela and Colombia: one of 100 MW capacity and the other of 150 MW. Considering the lack of information about the system in Venezuela, no further connections have been considered.

Between Colombia and Ecuador there is an operative line of 500 MW. In this model, a candidate of 1500 MW is built. In the case of Ecuador and Peru, there is a non-operative line of 332 MW

already built. In the model, this line is considered as potentially operative, with a candidate of 1000 MW being added.

The last current interconnection is between Argentina and Chile. It has a physical capacity of 717 MW, but its operation is limited by both system operators. Nevertheless, the full capacity of this line has been considered in this study.

According to previous studies, new interconnections are considered between countries that do not currently have electricity exchange. In the area between Chile, Bolivia, Peru, Brazil and Argentina, the following candidates are included: one connection between Bolivia and Argentina of 440 MW capacity; one between Bolivia and Peru with a 150 MW capacity; two lines between Chile and Peru of 100 MW and 1000 MW; two between Chile and Bolivia of 140 MW and 340 MW of capacity, respectively; one 800 MW interconnection between Bolivia and Brazil; one connection between Peru and Brazil of 2200 MW; and, finally, the Arco Norte project, which connects the North of Brazil with French Guiana, French Guiana with Suriname, Suriname with Guyana, and Guyana again with the northeast of Brazil, with a transmission capacity of 3000 MW.

4.1.2. Load Forecast

A load forecast has been defined for each country, based on the last publications of the local authority. The entire load energy for the 21 countries is showed in Figure 4-4.

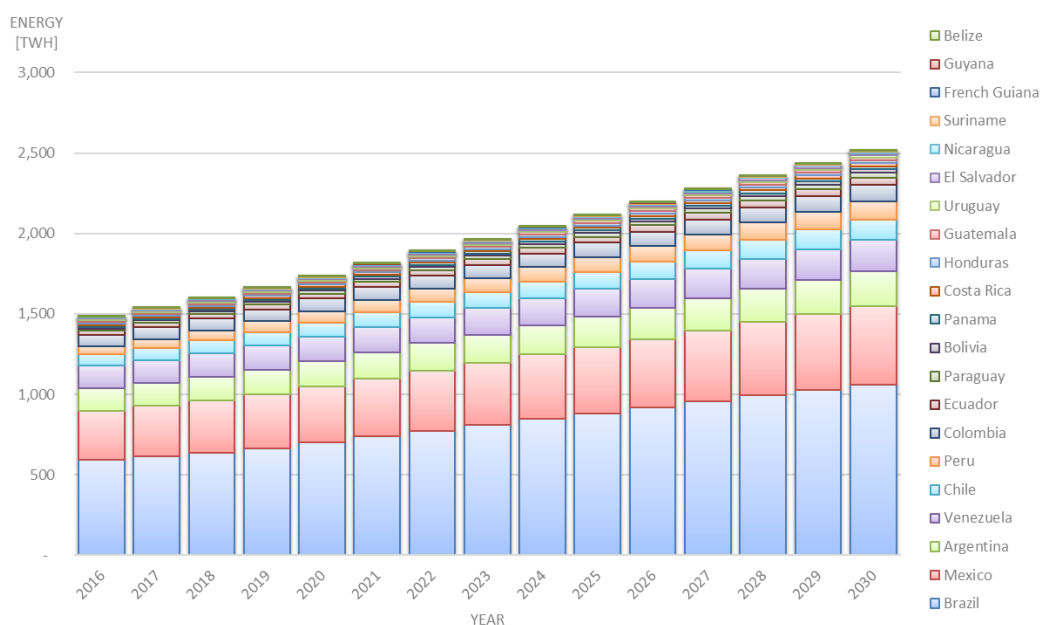


Figure 4-4 Load Energy for Latin America

Even though the load growth rate for the continent is in average 3.7% and varies from 4.1% to 3.6% over the years, there is a relevant difference between the countries of the region. The average growth rate over the years for each country is presented in Figure 4-5. A major difference can be

observed between the 6.5% average growth expected for Bolivia and 1.7% for Uruguay. In the case of Brazil, the information has been divided in four regions: South, Central West, Southeast and Northeast.

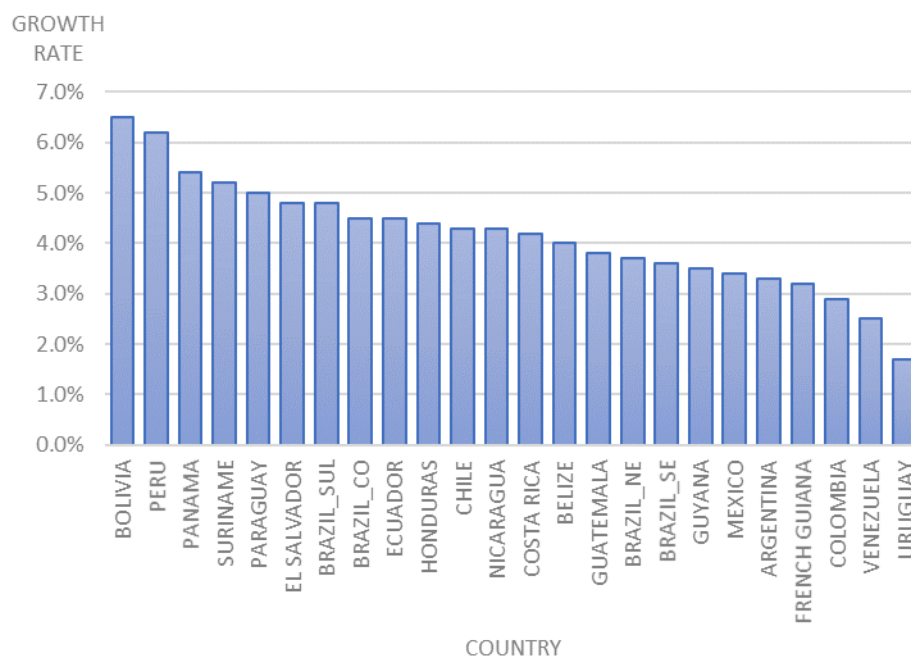


Figure 4-5 Average Load Growth Rates in Latin America

In the specific case of Venezuela and Belize, where there is no projection for the electric demand in each country, the average growth rate was used for the last available load information.

4.1.3. Fuel Price Forecast

The methodology used for the fuel price projection is unified for all the countries studied. This implies that an international price and projection is defined for each fuel. Then, from that international price, a regional factor has been used to correct the price for each country. This regional factor has been calculated considering the proportion between the current fuel price in each country and the current international price, in other words, this factor is a ratio of the local fuel price and the international fuel price.

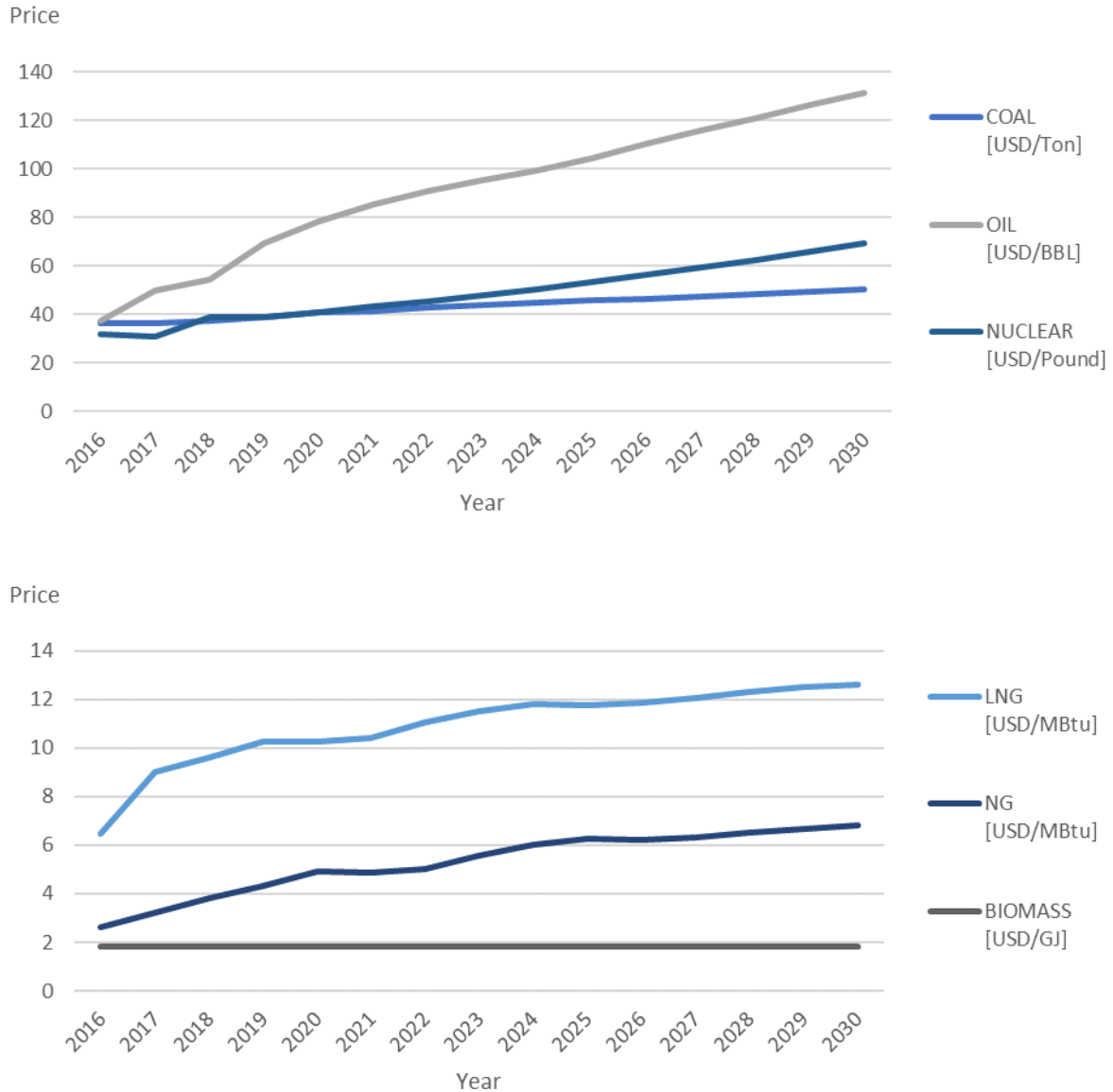


Figure 4-6 Fuel Price Forecast

The projection for coal, oil and natural gas has been obtained from the Annual Energy Outlook 2016, published by the Energy Information Administration [28]. The liquid natural gas projection has been created as follows:

- Until 2017, it is calculated as 12% of the Brent price plus 0.6 US\$/MBtu.
- From 2018, it is calculated as 1.115 times the Henry Hub price plus 4.5 US\$/MBtu.

Biomass has been projected at the same price defined by 2016 [29]. Meanwhile, the nuclear price has been set according to [30] until 2019. After that year, an annual growth factor of 5.4% is predicted. Figure 4-6 presents the fuel price international forecast. As it was mentioned above, a

regional factor has been set for each country in order to correct the international price. Figure 4-7 presents the main factors for different countries.

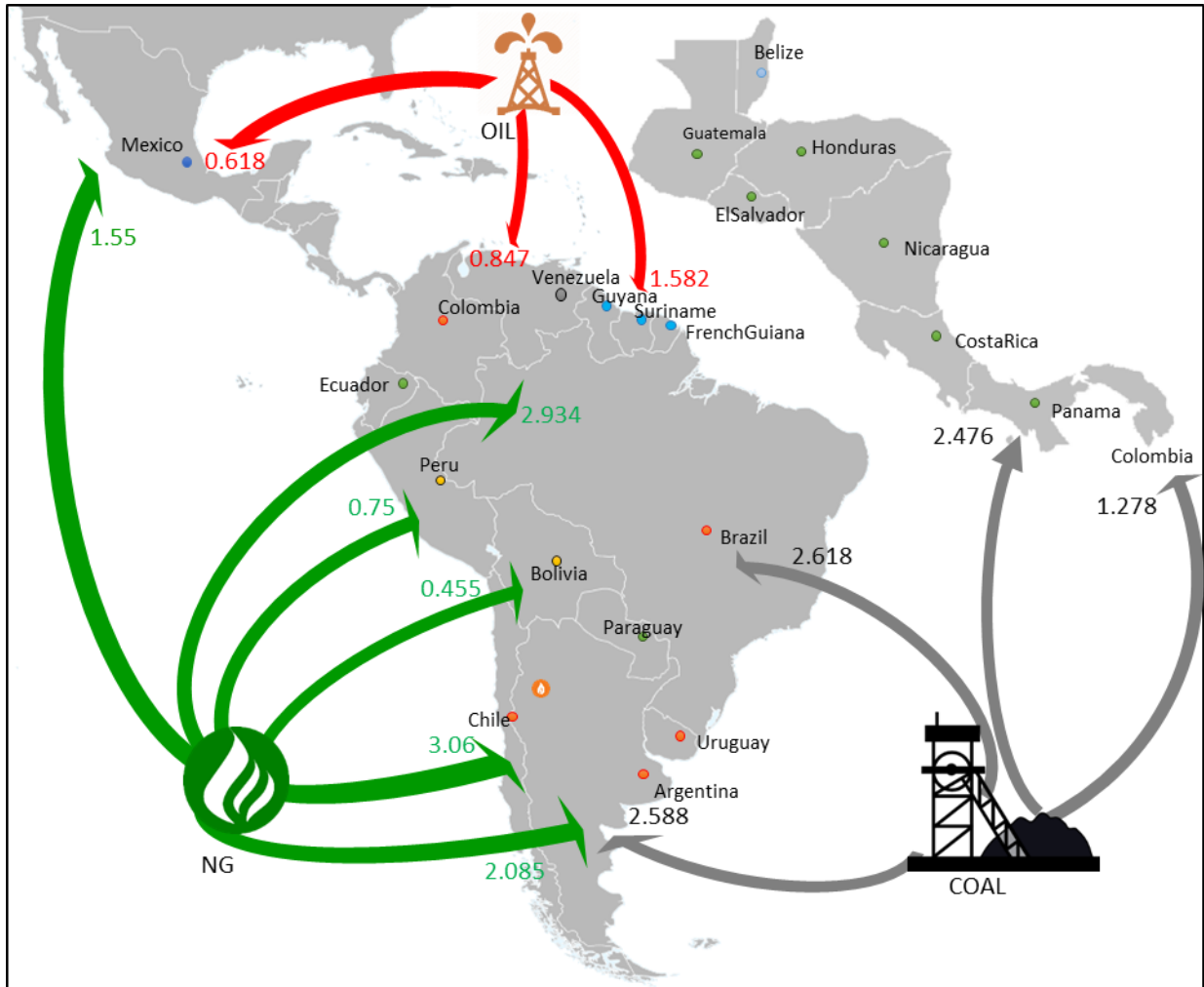


Figure 4-7 Regional Factors for Fuel Prices [pu]

4.1.4. Capital Cost Forecast

One of the key input data for these models is the capital cost for new generation power plants. The definition of this cost is similar to the fuel price methodology, which is defined by the international cost projection and then corrected with a regional factor to each country. As well as the fuel price regional factor, the regional factor of capital cost has been calculated from the relation between the current international capital cost and the current cost of investment by each country for each technology.

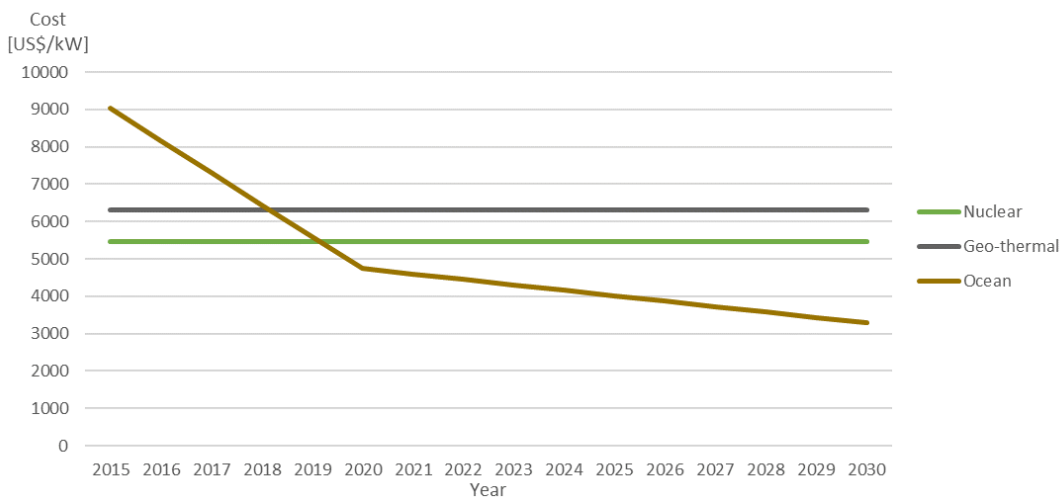
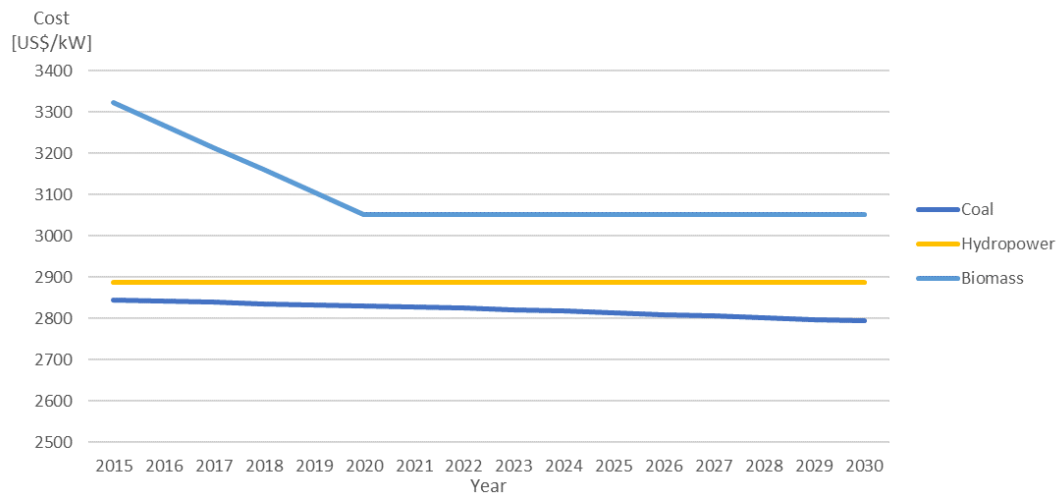
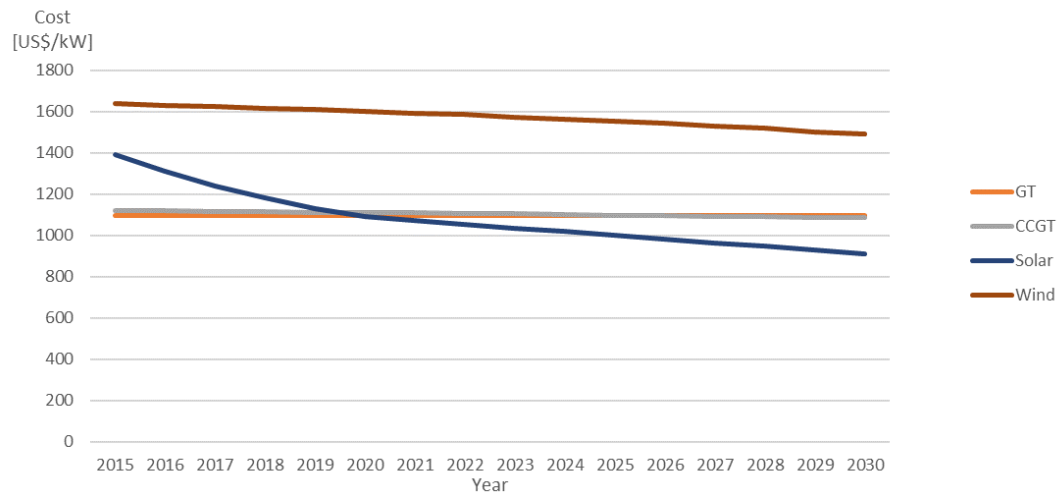


Figure 4-8 Capital Cost Forecast

Figure 4-8 illustrates the capital cost projection for each technology considered in the model. In the case of coal, the references for the capital cost are [31] [32] [33]; [34] for gas turbines; [31] [33] [35] for combined cycle gas turbines, biomass technologies and wind technologies; [33] [35] for hydro; and [36] for nuclear. The references for solar technologies are [31] [35] [33] [37]; for geothermal, they are [38] [39]. Finally, the references for the capital cost of ocean technologies are [40] [41].

The main regional factors for conventional technologies are presented in Figure 4-9 and, for non-conventional technologies, in Figure 4-10.

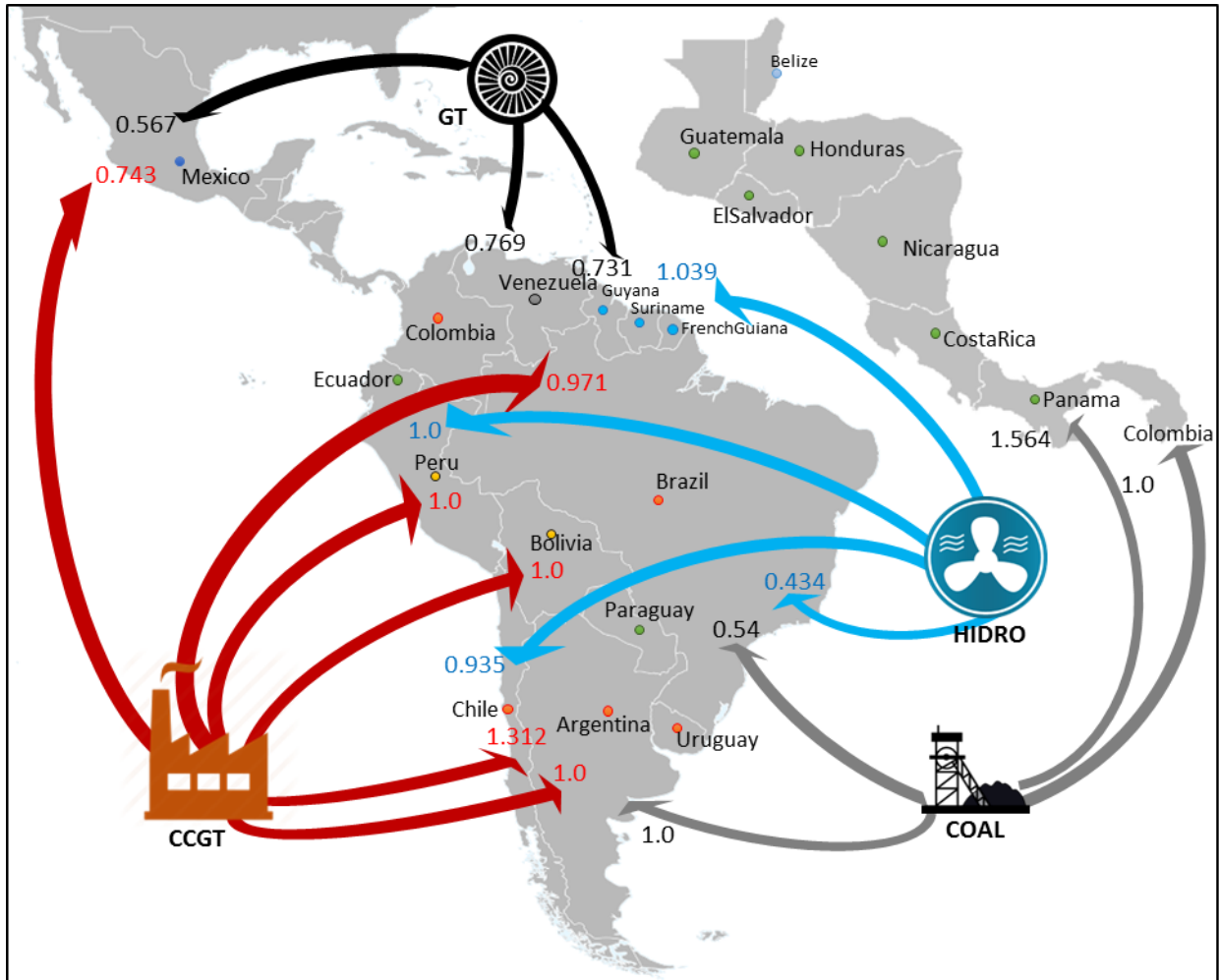


Figure 4-9 Regional Factors of Capital Cost for conventional generation technologies [pu]

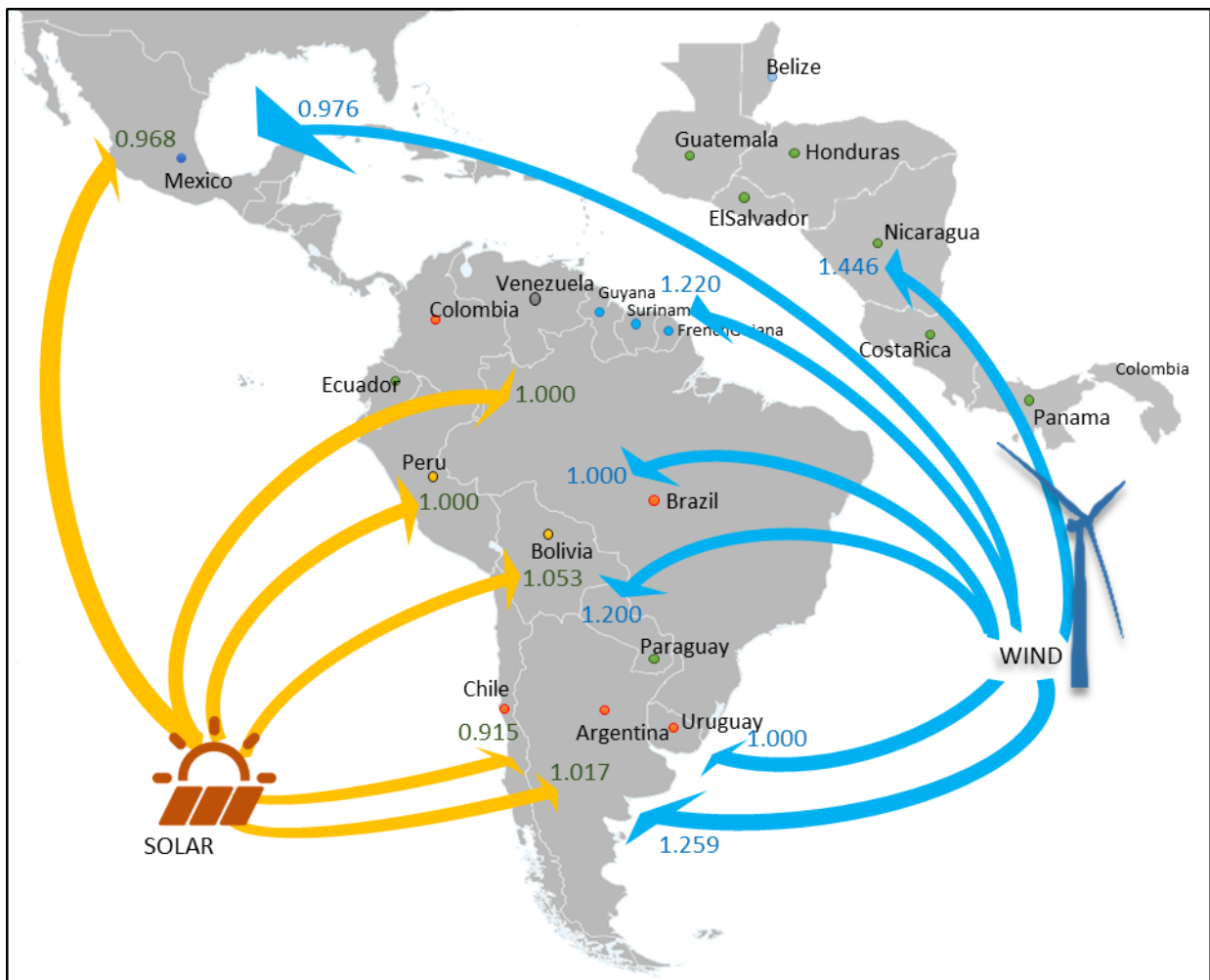


Figure 4-10 Regional Factors of Capital Cost for non-conventional technologies [pu]

4.1.5. Renewable Energy Potential and Profiles

The renewable potential has been estimated by the consultant AWS Truepower in the context of the project “IDB LA Clean Energy”, which was financed by the Inter-American Development Bank. Table 4-1 presents the total potential for each country and technology in the model.

Table 4-1 Renewable Potential for Latin America

Country	Renewable Potential [GW]						
	Solar	Wind	Hydro	Small Hydro	Biomass	Geothermal	Wave
Argentina	37,273	13,953	45	0.43		2.01	72.7
Bolivia	6,786	579	39	0.02		2.49	
Brazil	44,537	7,799	185	1.023		3.00	122
Chile	5,898	952	25	7		3.35	224.5
Colombia	4,026	78	118	50		2.21	22.9
Ecuador	263	52	22	0.38		1.70	10.4
Paraguay	2,780	1,381	13				
Peru	3,699	81	69	0.25		3.00	61.3
Uruguay	3,839	1,381	2	0.01			16.7
Venezuela	2,721	500	66			0.91	22.8
Belize	33	4		0.05			3.2
Costa Rica	141	49	7	0.09		2.9	11.2
El Salvador	142	5	2	0.11		2.1	4.2
Guatemala	429	13	5	0.06		3.3	4.6
Honduras	142	18	5	0.39		0.99	5.9
Nicaragua	206	103	2	0.04	0.20	3.3	9.6
Panama	103	10	5	0.12		0.45	14.6
Mexico	3,699	1,543	53	9.20	2.40	6.50	103.3
French Guiana	10.6	1	0.139		0.046		0.67
Guyana	160.8	102	7.166		0.026		
Suriname	54.7	5	2.98				

The wind and solar generation profiles were also estimated by the consultant AWS Truepower. Several local areas have been defined: 256 zones for wind candidates and 200 for solar candidates, each with a different solar and wind potential, hourly profile and capacity factor. The details of the potential and the estimation of profiles will be published in the “IDB LA Clean Energy” book release.

In the case of the hydro generation resource, this work includes the estimation of natural hydro inflow profiles for several nodes in the basins of Latin America. A total of 872 natural inflows have been considered in this project.

The methodology used for the natural inflows considers an estimation of the statistical parameters of a spatially-correlated auto-regressive stochastic process. For this, the available historical values for each basin are employed. The process was carried using a P-ARMA model for each natural inflow, including a correlation matrix between each variable. This procedure allows to generate future natural inflows while keeping the same statistical characteristic of each historical series, as well as the correlation with other series, using a Cholesky factorization. In this work, 100 future samples have been generated and then reduced to 3 representative series through a Kantorovich

distance-based algorithm. Each one has a probability of occurrence and, as was explained in section 3.1, are included endogenously in the optimization model.

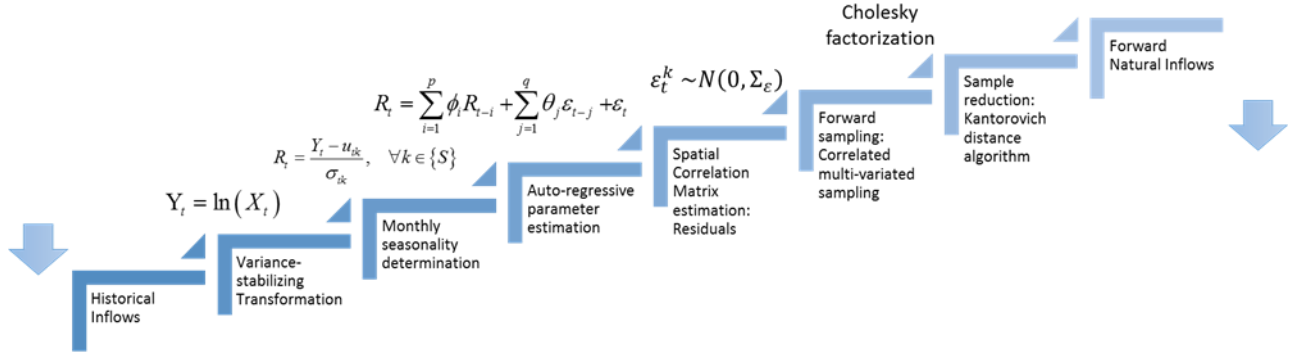


Figure 4-11 Algorithm for Synthetic Correlated Hydro Inflow Sampling

4.2. SCENARIO DEFINITION

To apply the methodology proposed, it is necessary to define the three incremental scenarios according to the objective raised in this work. The difference between scenarios will be related with the renewable generation target and the candidates available for interconnections between countries.

For the base scenario considered as the reference case to compare the incremental cases, the renewable potential was defined according with the AWS Truepower estimation. The only exception is Mexico, where the potential was restricted to the technologies, location and capacity published in the official expansion plan. In terms of interconnection between countries, this scenario considers only one future line connecting Panama and Colombia, considered as a firm project. Additionally, this scenario allows for the optimal expansion of the interconnection between Mexico and Guatemala and the second line of the SIEPAC, in case the optimization model decides to build such expansion.

In the renewable scenario, a renewable generation target of 80% of the Latin America total load has been set for 2030. This target is to be reached with renewable technologies including all the hydropower generation. On the other hand, all countries in this case have the full estimated renewable potential available, including Mexico.

Finally, the integrated renewable scenario includes the same target of 80% production met by renewable resources by 2030, the full renewable potential available for all the countries, and new interconnection candidates available to be built. These candidates have been defined according to previous studies.

4.3. RESULTS

4.3.1. Benchmarking Results

The first step in the modeling process is to test the model with a validated expansion exercise, using the same assumptions and comparing the results of both simulations. This benchmark step has been executed for each country individually. As key comparable results, the main values were the annual generation by energy source and the energy marginal prices of the system.

In the case of Chile, the reference exercise is the publication released by the Ministry of Energy as part of the national prospective process [42]. Using the same assumptions, Figure 4-12 illustrates the results of generation for each energy source obtained by comparing the reference model with the model developed in this work.

In general terms, it can be observed that most of the technologies are well represented. The largest differences between the models are present in the small hydro resource and the thermal generation based on liquid natural gas. Table 4-2 presents the annual absolute error by energy source. Finally, as renewable participation is one of the key results in this work, Figure 4-13 shows the percentage of non-conventional renewable energy in both models. It is possible to identify the similarity between both trajectories, as well as the Chilean target set by 2025.

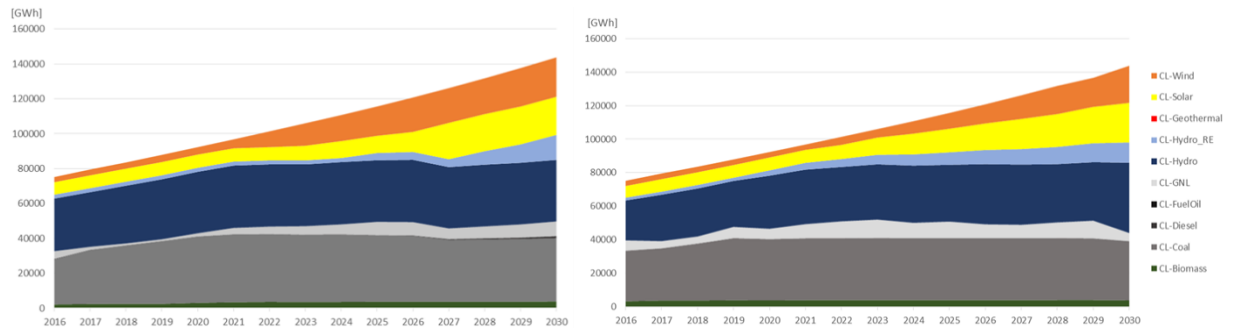


Figure 4-12 Generation by Energy Source for Reference and with the Model developed, respectively.

Table 4-2 Annual absolute error by energy source

Year	CL-Biomass	CL-Coal	CL-Diesel	CL-FuelOil	CL-GNL	CL-Hydro	CL-Hydro_RE	CL-Geothermal	CL-Solar	CL-Wind
2016	1%	7%	0%	0%	1%	9%	0%	0%	4%	1%
2017	2%	7%	0%	0%	0%	3%	0%	0%	0%	1%
2018	2%	4%	0%	0%	3%	3%	0%	0%	0%	0%
2019	2%	4%	0%	0%	6%	6%	0%	0%	0%	0%
2020	2%	1%	0%	0%	6%	3%	1%	0%	0%	1%
2021	1%	1%	0%	0%	7%	3%	2%	0%	0%	1%
2022	1%	2%	0%	0%	6%	3%	2%	0%	1%	0%
2023	0%	2%	0%	0%	6%	3%	3%	0%	3%	4%
2024	0%	1%	0%	0%	4%	1%	4%	0%	4%	5%
2025	0%	1%	0%	0%	4%	2%	4%	0%	4%	5%
2026	0%	1%	0%	0%	1%	0%	4%	0%	5%	4%
2027	0%	1%	0%	0%	0%	0%	4%	0%	5%	4%
2028	0%	1%	0%	0%	2%	0%	4%	0%	1%	2%
2029	0%	1%	0%	0%	3%	0%	3%	0%	0%	2%
2030	0%	0%	0%	0%	2%	5%	1%	0%	1%	0%

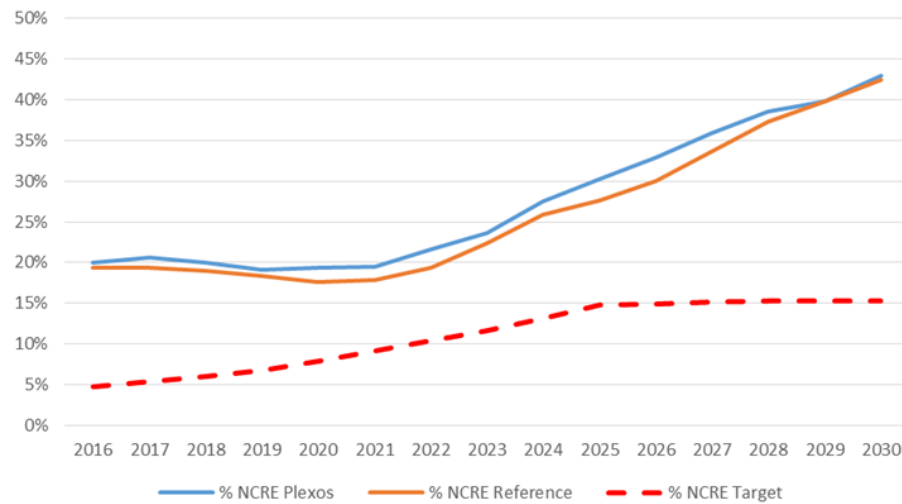


Figure 4-13 Non-Conventional Renewable Energy Participation in PLEXOS Model, Reference document and Chilean Target

4.3.2. Simulation Results

The methodology proposed considers a comparative analysis between the incremental scenarios defined. For that reason, this chapter will be dedicated to establishing a comparison between several key results of each scenario.

The first key result is the total cost of investment and operation over time. Figure 4-14 presents the result for each scenario, separated by the investment and production component. From this chart, the time horizon can be divided in two periods: from 2016 to 2024, there is a tendency in which the base scenario has a lower cost than the renewable and the integrated renewable; on the other hand, the tendency in the period from 2025 to 2030 clearly indicates that the base scenario is the most expensive, while the integrated scenario is the most inexpensive. The reason for these pronounced periods is that the renewable and integrated renewable scenarios involve higher investment in renewable sources, which are intensive in capital cost. This derives in a higher cost in the first years; however, such sources are inexpensive in operational cost, which generates a lower cost in the last years of the horizon. That is also reflected in the investment and operational cost of each scenario, where the investment cost is consistently higher in the renewable scenarios, while the operational cost is consistently lower for the same scenarios.

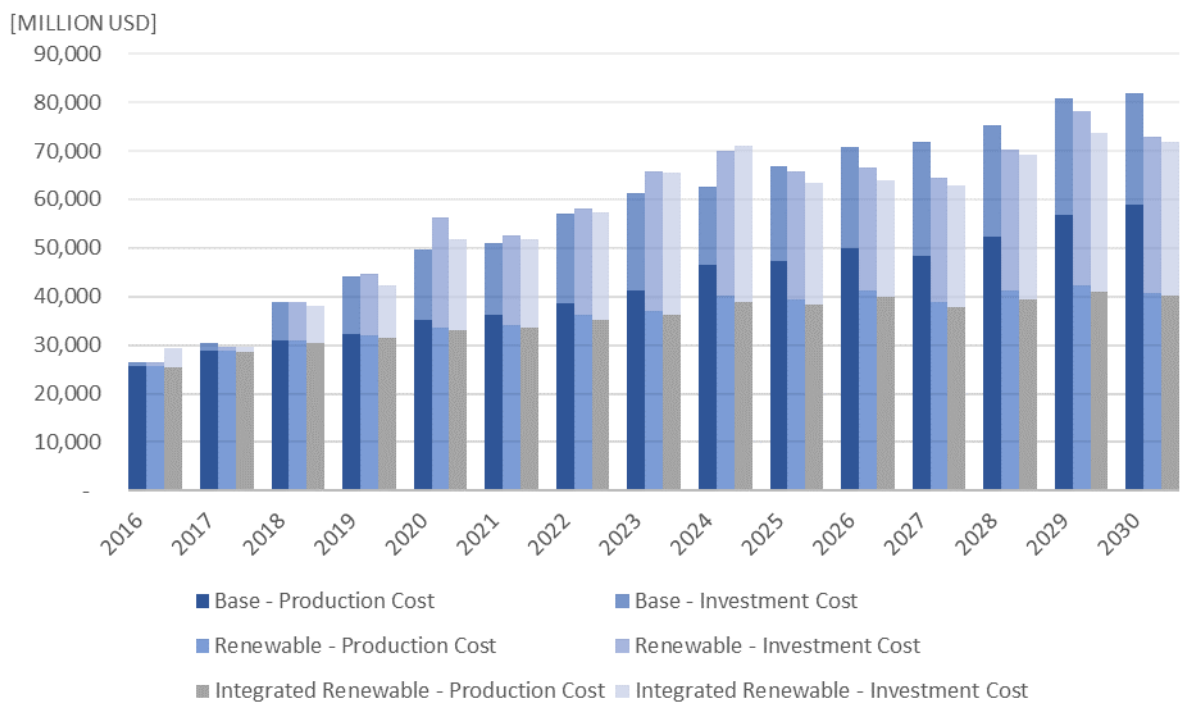


Figure 4-14 Annual total cost of investment and operation for each scenario by component

Analyzing the sum of the cost in each year, the total costs for each scenario are: US\$872,808 million for Base; US\$865,899 million for Renewable; and US\$853,523 million for Integrated Renewable. This result indicates that, although the renewable and integrated scenarios have a higher cost in the first years due to strong investments, this is compensated by the lower operational costs of the last years. This entails a lower total cost for the entire horizon.

Nevertheless, the optimization model considers the present value of the total cost. If these costs are brought to the present value, it can be obtained the following results: 429,860 million US\$ for base; 432,864 million US\$ for Renewable; and 428,501 million US\$ for Integrated Renewable. In this case, the present value for the Renewable scenario is higher than the Base scenario, which is

expectable considering the main difference in the addition of the renewable target. This means that the lower operational cost in the future years cannot compensate for the higher investment cost in the first period. However, the main result of this analysis stems from the fact that the Integrated Renewable scenario has a lower present value of the cost than the Base scenario. From this, it can be concluded that a future scenario with a high renewable target can be achieved with an even lower cost than the expected future scenario, if new interconnections are built in the region.

Another fundamental result in this study is the renewable participation in the future generation. Participation by energy source is presented in Figure 4-15, Figure 4-16 and Figure 4-17, for Base, Renewable, and Integrated Renewable scenarios, respectively. These charts indicate that the current generation in Latin America is highly renewable, with prominent participation of hydropower generation. In the future, it is expected that hydro participation will be reduced considering that other technologies, such as solar and wind, are achieving a competitive capital cost, which is captured by the model, as well as other causes not incorporated by the model: the effect of the climate change on the natural inflows and the assumption that the best hydro resource locations have been exploited, causing future ones to be more expensive to develop or less efficient.

Considering this lower hydropower participation in the future, it is necessary to invest in other renewable resources such as solar and wind, in order to keep –or even increase– the renewable participation in the region. From the Base scenario, the business-as-usual orientation indicates that solar, wind and biomass technologies will compensate for the reduction of hydropower energy participation and, eventually, increase renewable production from 64.3% in 2016 to 70.8% by 2030.

In the Renewable and Integrated Renewable scenarios, there is a target of 80% renewable generation set for 2030. Therefore, both scenarios increase their renewable participation to achieve this target. It is interesting to notice in both cases that this increment is led by solar and wind technologies; however, the Integrated Renewable scenario has a 2% higher hydropower participation, since the interconnections allow the development of efficient but isolated hydro resources in regions such as Guyana.

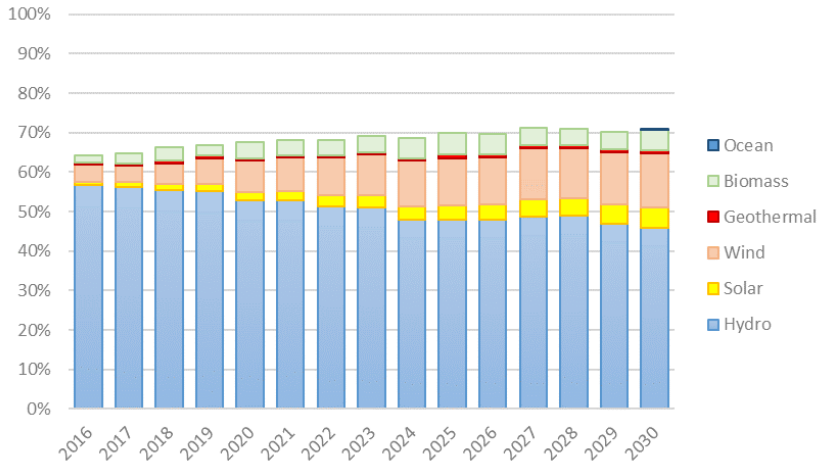


Figure 4-15 Renewable participation in generation by source for Base scenario

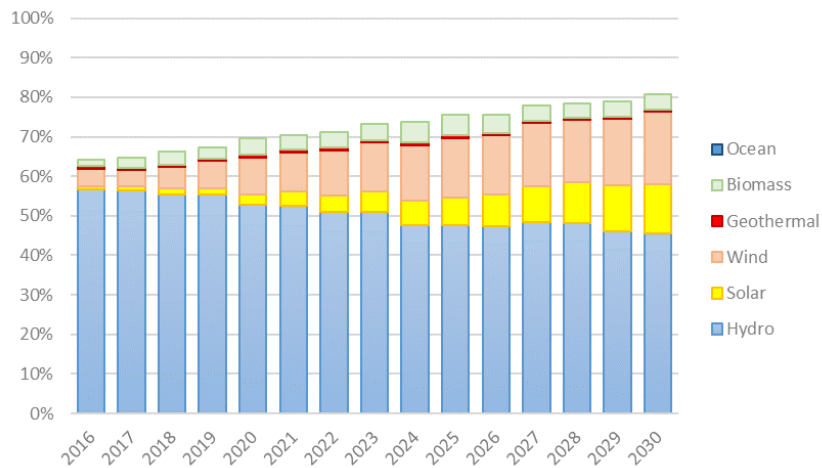


Figure 4-16 Renewable participation in generation by source for Renewable scenario

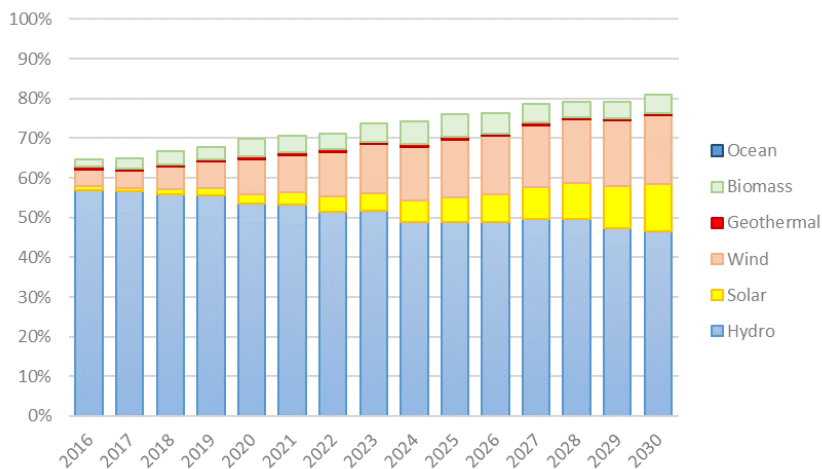


Figure 4-17 Renewable participation in generation by source for Integrated Renewable scenario

From the current renewable participation in Latin America, the target can be expected to surpass 80% by 2030. However, it is necessary to understand that this participation is extremely different in some regions. Establishing a division between South America and the region composed of Central America and Mexico, Figure 4-18 and Figure 4-19 present generation rates by energy source for each region. It is relevant to keep in mind that the target used in the model considers the total generation in Latin America. This does not mean that the same target must be reached in every region or country.

From these results, it can be stated that the South American region is highly renewable already, especially for the participation of hydro resources. Thus, the achievement of the target will be based on maintaining the current thermal generation and cover the incremental load with new renewable projects.

The region of Central America and Mexico is significantly different. In this case, the main generation resource is gas, with a participation of 47%. As for 2016, the renewable generation of this area is only 31%. Consequently, the only way to contribute to the target completion is to replace part of the thermal generation with new renewable resources. For this reason, it can be inferred that achieving a higher renewable target is a significant challenge.

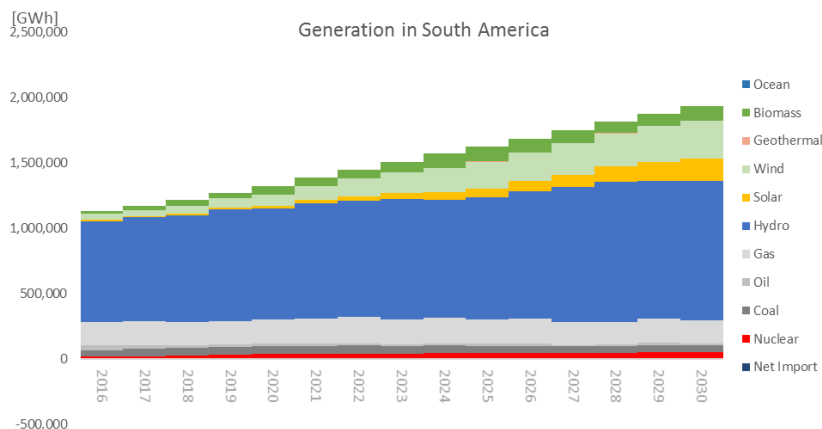


Figure 4-18 Generation by energy resource in South America for Integrated Renewable scenario

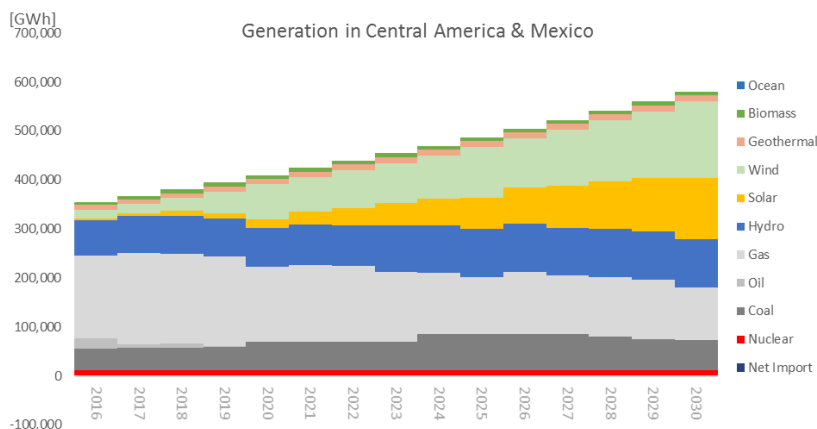


Figure 4-19 Generation by energy resource in Central America and Mexico for Integrated Renewable scenario

Comparing the installed capacity by the end of the horizon for each scenario—as presented in Table 4-3—the first relevant result is that the Renewable scenario needs a higher total installed capacity to achieve the renewable target than the Base scenario. This higher capacity is marked by a relevant increment in solar technology, with more than two times the capacity of the Base scenario, and an increase of 37% in wind technology. Meanwhile, thermal technologies maintain their capacity, except for the gas based technology that is reduced in 17%.

On the other hand, the Integrated Renewable scenario needs a lower installed capacity to reach the same target than the Renewable scenario. This can be explained by the effect of building interconnections: the access to more efficient renewable resources that could not be developed

without this international transmission. Additionally, such access accounts for the Integrated Renewable scenario being more inexpensive than the Base and the Renewable scenarios.

Table 4-3 Installed Capacity in MW by technology for each scenario by 2030

Technology	Base	Renewable	Integrated Renewable
Coal	21,353	21,353	21,345
Gas	144,422	119,883	121,128
Oil	40,861	40,522	40,522
Nuclear	8,844	8,844	8,844
Hydro	251,277	247,760	253,809
Solar	50,339	122,696	113,392
Wind	80,525	109,952	103,416
Geothermal	2,924	1,861	1,861
Biomass	25,419	21,967	21,993
Ocean	100	0	0
Total	626,065	694,838	686,311
Peak Load	369,003	369,003	369,003

To understand the development of each one of this technologies in comparison with the current capacity, the capacity built by optimal decision is presented in Table 4-4.

Table 4-4 Capacity Built by optimal decision by 2030 for each scenario.

Technology	Base	Renewable	Integrated Renewable
Coal	3,807	3,807	3,800
Gas	36,114	11,575	12,820
Oil	2,339	2,000	2,000
Nuclear	-	-	-
Hydro	18,366	14,849	19,981
Solar	45,782	114,578	105,274
Wind	64,634	87,429	80,893
Geothermal	1,264	80	80
Biomass	7,322	3,869	3,896
Ocean	100	0	0
Total	179,728	238,187	228,743
Peak Load	369,003	369,003	369,003

As mentioned in previous sections, one of the objectives of this work is to determine where these technologies are developed according to the optimal solution. In the Integrated Renewable scenario, the solar capacity built represents 46% of the total new capacity, while wind represents 35%. It is pertinent to focus on both resources and the location of these developments. Figure 4-20 presents the participation per country of the wind capacity built in the Integrated Renewable scenario. The same result is presented for solar capacity in Figure 4-21.

In this aspect, it is important to keep in mind that the major part of the demand is concentrated in Brazil, México and Argentina, both countries with a relevant number of wind and solar resources. Therefore, and although there is a possibility of developing interconnections in various zones, these interconnections are limited to previous studies, so it is expected that a big part of the generation resource will be developed in those countries. That result can be observed in the case of wind development, where Brazil, Mexico and Argentina lead the new capacity built, this also match with the fact that these three countries have excellent wind resources.

In the case of solar it is necessary to split the analysis in South America, and Central America and Mexico. In South America, even when Brazil and Argentina have the higher demand in the region, there is a relevant development in Chile and Peru, in fact, Chile has the larger solar development of the south American region. This is caused by the excellent solar resource in the north of Chile and south of Peru, which with the development of interconnections can be exploited. On the other hand, in Central America and Mexico, there are two effects: the first is that this region has a lower share of renewable energy, so to contribute to the renewable target it is necessary to increase the amount of new renewable capacity built; the second effect is the limited amount of interconnection capacity considered in this simulations, that does not allow an infinite capacity to transfer renewable energy from South America to Central America, this in addition to the margin reserve capacity constraint included in the model. The result of these effects is a high solar capacity built in Mexico, which is the country with the highest demand and solar resource in the central American region.

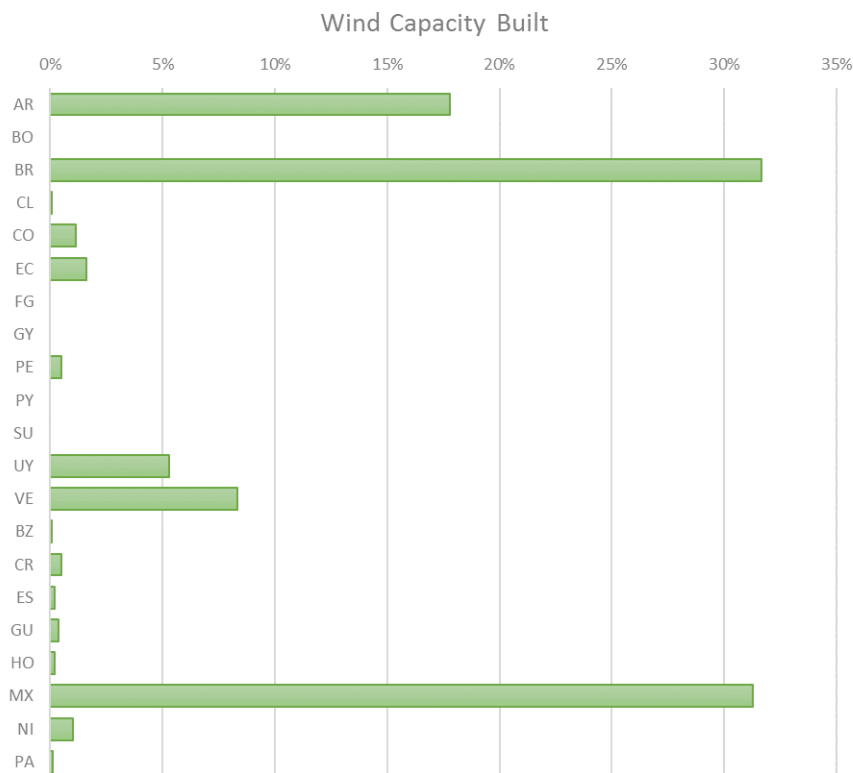


Figure 4-20 Wind Capacity Built participation per country by 2030 for Integrated Renewable scenario.

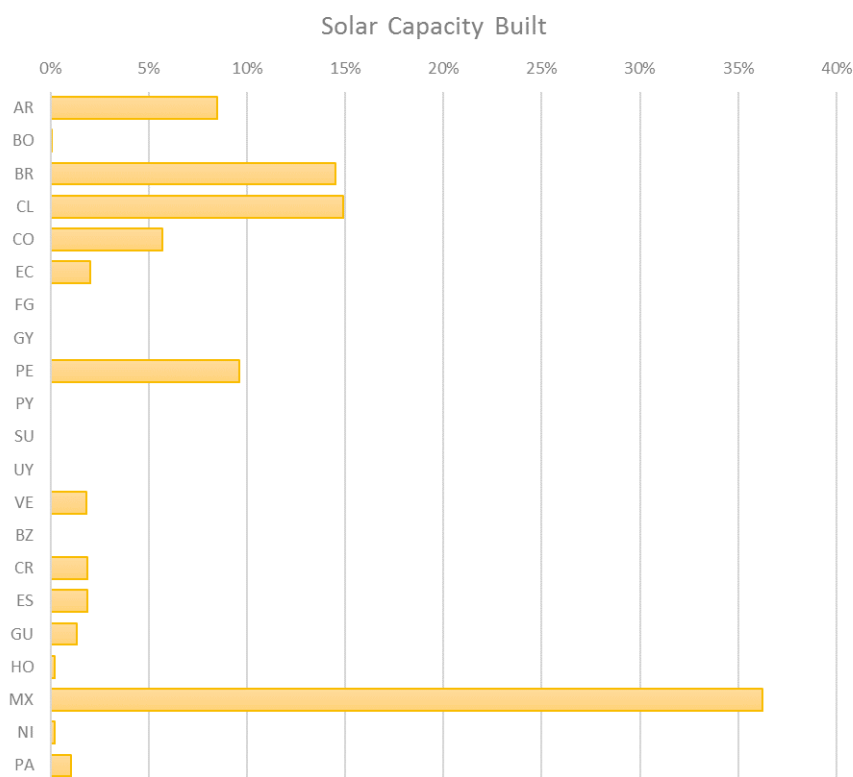


Figure 4-21 Solar Capacity Built participation per country by 2030 for Integrated Renewable scenario.

One of the major concerns for the world authorities in the last years is the amount of greenhouse gases (GHG) emission, which has led to actions such as the compromises adopted by all countries in the COP21 convention. Even though this study does not include constraints related to GHG emissions or an analysis of the achievement of the commitments taken in the COP12, it is pertinent to compare the results of this values regarding each scenario. Considering the increment of electric load in the studied horizon, the result compared in this case is the amount of CO_2 emissions per load, in [ton/GWh] units, for each scenario. This is illustrated in Figure 4-22. In this graph, it can be noticed that the Base scenario presents a reduction in this factor over time, reaching a decrease of 14% by 2030. Meanwhile, for the Renewable an Integrated Renewable scenario, the reduction is more intensive, reaching a decrease of 38% by 2030.

Comparing the total amount of CO_2 emissions in [ton] unit, for each scenario presented in Figure 4-23, it can be observed that the Base scenario presents an increment of almost 50% between 2016 and 2050. On the other hand, both the Renewable and Integrated Renewable scenarios report a lower increase in the total of emissions over time. However, for the final year, and despite the significantly higher load, the total emission is nearly equal to the total emission for the first year of the horizon.

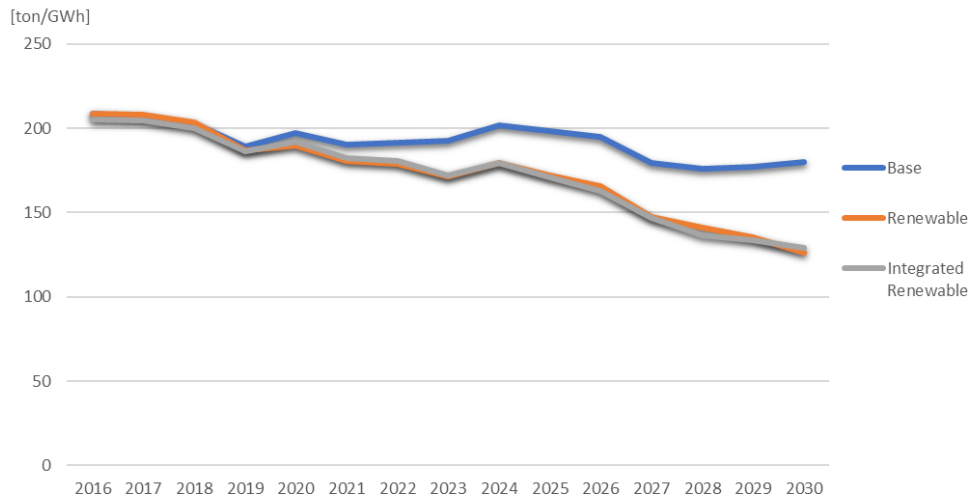


Figure 4-22 CO₂ emissions per load factor for each scenario

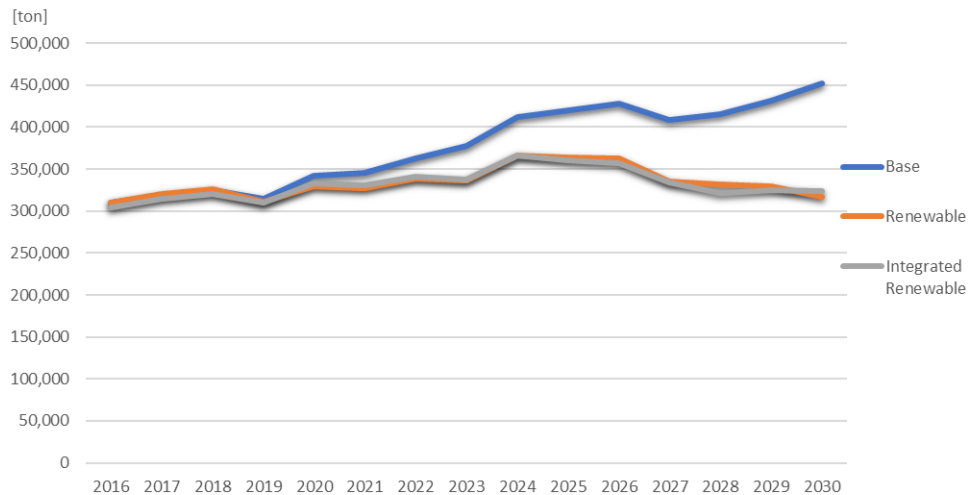


Figure 4-23 Total CO₂ emissions for each scenario

The results of the interconnection expansion are meaningful. Except for the second interconnection between Nicaragua and Costa Rica, and a third line between Honduras and Nicaragua, the rest of the interconnection candidates have been built in the Integrated Renewable scenario.

In Central America and Mexico, the Base and Renewable scenario allows for the extension of the SIEPAC system, which was expanded completely by 2020, and a reinforcement of the line between Mexico and Guyana, also installed by 2020 in the results. In the Integrated Renewable scenario, not only a second line of the SIEPAC system has been built, but also a third line of some zones of the system: specifically, the lines between Costa Rica – Panama, El Salvador – Honduras, Guatemala – El Salvador and Guatemala – Honduras, between 2028 and 2030. Between Mexico and Guatemala, there are three interconnections developed from 2020 until 2028, reaching a total

capacity exchange of 1340 [MW]. The result for the Integrated Renewable scenario is presented in Figure 4-24.

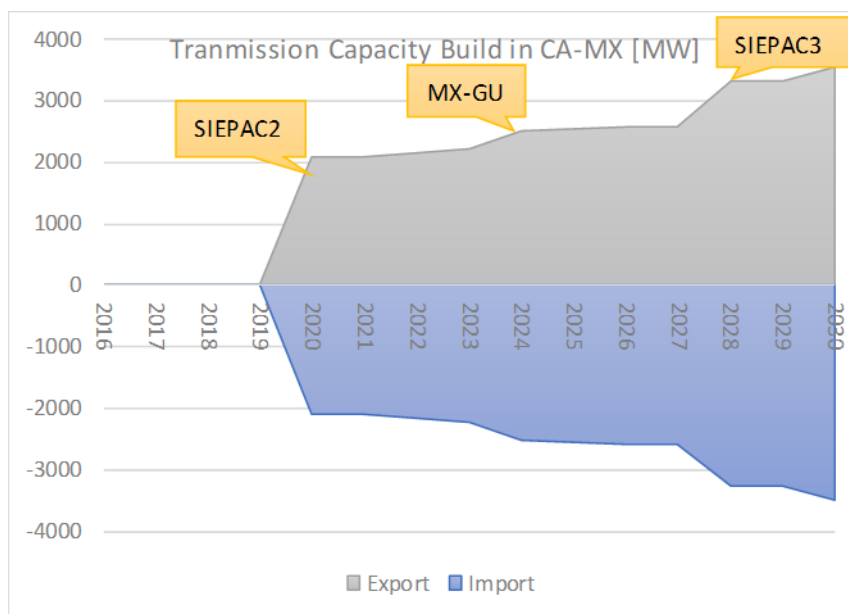


Figure 4-24 Transmission Capacity Expansion in Central America for Integrated Renewable Scenario

The electricity flow through Central America interconnections are presented in Figure 4-25, where can be seen that even when flows are bidirectional over time, and this effect is divided in countries that are mainly exporters and other ones' importers. Guatemala is net exporter, and its energy goes to El Salvador and Honduras that are mainly importers. In the case of Panama, in the first years of the horizon, until 2023, is a net exporter, then for the rest of the horizon is a net importer. In Nicaragua, the effect is the opposite, from 2016 to 2019 is net importer, and from 2020 onward, when SIEPAC 2 is built, becomes a net exporter. Costa Rica is mainly exporter until the building of SIEPAC 3, when becomes a net importer.

In Figure 4-27 are illustrated the marginal cost of energy of each SIEPAC' country for the Integrated Renewable scenario. In this graph can be noticed the effect of the SIEPAC 2 line, where marginal cost converges to values around 40 and 50 [US\$/MWh]. In addition, in the year 2023 there is a turning point, where the marginal cost of Guatemala goes lower than Panama's, that is the reason why Panama goes from being an exporter to an importer in that year. Similarly, in 2028, where SIEPAC 3 is built, the marginal cost of Costa Rica goes over Honduras and Nicaragua, so Costa Rica goes from being an exporter to an importer.

In Figure 4-26 is presented the amount of energy exchanged inside the SIEPAC system, where can be seen that 25% of the electricity demand consumed among these six countries goes through international interconnections.

In the case of Mexico and Belize, the flow is completely unidirectional and comes from Mexico, in all scenarios Belize' imports supply 42% of the demand by 2016, and this value goes up to 51%

by 2030. The interconnection between Mexico and the SIEPAC system is bidirectional, but the main flows goes from Mexico to Nicaragua.

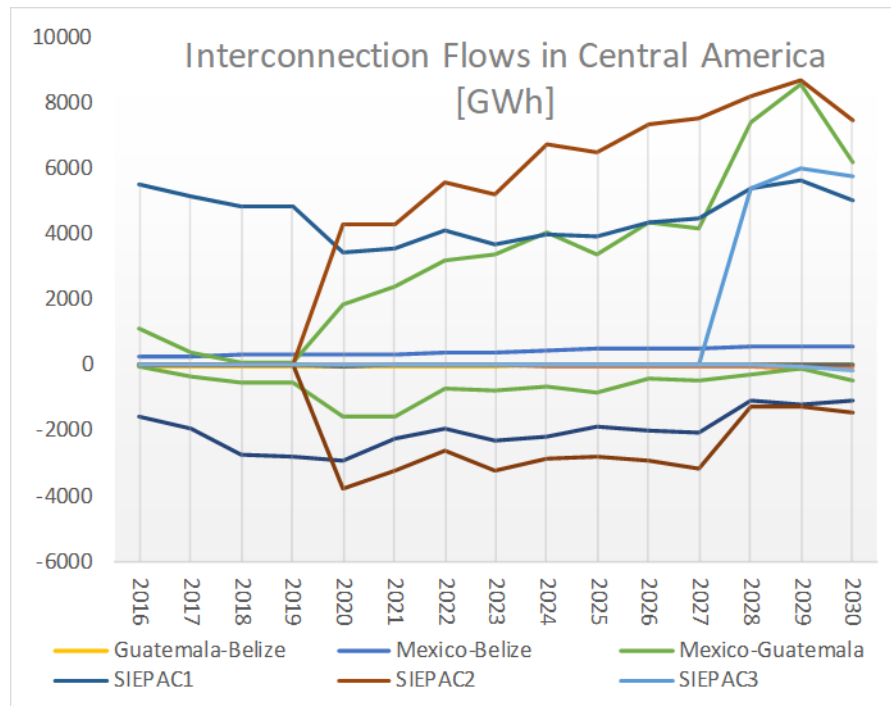


Figure 4-25 Electricity exchanges in Central America for Integrated Renewable Scenario

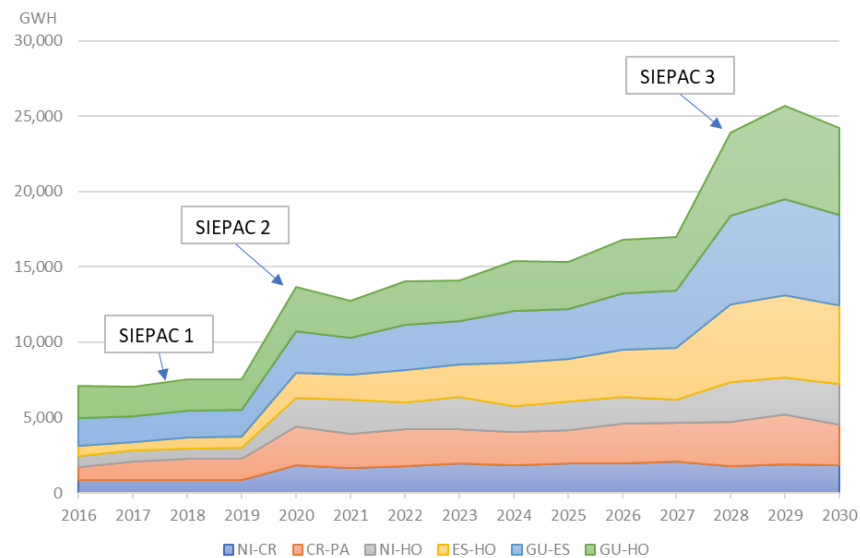


Figure 4-26 Electricity exchanges in SIEPAC for Integrated Renewable Scenario

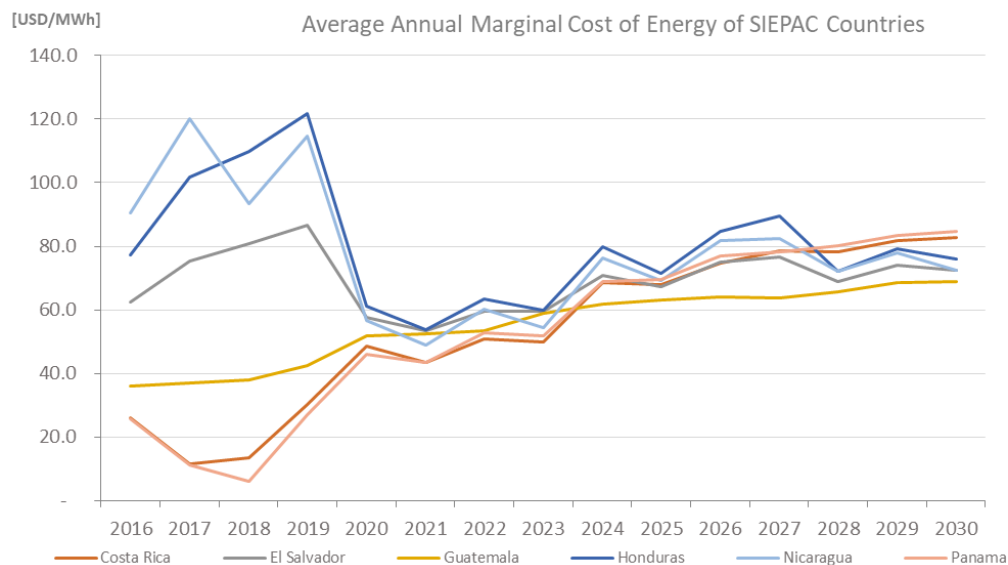


Figure 4-27 Average annual marginal cost of energy of SIEPAC countries for Integrated Renewable Scenario

In South America, all the interconnection candidates have been built. In this context, it is relevant to highlight the total exchange capacity of Bolivia –1870 [MW]— with all its neighbor countries. The biggest exchange capacities between countries reached in the exercise are registered between Peru and Brazil, with 2200 [MW] of capacity, a 1680 [MW] reinforcement of the interconnection between Brazil and Paraguay, and two interconnection projects between Chile and Peru with a total capacity of 1100 [MW]. Also, the Arco Norte project is built with capacities that goes from 2300 to 3000 [MW] depending on the section. Figure 4-28 presents the transmission capacity built in South America.

In the case of Brazil, in the Integrated Renewable scenario it becomes a net import country, even when the flow with its neighbors is bidirectional. In Figure 4-29 are presented the imports and exports of Brazil, where can be seen that its main exports go to Uruguay and Peru; meanwhile, its main imports came from Argentina, and in a minor proportion from Guiana and French Guyana. In the interconnection with Bolivia, in the first year of the horizon, between 2017 and 2022, the flow goes mainly from Brazil to Bolivia, then from 2023 onward, the flow goes mainly in the opposite direction. The exchange with Paraguay is not presented since the binational hydropower plant Itaipú is included in the model in the Brazilian system, so all the flow between Brazil and Paraguay is energy from that power plant.

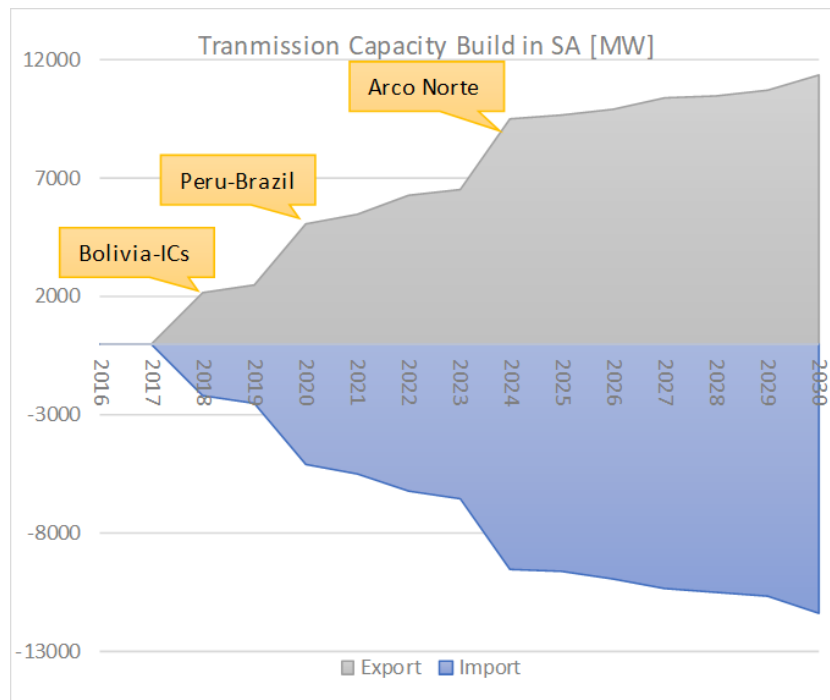


Figure 4-28 Transmission Capacity Expansion in South America for Integrated Renewable Scenario

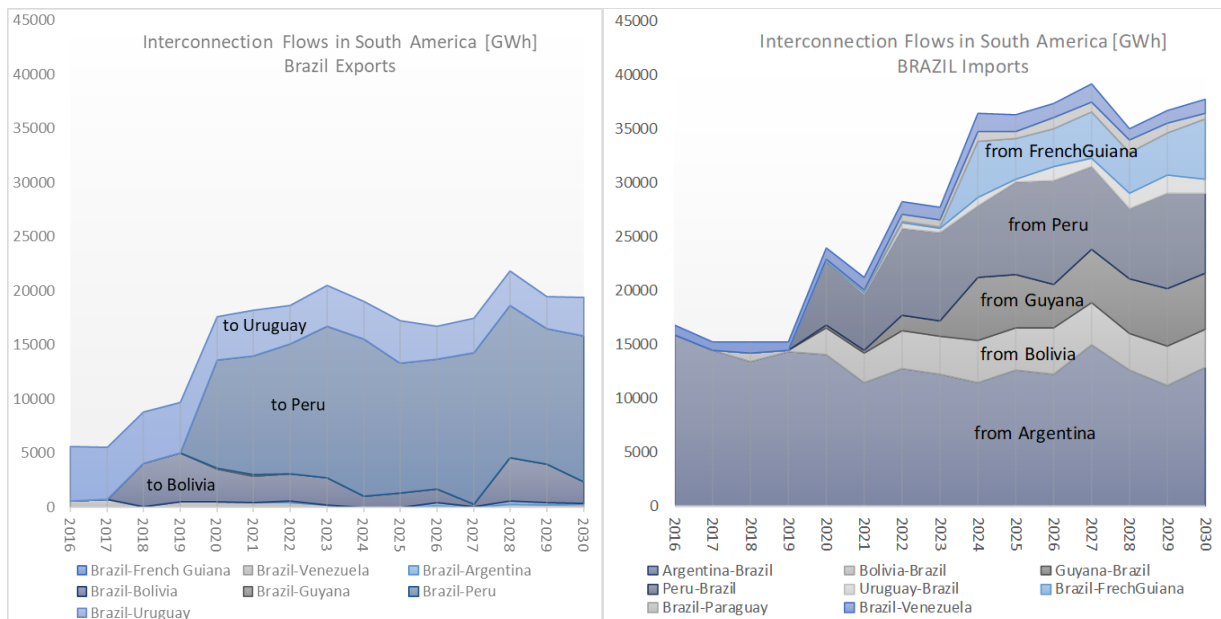


Figure 4-29 Brazil exports and imports for Integrated Renewable Scenario

For Argentina, also a net import country in the Integrated Renewable scenario, the main export flow goes into Brazil. Its imports come from Uruguay, Chile and Bolivia. The flows for Argentina are presented in Figure 4-30. In this case, the exchange with Paraguay is also not presented, since the binational hydropower plant Yacyretá is included in the Argentinean system, therefore, the exports to Paraguay are mainly from this power plant generation.

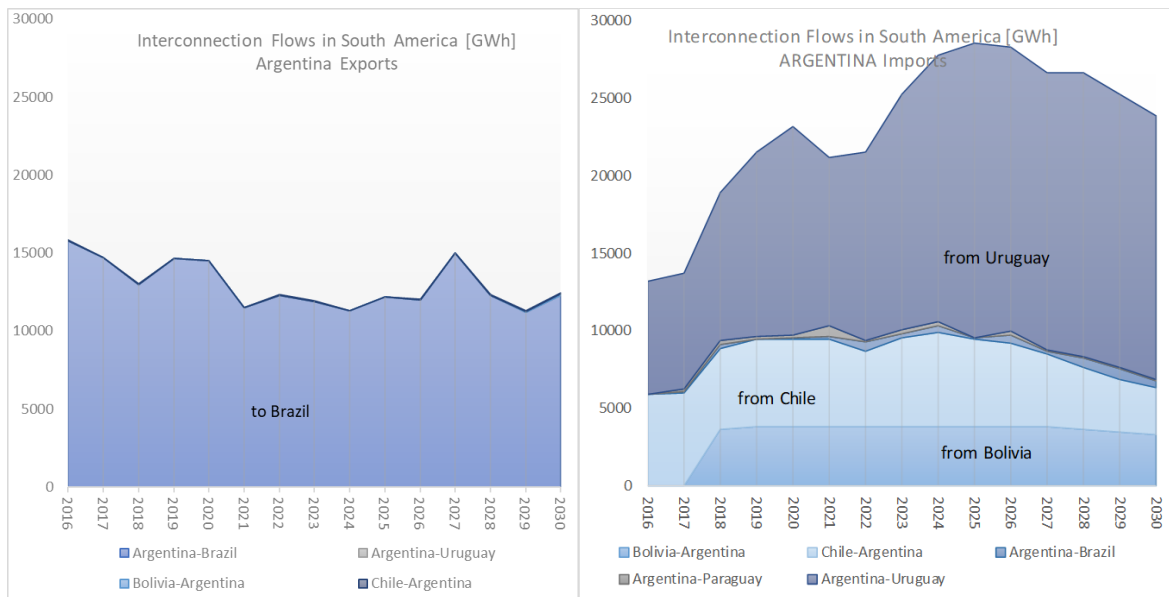


Figure 4-30 Argentina exports and imports for Integrated Renewable Scenario

A particular case in South America is Bolivia, given its central location in the region, enables the interconnection among Chile, Peru, Argentina and Brazil. In Figure 4-31 are presented the exchanges of Bolivia, where can be noticed that the flow comes mainly from Brazil and goes to Chile, Argentina and Peru. In this graph are two interesting results in the imports, the first one is the flow coming from Chile and Peru in the last years of the horizon, that even when the Bolivian marginal price is lower in average, this energy is related with the high amount of solar generation, that in the daily hours is exported through Bolivia, while the rest of the time the flows goes in the opposite direction. The second result is the imports from Argentina, where the effect is similar but related with the high amount of wind energy installed in this country.

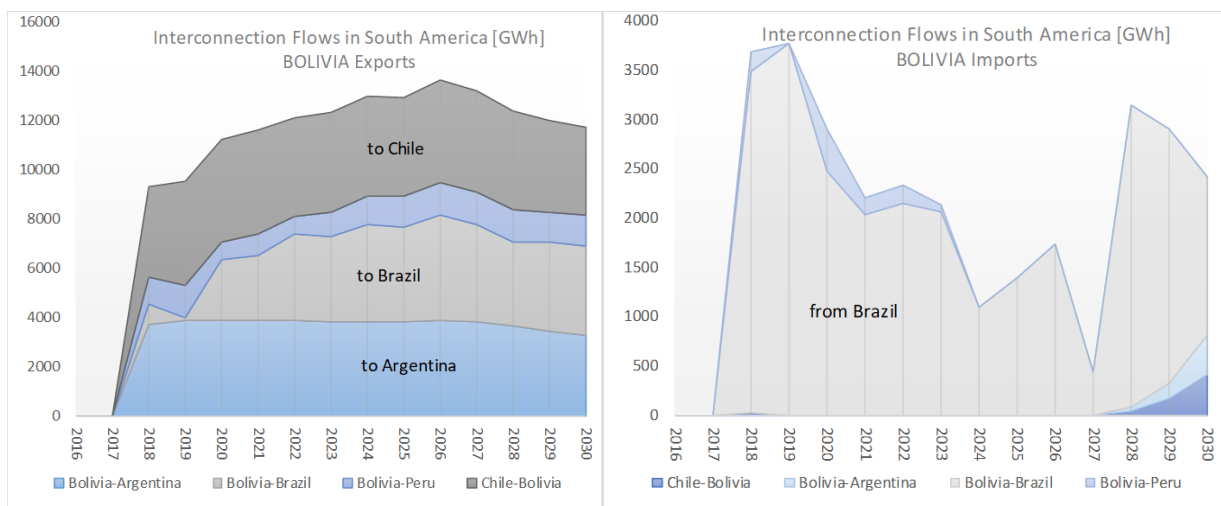


Figure 4-31 Bolivia exports and imports for Integrated Renewable Scenario

The energy flow through Bolivia can be explained with Figure 4-32, where the average annual marginal cost is presented for this group of countries, and can be noticed that the Bolivian marginal cost is the lower among them, while Chilean and Peruvian marginal cost goes lower than Brazil in the last years of the horizon.

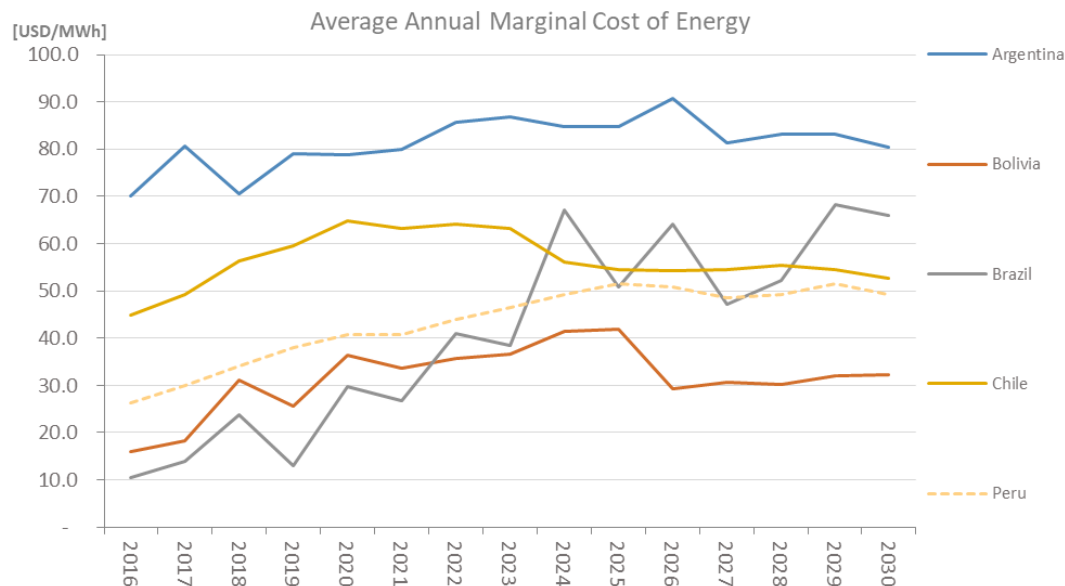


Figure 4-32 Average annual marginal cost of energy of South American countries for Integrated Renewable Scenario

One case where the effect of interconnections can be appreciated is the Arco Norte project connecting Brazil, Guyana, Suriname and French Guyana. This project was developed in the Integrated scenario with a mean capacity of 780 [MW] between countries, the major effect being concentrated in the future capacity in Guyana. Figure 4-33 presents the installed capacity of Guyana for the Base scenario and the Integrated Renewable scenario. The result for the base scenario is expected according to the load projection of the country and the hydropower resource available. Furthermore, in the Integrated Renewable scenario the installed capacity became completely out of proportion regarding the peak load of the country. This means that most of the hydropower capacity installed serves the purpose of exporting the energy through the Arco Norte project. This result has an impact in Guyana in two aspects. The first one is the possibility of a 100% renewable operation from 2020 until 2030 with a high installed capacity for reserve. The second impact is the opportunity to develop a hydropower industry, with the economic benefits that this development may bring to the country.

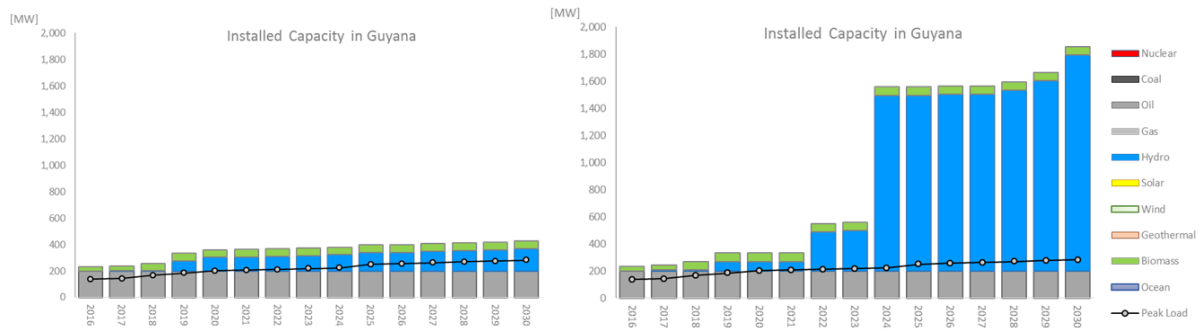


Figure 4-33 Total Installed Capacity in Guyana for Base scenario and Integrated Renewable scenario respectively

5. FINDINGS AND CONCLUSIONS

At large, this chapter presents the main findings and conclusions that have been mentioned in the results section, highlighting the key aspects of this work to reach the objectives proposed. This section is separated in general and specific conclusions, in correlation with the general and specific objectives proposed in section 1.3.

5.1. GENERAL CONCLUSIONS

The main objective of this work was to quantify the economic benefit of develop an integrated grid in Latin America, in order to achieve a high renewable participation in the electric generation. With the proposed methodology, it has been possible to quantify the expected total cost of investment and operation of each scenario, and ascertain that a scenario with a higher integration can reach a high renewable participation without increasing the total cost.

5.2. SPECIFIC CONCLUSIONS

In terms of applying a centralized optimization model, it has been relevant to achieve a Benchmarking process that ensures the proper representation of each system in this general model. Then, the use of a co-optimization model of the generation and transmission for the entire Latin American system guarantees the objective of obtaining a centralized vision for the development of the electric system.

Another specific objective for this work was the determination of the most relevant areas of the continent in the development of generation resources. In that sense, it has been possible to verify that not only Mexico and Brazil are the main load centers in the continent, but also have massive solar and wind resources in terms of quantity and quality. However, a key conclusion of this work is that, in South America, the south region of Argentina is a relevant zone for the development of wind energy, while the north region of Chile has the same relevance in the solar expansion.

In terms of interconnections, the lines proposed among Chile, Bolivia, Argentina, Peru and Brazil are clearly relevant to develop the wind and solar resources in the south, considering that without those interconnections the amount of solar and wind potential developed in the south was lower. Another interconnection project that can be relevant for the development of local resources is the Arco Norte project, which allows the investment in hydro power resources in the area. Finally, the model proved useful to conclude that the current interconnections in the SIEPAC system and Mexico should be reinforced, in order to increase the renewable share in the region.

Finally, one of the key results of this work has been the finding of the lower installed capacity needed in the Integrated Renewable scenario to reach the same target than the Renewable scenario, in the first case it is needed 10 GW less than the last one which is equivalent to 4% of the new installed capacity needed. This result reinforces the idea that the interconnections allow the development of better resources, with higher capacity factors and the possibility to reach the same generation with a lower capacity. In terms of emissions, results show that a higher renewable share can cause the same amount of total emission, despite the increase in the load in future years. This

will eventually result in a lower intensity factor of emission per load unit. In comparison, the Renewable and Integrated Renewable case can reach 30% less emissions than the Base scenario by 2030.

5.3. FUTURE WORK

The relevance of this work is that, regardless of the numerical assumptions used, the methodology proposed and the model applied have proved useful in the analysis of integration and renewable development between power energy systems. In terms of the assumptions considered, the limit of interconnection candidates provokes a suboptimal result for the entire region, therefore, a relevant analysis will be including a higher amount of capacity of interconnection candidates.

In terms of the model applied, have been explored in [42] that the limitations of expansion models, particularly the use of non-chronological energy blocks, can provokes suboptimal solutions that includes a high share of variable generation, like solar and wind. The results of this work reach 30% of solar and wind generation, then will be necessary to apply a short-term simulation to measure the difference between the operational cost of the expansion solution and the cost of a unit commitment based optimization. In that sense, there are models developed that includes short-term constraints, where the simulation time is critical with large-scale study cases like the proposed in this work.

Several references considered in this work have developed a different approach to address transmission expansion planning, where the methodology includes generation scenarios instead of a co-optimization of generation and transmission. In addition, integrated regions like the European network are considering not only technical and economic issues, but also environmental, social and security criteria, among others.

Finally, one aspect that this work has not considered is the regulatory approach in the development and operation of the interconnections. This can be treated in an endogenous way, by including into the model constraints related to minimum development times and power flow limits. A second alternative is an *ex post* analysis following this technical and economical approach.

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