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# *Energy security in power systems within the frame of energy transitions*

## Sergio Fuentes Ruiz

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## Departament d’Enginyeria Elèctrica

# Energy Security in Power Systems within the Frame of Energy Transitions

## PhD Thesis

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“A nation that can’t control its energy sources can’t control its future.”

Barack Obama

A México

# Acknowledgements

Through this doctoral thesis I have had the opportunity to develop a topic I am passionate about, while I consider it of high impact for the achievement of sustainable development.

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# Summary

Climate change is real. Global human population is growing as never before. Natural resources are limited. These factors have taken different countries to embrace new pathways in order to fulfill the energy needs of their population, understanding that energy is a fundamental instrument for achieving sustainable development. Since each economy decides, according to its needs, possibilities and interests, its own shift of energy production and consumption, this tendency has received the name of energy transitions. Energy transitions, through digitalization, decentralization and decarbonization of the energy system, have placed the power sector as the center of modern infrastructures, making it imperative to procure its security in the long-term.

This thesis is focused on the security of electrical systems, for which, after performing a thorough review on energy policies of different economies, it presents a multi-dimensional index as a tool for policy makers aimed to assess long-term security of power systems. The composed index is subsequently applied to different nations from two different approaches: the tracking of a country's development and the evaluation, comparison and ranking of different economies in a specific time frame.

The designed tool represents a comprehensive framework for assessing -and improving- energy security in power systems, being this precisely the main contribution of the present thesis: the development and proposal of an instrument that contributes, through the betterment of energy systems by making them more secure, to achieve sustainable development.

# Resumen

El cambio climático es real. La población humana global está creciendo como nunca antes. Los recursos naturales son limitados. Estos factores han llevado a los distintos países a adoptar distintas rutas encaminadas a satisfacer las necesidades energéticas de su población, entendiendo a la energía como un instrumento fundamental para alcanzar el desarrollo sostenible. Debido a que cada economía decide, de acuerdo a sus necesidades, posibilidades e intereses, su propio cambio en producción y consumo de energía, esta tendencia ha recibido el nombre de transiciones energéticas. Estas, a través de la digitalización, descentralización y descarbonización del sistema energético, han colocado al sistema eléctrico como el centro de las infraestructuras modernas, haciendo imperativo el procurar su seguridad en el largo plazo.

La presente tesis está enfocada en la seguridad de los sistemas eléctricos, para lo que, luego de una exhaustiva revisión de políticas energéticas de distintas economías, se presenta un índice multidimensional como herramienta para los encargados de la elaboración de políticas orientadas a procurar la seguridad de los sistemas eléctricos. El índice compuesto es posteriormente aplicado a diferentes naciones desde dos perspectivas distintas: el seguimiento temporal del desarrollo de un país y la evaluación, comparación y jerarquización de diferentes economías en un tiempo específico.

La herramienta diseñada representa un marco integral para la evaluación y mejoramiento de la seguridad energética de los sistemas eléctricos, siento precisamente esta la mayor contribución de la presente tesis: el desarrollo y propuesta de un instrumento que contribuya, a través del mejoramiento de los sistemas energéticos, haciéndolos más seguros, a alcanzar el desarrollo sostenible.

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# 1. Introduction

Energy constitutes a priority for policy makers, since an adequate and sufficient energy supply is critical for guaranteeing the sustainable development of a nation (Kharrazi et al., 2015). Societies have, since memorial times, tried to enhance energy security in order to be able to provide not only basic services to the people, but also to defend themselves from either natural or human threats. There are several perils that may hazard the energy supply of a country; the absence of indigenous resources, the lack of technology to exploit them or adverse geopolitical situations are some examples of challenges that governments must find the way around to guarantee energy access at an affordable cost, besides unexpected threats like armed conflicts, natural disasters or malfunctions of power sources or of energy transport systems.

Energy security, defined by (International Energy Agency, 2017) as the uninterrupted availability of energy sources at an affordable price, constitutes a priority in national development strategies, since on this source depend all the industry, infrastructure and security of a country and, by these means, the ability of the State to provide basic services to the people, such as health care or sanitary services. These are the reasons that have taken energy security to be one of the main targets of energy policy (Kruyt, van Vuuren, de Vries, & Groenenberg, 2009; Winzer, 2012). The main objective of energy security is to assure that the energy demand of a territory is satisfied, which is determined by several factors, such as population, weather, industrialization level and efficiency requirements.

Since the last century, it has already been identified that along its history, the mankind has experienced several energy transitions, and each one of them has represented an increase on energy consumption (Grübler, Nakićenović, & Victor, 1999). Nevertheless, the current transformation the globe is facing is substantially different from the previous ones; the global population has been increasing constantly due to improvements in life expectancy and a long-term peace period in most parts of the planet, which means that people's needs have changed in a rate the world has never seen before. The new scope of energy includes an important effort to reduce its consumption and to use it more efficiently, at the time that concepts like sustainable development and environmental protection have arisen, augmenting the complexity of designing strategies focused on procuring security of energy supply, taking the concept of energy, as it is stated by (Fouquet, 2016), to be reconceived.

The shift from traditional energy systems, normally based on fossil fuels, to new ones relying upon renewable technologies, has led policy makers to generate a global transition towards a sustainable energy system. However, since different economies present distinct characteristics, it is not possible to have one single transformation, but a series of energy transitions, one for each nation aimed to transform its energy system. The variability takes governments to approach their transitions from different perspectives, and to issue and implement strategies that might diverge notably among them. Within this context, countries try not only to guarantee access to energy sources, but they rater orientate their strategies to delineate sustainable energy solutions, all in order to achieve a sustainable development (World Energy Council, 2016).

Energy transitions are driven by international efforts to increase competitiveness efficiently, while respecting the environment and guaranteeing supply of energy (World Energy Council, 2018). They are reshaping the global energy system, not only by boosting the presence of renewable energy technologies, but also by improving the system's flexibility through innovative infrastructure solutions, at the time that enhancing energy productivity has become a priority worldwide (Hoggett et al., 2014; IRENA, 2018). This new paradigm presents also new challenges, being the security of energy supply an utmost important matter for the efficient functioning of modern economies (Kruyt et al., 2009).

Energy transitions have taken the power system to occupy a central role for policy makers, since electrical systems, as the linking network among other public facilities, have become the center of modern infrastructures (Fischer, Hake, Kuckshinrichs, Schröder, & Venghaus, 2016). Moreover, the electrical system is crucial for the integration of renewable energies at a large scale, a key measure for fight against climate change. The power system, occupying such a prominent role in the energy system, makes of assuring its security a priority for governments global wide. Procuring an appropriate, integrated and reliable network is, besides an energy policy objective, a part of a national economic strategy (Yusta, Correa, & Lacal-Arántegui, 2011).

Thanks to its flexibility and versatility, electricity has substantially extended its presence in the global energy matrix; its consumption as final energy increased 215% between 1990 and 2016 (International Energy Agency, 2018). Furthermore, due to the integration of renewable energies, electricity occupies a central role for decarbonizing the energy system (International Energy Agency, 2015a). Therefore, procuring reliability of the power system, becomes crucial for the development of modern societies, not only in energy terms, but also as part of a national economic strategy (Shivakumar et al., 2017; Yusta et al., 2011). Moreover, electricity is the main pillar for most energy transitions in the planet.

Latin America[1] is an energy rich region, not only in fossil fuels reserves, but also in renewable energies potential, both conventional and unconventional. Nevertheless, the distribution of sources is eminently uneven; while several Latin American countries possess some of the largest oil and gas reservoirs in the world, some other nations lack of natural fuels to fulfill their own basic energy needs. Due to this diversity, jointly with the deep economic contrasts among countries in the region, it results pertinent to evaluate how policies of different economies in Latin America are translated into improvements on energy security in their respective power systems.

In the today's globalized world, it is practically impossible for a developed country to rely only on its own means to completely fulfill the needs of its population, standing against this tendency is a risk that might jeopardize the stability of the country that may want to live isolated from a globalization; countries rather promote an exchange of added value products, and the energy industry has been a fundamental part of this tendency; decisions taken by an economy do affect directly or indirectly all those they have relationships with, and this is particularly true for energy related matters. Latin America is a very interconnected region energetically: there are not only very important international electrical interconnections, but there are also binational hydro power plants located in the continent. Such model makes Latin America a unique region energetically, reason that have taken this work to focus on it for the study of its energy security.

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[1] Latin America is in this work considered to be comprised by the members of the Latin American Energy Organization, i.e. Argentina, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Dominican Republic, Suriname, Trinidad and Tobago, Uruguay and Venezuela.

## 1.1. Objectives and scope

It is the aim of this work to present, framed in the international regime of energy transitions, a tool focused on evaluating long-term energy security in power systems at a national level. This tool shall consist of a multi-dimensional index, possessing, in turn, several indicators grouped into categories within each dimension.

It is desirable that the tool can be applied to any territory, for which it will be used for studying countries in the Latin America and the Caribbean region, so their performance on achieving energy security on their electrical systems can be, through and statistical analysis, evaluated, compared and ranked.

## 1.2. Thesis outline

For accomplishing its objectives, this thesis is structured as follows: a definition of energy security will be handled in the next section in order to establish the frame within the work has been developed; the concept of energy security will be then applied to power systems at a national level and from a long-term perspective. In the third section, a review of energy trends in different regions is made, for a further and deeper study on specific countries, particularly those ones with high impact on their respective regions in electrical energy terms, analyzing their current objectives and strategies regarding the procurement of energy security in their respective power systems, this in order to constitute a state-of-the-art analysis on energy policies and to provide a context for the subsequent study of Latin America. The construction of the multidimensional index is covered in the fourth section, in which its corresponding dimensions and indicators are also described, according to the defined scope of the work. The fifth chapter consists of the application of the index to the case of the Argentinian Republic, in order to make a time tracking on how the country has evolved in energy security terms. Section six consists of the application of the tool to the Latin America and the Caribbean region; subsequently, a statistical study is performed in order to identify common trends in the continent as well as where the deepest differences among countries lie. Finally, conclusions on the work are presented.

# 2. Methodology

The research methodology that has been defined to provide the overall guidelines of this work is presented in this section. It comprises aspects concerning review of literature on energy security, acquisition of data and information delimitations.

## 2.1. Literature review

The literature review for this work has been performed in such a way that the most reliable and up-to-date data could be obtained, as long as it was available. The main desired characteristic of the information sources is that they are credible, which means that the information must come from a well-recognize and authoritative entity. In order to try to gather the most up-to-date information, it is intended that it comes from online references, due to the fact that it is updated more frequently than physical sources, always focusing in the meaningful data that these might contain.

Since the gathering of information constitutes an essential part of this work, particularly in the section relative to the application of the composed index, the following classification frame has been established in order to guarantee the quality of the quoted sources, by prioritizing the use of a certain kind of information sources. According to the nature of the source, the classification shown in Table 1 was followed:

**Table 1**
*Classification of sources according to type of source and publisher*

| | By type of source | By publisher |
|---|---|---|
| 1 | Peer-reviewed literature | Research centers |
| 2 | Official reports | Universities |
| 3 | Others | International organizations |
| 4 | | Government agencies |
| 5 | | Business/Professional associations |
| 6 | | Non-governmental organizations |

The category of *others* in the type of source classification may include reports by think tanks, research institutes, business or professional entities.

It is the purpose of the research process, to obtain information from the upper categories and, in case that an opposed or con-concordant information derived from using two or more different sources, the classification of Table 1 will guide the selection of data by considering the source of an upper category a more trustful one that one in a lower position, so a conflict of interpreting information is avoided.

The information regarding national data is controlled by each state and in a further stage, different organizations, either national or international, gather and interpret these data in order to make reports or statistical studies. Because of this reason, in numeric terms, the data that will be managed is not supposed to present large differences from one information source to other.

In contrast, the data that deals with policies and the interpretation of data trends, or of the data itself, may differ drastically among sources.

### 2.2. Data acquisition

Composite indicators, when referring to countries' development, allow a relatively easy and illustrative comparison of large amounts of data in a synthetic way. They consist of a set of individual indicators arranged into a single index on the basis of an underlying model (OECD, 2008).

Specifically, for the case of energy security, manifold indicators allow a broader understanding of the concept and are indispensable for its measurement (Kruyt et al., 2009; Reddy & Ulgiati, 2015). Indicators are useful instruments for identifying trends and drawing attention to particular issues, either among different countries or in different time frames (OECD, 2008); as such, they are of particular relevance for the study of security of energy supply.

In order to achieve a reliable energy security measurement tool design, it is essential that the indicators shaping it follow minimum quality standards that ensure the trustworthiness and coherency of the composed index. Indicators are entitled to go beyond basic statistics and to contribute to a broader understanding of the main treated issues (International Atomic Energy Agency, 2005).

Within a composite indicator, dimensions constitute the highest hierarchical level of analysis (OECD, 2008). The dimensions group different indicators and point out the scope of the variables that they measure. The indicators assigned to each dimension within the index must fulfill the following criteria:

- Analytical soundness: Chosen indicators must pertinently measure a significant condition according to the index scope.
- Measurability: Objective assessment must be possible for values of the treated variable.
- Robustness: The data source must be reputable, well-recognized, and authoritative.
- Accessibility: The data must be publicly available.
- Updatability: Historical data must be able to be replaced with new data outlooks.
- Timeliness: The time between the data becoming available and the phenomenon it describes happening must be as short as possible.
- Coherence: The same methodologies, concepts, and definitions must be applied both over time and across countries.

- Consistency: Data should come from a single, common, unique source to the extent possible.

### 2.3. Data delimitation

Geographically and as it has already been established, this work will be focused in the study of Latin America and the Caribbean region. The countries to be considered within this region are those that are active members of the Latin American Energy Organization, namely Argentina, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay and Venezuela.

For providing a context, a state-of-the-art analysis of energy policies is developed, in which policies and strategies of different countries are covered. For these countries, as well as for those belonging to Latin America, the power system data to be handled is the one corresponding to their continental part, with the only exception of the United Stated for which the data presented includes all the 50 States.

Regarding energy technologies, in renewable sources will be considered solar, both photovoltaic and thermal, wind, both onshore and offshore and hydropower, independently of the installed capacity. Other kinds of renewable energies do fall in the category of *others.* In the conventional sources' classification, there will be fuel, which includes gasoil and fuel oil, natural gas, which includes turbo gas power plants and those of combined cycle and coal thermal plants; other forms of technology will be included in *others*. Nuclear power plants have their own classification in this work.

All this information is valid through all the document unless otherwise stated.

## 3. Energy Security

Security of energy supply constitutes presently one of the main targets of energy policy (Winzer, 2012). Nevertheless, and as it has been stated by (Chester, 2010), due to the polysemic nature of the concept, there does not exist a universally accepted definition for the term, thus, energy security covers a broad spectrum of factors that are, to a greater or lesser extent, related to it. Governments around the world have established different approaches for determining what energy security is, and they have also conducted their energy policies in diverse priority lines when referring to energy strategies, which range from energy poverty to climate change (Cherp & Jewell, 2014).

In the United States, for instance, the term of energy security is associated with reducing the vulnerability of the country due to their dependence on foreign energy supplies, leading their energy policies to promote the use of domestic energy sources, foster energy research, increase efficiency and boost the use of renewable fuels, all in order to improve the country’s energy security and to achieve energy independence (Congress of the United States of America, 2007).

The European Union, for its part, has also developed a series of strategies targeted to improve energy security of its member countries. These strategies have several lines that share targets with the one of the United States, but unlikely this one, they also include fomenting the inner European energy market (European Commission, 2014b). However, the European Union strategy does not seek to maximize energy self-sufficiency or to minimize dependence (Chester, 2010), unlike the one of the United States, for which this is a central matter.

Accordingly, it becomes clear that the concept of energy security is highly context dependent and differs significantly from one policy maker to another, but independently of the exact definition, security of supply constitutes a major objective for energy policy makers (Kruyt et al., 2009). It is hence necessary the establishment of a clear frame and the boundaries in which energy security will be studied in this work, as well as the parameters that will be used to measure the effectiveness of policies concerning energy security.

## 3.1. Definition

Historically the term of energy security had been associated to national oil supply, but nowadays that concept has been widely expanded. Today, for instance, gas and electricity constitute also priorities for the governments in order to assure the quality of life of the population, and to meet objectives related to economic growth (Gill, Gill, & Singh, 2015). Unlikely in the past, the price of energy is considered to be a central factor for the definition of the concept of energy security (Jewell, 2011).

There is still no one commonly-accepted definition for energy security (Cox, 2016) and they vary depending on the priorities that the defining implicated entity wants to emphasize. The International Energy Agency defines energy security as “the uninterrupted physical availability at a price which is affordable, while respecting environmental concerns” (Jewell, 2011).

The meaning of energy security is highly context dependent and the framework the concept is defined in may be constituted by specific circumstances of a country, its level of economic development, risk perceptions and the robustness of its energy system and prevailing geopolitical issues (Ang, Choong, & Ng, 2015). Moreover, the definition for energy security has changed over the time; whereas concepts such as availability have always been present when trying to define energy security, some other terms have appeared recently, like those of sustainability or environmental protection. Presented by (Cherp & Jewell, 2014), there is an explanation for all these different meanings; energy systems vary from one place to another, which leads to having different security problems and the term of energy security tends to be extended to also cover other energy policy issues, ranging from energy poverty to climate change.

Despite the variety of definitions for energy security, common lines of the concept can be identified. The Asia Pacific Energy Research Centre introduced the “four As of energy security”, which are availability, accessibility, affordability and acceptability (Asia Pacific Energy Research Centre, 2007). Some authors identify other factors that may help to dimension the concept of energy security such as technology development, sustainability and regulation (Sovacool & Mukherjee, 2011). Thus, the approach from which energy security is studied as well as the relevance of the factors affecting security are dependent on the specific analysis that would be conducted (Månsson, Johansson, & Nilsson, 2014). It is also suggested that the term of energy security should be separated from some of these factors, and instead, they should be identified as independent policy objectives, since they are not directly related to the security of energy supply, leading to simplify the definition of energy security as a matter of continuity of energy supplies relative to demand (Winzer, 2012). However, such a definition would mean a short-term perspective, hence inadequate for a sustainable approach on energy security.

For the development of this work, energy security will be understood as the sustainable supply of energy.

### 3.2. Boundaries

Since the quantity of features that conform energy security is quite wide, it is necessary to restrain the range of these variables in order to make possible a more focused study of it, according to the described scope. For this work, and from all the multiple aspects conforming energy security (Chester, 2010), those to be taken into account for its characterization will be the management of risk and its area of applicability, the geographical area in which energy resources are intended to be assured, the time horizon of the approach, the energy market of the policies to be applied and the intent of the energy strategy.

Regarding risk management, in this work energy security will be related to dealing with the threat of unavailability of energy supply, the insufficient capacity to meet energy demand and the reliance on unsustainable energy sources. The area of applicability of risk management will cover the availability to supply energy at an affordable cost with the current technologies or, if not available, the capacity to develop them.

There will be two different approaches regarding geographical areas. The first one will deal with energy trends from a regional, or multinational, perspective. The second stage will focus on national energy policies, in which current status of power systems, strategies and objectives of countries will be covered.

The study of energy security in the power system will be focused on evaluating energy policies in a long-term horizon. Despite the fact that energy security can also be evaluated from a short-term perspective, covering by those means the ability of an energy system to react promptly to sudden changes in the supply-demand balance (Jewell, 2011), it is not relevant for this work. Thus, sudden risks of interruptions to the energy supply will be neglected and this study will center on adequacy of supply and infrastructure, as well as technology development and its implementation for assuring security of energy supply.

The procurement of energy security can be applied to the whole energy system of an economy, shown in Figure 1, which covers from energy supply sources to the final consumers. This work will focus on power generation, covering a fuel security, adequacy and system security approach, as proposed by (Varro, 2012), leading to the study of electrical energy security.

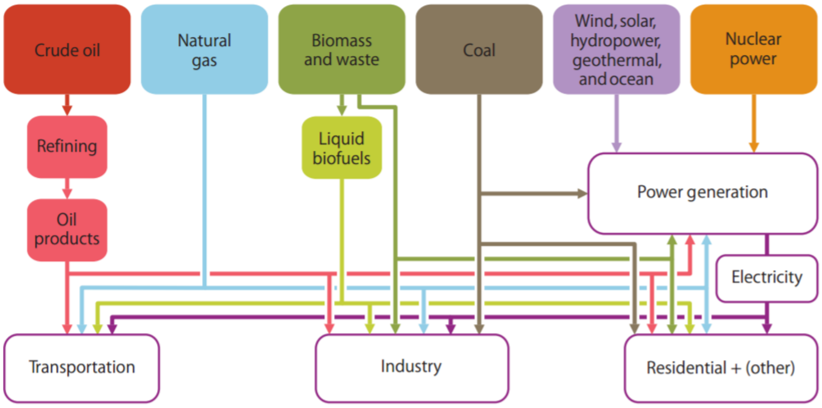

*Figure 1*. Energy system approach (Jewell, 2011)

Lastly, the aim that will be considered throughout this work is, through the betterment of energy policies, the improvement of energy security as a way to contribute to a sustainable development.

### 3.3. Energy Transitions

In an international frame, countries from all over the world have issued policies focused on transforming their energy systems towards less carbon-intense, clean and efficient systems, with the purpose of mitigating the anthropogenic causes of global warming and procuring sustainable development, both locally and globally. This tendency has received the name of energy transition (China National Renewable Energy Centre, 2018).

Such a global trend on energy policies has taken different nations to assume compromises at a multinational level, being the Paris agreement an example of one of these cooperation frames, in which the signing countries establish the commitment to limit the global average temperature increase to 2°C above pre-industrial levels through

GHG reduction targets (United Nations Framework Convention on Climate Change, 2015).

Nevertheless, the transformation that every country is implementing on their own responds to diverse circumstances, not only to the resources they possess but also to the political situation they are going through. This variability of conditions has led different countries to take distinct paths for improving their energy systems and align them according to international regimes. This series of frames has taken policy makers to consider, unlike in the past, that there is not a unique global energy transition, but individual transitions, carried out by each country that has decided to implement them.

Notwithstanding the differences among diverse energy shift strategies, several common lines can be identified, such as the implementation of efficiency measures and the deployment of renewable energy installations for electricity generation (Child, Koskinen, Linnanen, & Breyer, 2018), jointly with the reduction of fossil fuels usage for stabilizing the world’s temperature increase (International Energy Agency, 2015a). This has, in turn and consequently, taken security of electrical energy, to become a critical factor for the adequate functioning of any economy (Kruyt et al., 2009; Shivakumar et al., 2017; Wittenstein, Scott, Miza, & Razali, 2016; Yusta et al., 2011) and, moreover, an instrument for achieving sustainable development, moving energy security firmly up in the policy agenda (Internatonal Energy Agency, 2017).

## 4. National Policies on Energy Security

Due to the fact that energy sources are heterogeneously distributed around the globe thanks to geographical and geological reasons, it results intelligible that different regions around the globe have distinct ways for meeting their energy demand.

How different countries consumed primary energy in year 2017 is shown in Figure 2. The world's total primary energy consumption was 13,511.2 MToe in 2017 (BP, 2018), from which the Asia-Pacific region was notably the largest energy consumer with 43% of the world's total, and it did it mainly from coal. North America[2] occupied the second place with 21% of the total consumption and it did it mainly from oil, just like Europe, which consumed 15% of the world's total. By their part the Middle East, Central & South America and Africa consumed 7%, 5%, and 3%, respectively.

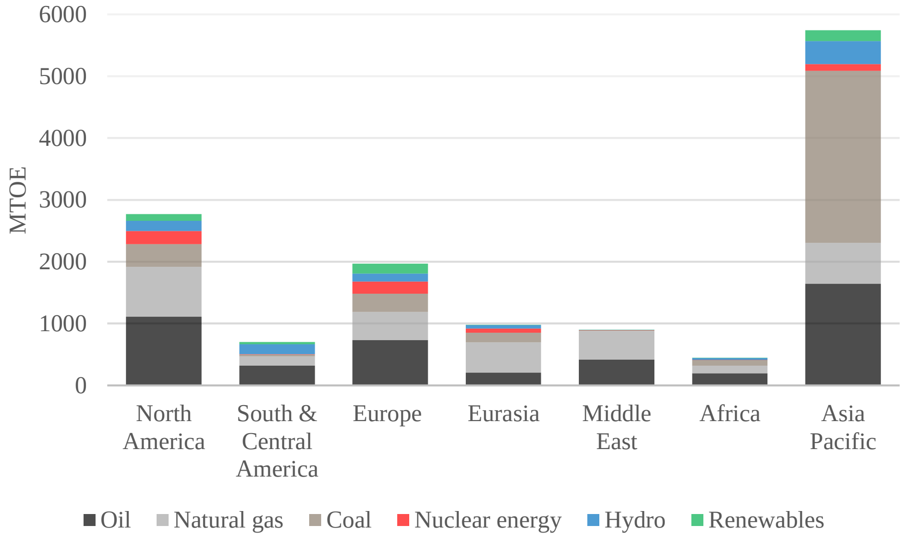

*Figure 2.* Primary energy consumption by continent and by fuel in 2017. Data from (BP, 2018)

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[2] North America is comprised by Canada, Mexico and the United States of America. Central America is comprised by Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama. South America is comprised by Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, and Venezuela.

The way each region in the world stablishes its own way of fulfilling its energy needs can be understood through the distribution of energy sources, shown in Figure 3. Different regions tend to rely upon indigenous primary energy sources in order to diminish their dependence on foreign suppliers (Brown, Wang, Sovacool, & D'Agostino, 2014). It is thus expectable that countries belonging to the same region might have similar strategies regarding the use of domestic resources in order remain energetically independent from third nations.

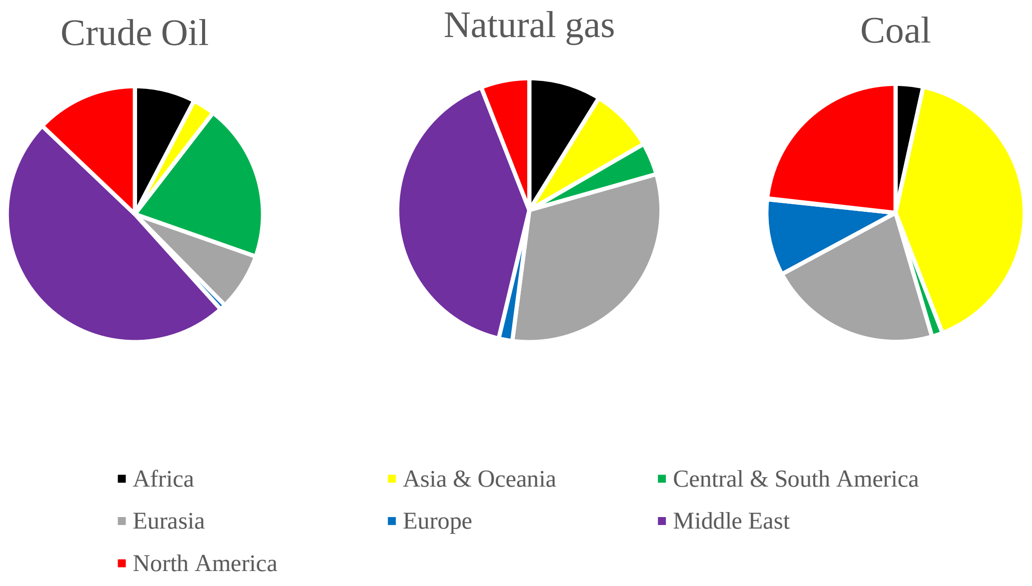

*Figure 3.* World shares of proved reserves of crude oil (2017), natural gas (2017) and coal (2015) in the selected regions (U.S. Energy Information Administration, 2018b, 2018d, 2018a)

The Middle East is by far, with 48% and 40% respectively, the region with the largest proved reserves of crude oil and natural gas in the world. Eurasia possesses large reserves of gas, 31% of the world's total, and 22% of those of coal. North America has important reservoirs of oil, 13% of the world's total, and 23% of the planet's coal. By its part, Asia is the region that possesses the largest coal reserves in the world, 41% of the total. Europe, on the other hand, has a virtual lack of oil and natural gas reserves, with only 1% and 2% of the planet's total, reason which explains the need of this region to focus on exploding alternative energy sources to procure energy security.

Energy transitions have taken the power sector to have a central role in the today's energy mix. Electricity, as a final energy consumption form, has acquired a very prominent role in the last decades, being the source with the largest percentage increase, 208%, from 1990 to 2015 (International Energy Agency, 2015c), which, as shown in Figure 4, places electricity as the world's second most important form of final energy, with a clear tendency to continue in this line. Moreover, among the different forms of energy, and as it is stated by (International Electrotechnical Commission, 2016), electricity stands out due to its versatility and easy-control features.

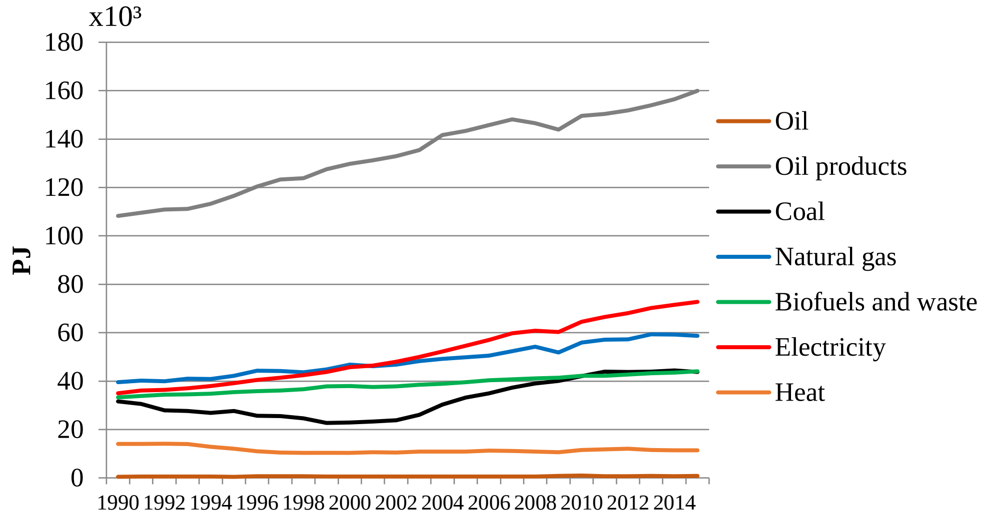

*Figure 4.* World Total Final Energy Consumption. Data from (International Energy Agency, 2015c)

Electrical systems are crucial since that they represent the link among many other public services, making the power system to be the center of modern infrastructures (Fischer et al., 2016). This means that is imperative to procure an "appropriate, integrated and reliable" network not only for energy policy makers but also as a part of a national economic strategy (Yusta et al., 2011).

The structure of each one of the national power systems depends, in most cases, on the indigenous resources that the country possesses. Thus, a country tends to use one specific kind of technology than another, so the country may be able to fulfill its own energy needs without compromising its energy independency in favor of an external entity.

Besides maximizing the use of local resources, implementation of new technologies, diversification of sources and suppliers, integration of markets, interconnections and storage facilities are some of the strategies that governments are implementing in order to assure energy security in their territories (Fuentes, 2015). It is important for a nation to consider that in an interconnected environment, alterations in the power system represent not only changes for the nation that applies them, but also for the neighboring economies, making it necessary to be prepared to changes in the system as a whole (Holzer & Le Anh Tuan, 2015).

Different regions around the world tend to use indigenous resources to satisfy their energy needs. In the frame of the current international electrification trend, governments are shaping their energy systems with the prominence of the electrical system and, to the extent of possible, draw upon fuels within their borders for satisfying their energy needs. In most of the globe are the countries themselves those stablishing strategies according to their own needs and interests. One particular case is the European Union, in which the member countries develop measures based on common directives. Even though the national governments have freedom of stablishing their own policies, common directives must be fulfilled. In this line, the current European targets include a reduction of 40% GHG emissions, a participation of at least 27% of renewable energies in the total energy consumption, an increase of 27% of efficiency in energy consumption and a level of 15% of interconnections by year 2030 (European Council, 2014). As it will be seen afterwards, European countries follow very ambitious strategies with the objective of sticking to these directives.

Regarding energy security, the European Council has, for instance, established several priorities, including the enhancement of the gas sector and procuring its diversification, the improvement of the interconnected energy network and to strengthen the Energy Community (European Council, 2014). The European Energy Security Strategy (European Commission, 2014a) enounces actions to increase the security of supply in the continent and among them are the diversification of energy suppliers and supply technologies, moderating energy demand through improvement of efficiency, and the enhancement of cross-border interconnections, maximizing indigenous sources of energy.

With the purpose of determining a frame for comparing regions, North America, South America and Europe will be covered in this work, so a wider perspective on national policies regarding energy security can be determined.

The difference of proven reserves of fossil energy fuels is huge among the analyzed regions. In Figure 5 it can be seen the virtually lack of crude oil in the countries conforming the European Union, accounting only 5 billion of barrels, while North- and South America possess large reserves of 216 and 328 billion barrels respectively. The case of Europe compared to North and South America is abruptly different. These latter regions count with some of the largest oil reserves in the world, being the leading nations the United States with 36,385 million barrels, Brazil with 16,184 million barrels and Venezuela with 300,878 million barrels of crude oil reserves in 2015 (Abdul-Hamid et al., 2016), which places this last country as the one with the largest oil reserves in the world.

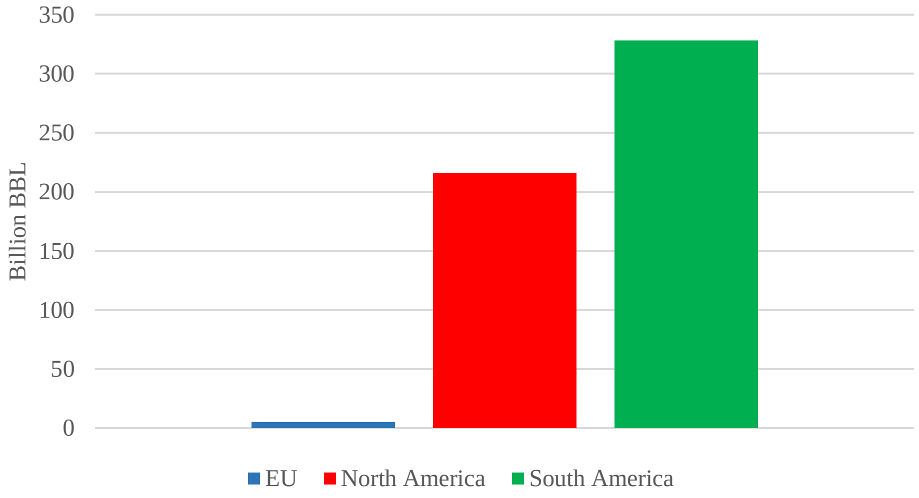

*Figure 5*. Proven Crude Oil Reserves in selected regions. Data from (U.S. Energy Information Administration, 2018b)

Precisely due to this lack of energy sources, in 2014 the European Union imported 53% of the total amount of energy it consumes. The crude oil dependency on foreign countries accounted almost 90%, natural gas 60% and solid and nuclear fuels 42% and 40%, respectively (European Commission, 2014a). The scopes of these regions to adapt their power system are thus abruptly different. The oil production and exports of North America have increased constantly (Abdul-Hamid et al., 2016) and the tendency is expected to continue in this line. The United States has for instance lifted its forty-year policy of banning petroleum exports in 2015 (Colgan & Van de Graaf, 2017) and is after Russia and Saudi Arabia, is the largest oil producer in the world (Abdul-Hamid et al., 2016).

Natural gas practically follows the same geographical distribution pattern to the one of oil as shown in Figure 6, with the difference that it is North America the region with the largest reserves of this source with 409.3 trillion cubic feet, followed by South America with 260.7 trillion cubic feet (U.S. Energy Information Administration, 2018d).

The country members of the European Union together do not reach 10% of the North American reserves, a fact that explains the need of the European Union to focus on exploding alternative energy sources to procure energy security in European territory (European Commission, 2014a). In the American continent, are again the United States and Venezuela the countries with the largest reserves, with 11,011 and 5,702 billion cubic meters of proven natural gas reserves, respectively (Abdul-Hamid et al., 2016).

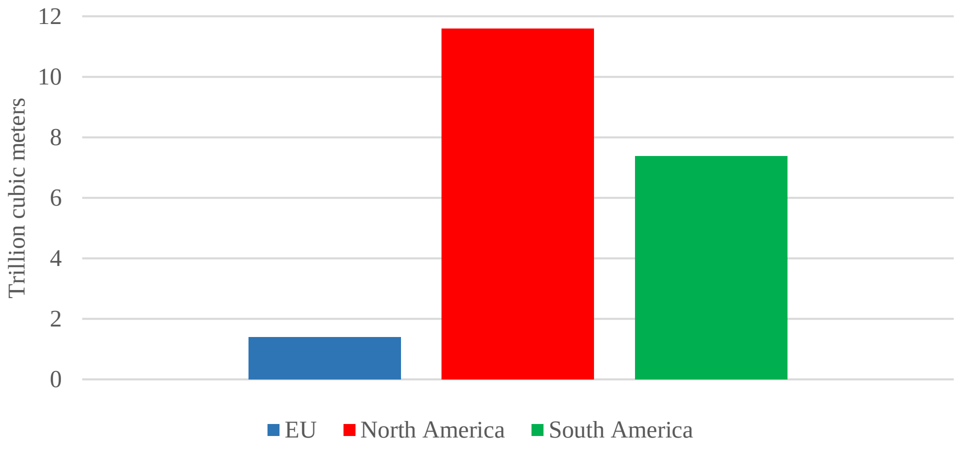

*Figure 6*. Proven Natural Gas Reserves in selected regions. Data from (U.S. Energy Information Administration, 2018d)

In both Figure 5 and Figure 6, it results evident the lack of conventional energy sources in Europe while North and South America are rich regions on oil and natural gas reserves.

Since the countries are entitled to act according to the sources they possess and the energy needs they have, procuring, as far as it is possible, to guarantee energy security for their population, it seems reasonable for the countries located in America to rely on gas and oil to fulfill their energy needs, while the European nations tend to promote the development and use of renewable technologies, as a measure to decrease their dependence on external energy sources.

In the European continent, most of the countries are net energy importers due to their virtual lack of fossil fuel deposits, condition that they have tried to mitigate through diversification of energy sources and lately, the promotion of renewable energy technologies and energy efficiency (Wang & Zhou, 2017).

North America is the top energy security performer region in the world (Wang & Zhou, 2017), being relatively self-sufficient due to its large reserves of oil, natural gas, coal and hydropower potential. The region strives to achieve 50% power generation by 2050, an objective to be reached through clean energy development and deployment, clean energy innovation and energy efficiency (Prime Minister of Canada, 2016). There are several projected lines to interconnect the electrical systems among the North American countries in order to achieve a higher level of integration of their energy markets. The total energy consumption of the three countries is expected to increase by 19% in a 2029 horizon (North American Cooperation on Energy Information, 2015).

By its part, South America, due to its vast reserves of fossil fuels as well as its large use of hydropower, is not only an energy-secure region, but also a leader in environmental sustainability.

Despite the fact that countries in the same region tend to possess generally the same available energy resources to be exploded, due to geographical, political, economic or social reasons, their power systems might have a very different structure from one to another, meaning that the approach of a nation to achieve energy security can be abruptly different, even if this approach is compared to those of neighboring economies.

For this thesis, and with the objective of delivering a state-of-the-art approach in energy policies and strategies aimed to achieve energy security in the power sector, the most relevant countries in terms of electricity production of the mentioned regions will be covered. Their electricity generation data is shown in Figure 7. The larger electricity producers of North America are the United States and Canada. Brazil is by far the largest generator of South America, followed by Argentina. By its part, Mexico, located in northern part of the continent but historically and culturally closest to the southern part of the continent -where it would occupy the second place as energy producer- has also been included for its analysis. Germany and France take the lead in Europe in the first and second place, respectively.

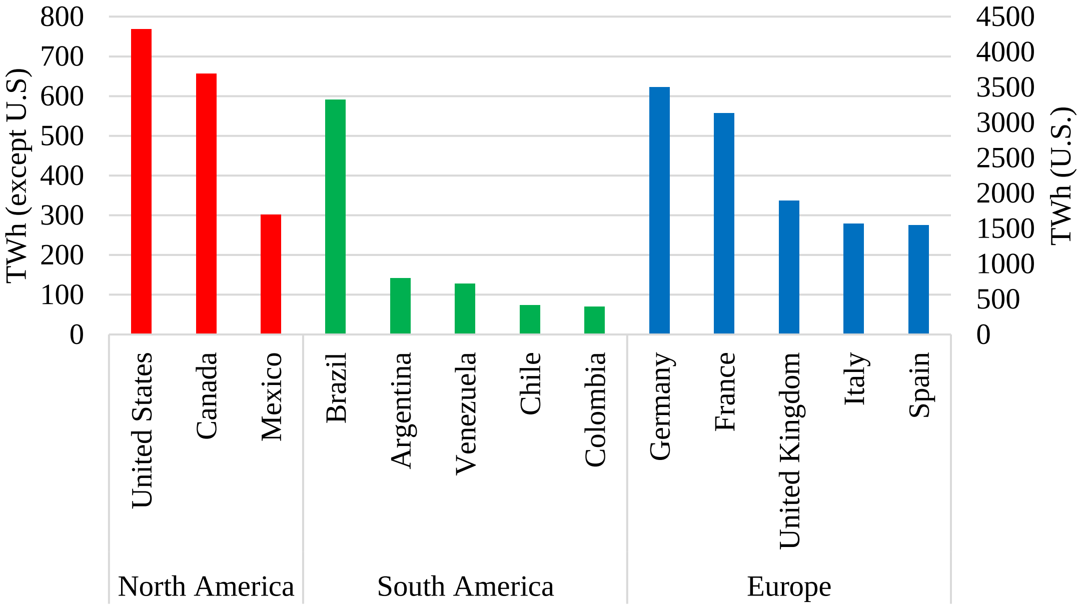

*Figure 7.* Total electricity generation in 2014. Data from (International Energy Agency, 2016b)

Besides these regions, China has also been included for its study. China is the most important country in terms of energy consumption both in Asia and in the world, having increased its primary energy consumption twofold in the period between 1991 to 2010 (Yuan, Xu, Zhang, Hu, & Xu, 2013), but the electric power consumption has escalated even faster, resulting in a boost of the electrical installed capacity and a rapid electrification, dominated mainly by coal-fired power plants (Yuan, Xu, & Hu, 2012). Nevertheless, China has made efforts to transform its energy system into a cleaner, safer and more efficient one, safeguarding its ES (National Development and Reform Commission, 2016).

Each country is able to determine its own power system's future under its own technical and political circumstances, as well as to set its dependence on electricity cross-border trades to establish suitable levels of energy security (Hawker, Bell, & Gill, 2017). This has taken different nations to supply energetically their respective populations in different ways, depending on the approach each one decided at the moment of structuring their energy systems.

Within the context of energy transitions, the starting point of each country is fundamental for designing the re-structuration of their energy systems, as well as how ambitious are the policies for this transformation. The following review of energy security strategies in the power system gives an overview of the current situation of the covered countries, as well as their most relevant series of strategies aimed to transforming them, seeking to achieve sustainable development.

### 4.1. Brazil

The Brazilian economy is, in terms of gross domestic product, the most important of South America according to (The World Bank, 2015). The country has, after Venezuela, the second largest oil and natural gas reserves in the region (Abdul-Hamid et al., 2016). Brazil is also by far the largest electricity producer of South America, with 50.2% of the total amount, followed by Argentina with 12.5% (Ministério de Minas e Energia, 2016a). Jointly with the largest population and territory (Instituto Brasileiro de Geografia e Estatística, n.d.), it is clear the importance of Brazil in the continent and so are the energy policies that the country implements for the development of the region.

The Brazilian economy, despite being the largest one in Latin America, has suffered a crisis recently; in 2015 the PIB contracted 3.8% and energy consumption in the country decreased 2.1% (Ministério de Minas e Energia, 2016c). The growing projections have been shrunk in both fields between 2014 and 2024, the PIB yearly expansion went from 4.3% to 3.2% and energy consumption from 3.7% to 2.7%. Nevertheless, the electricity consumption will increase in a 4.2% rate per year (Ministério de Minas e Energia, 2016b).

The Brazilian electrical model supported by the government seeks, among other objectives, to guarantee electrical energy supply at an affordable cost as well as promote social access to the electric system (Ministério de Minas e Energia, n.d.). In the installed capacity of the country shown in Figure 8 and abruptly dominance of hydropower in the Brazilian energy matrix can be observed.

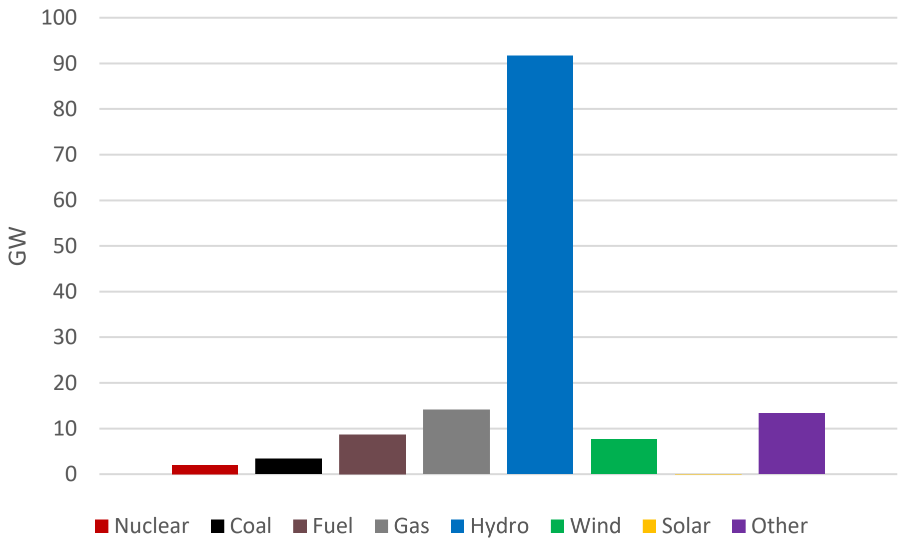

*Figure 8.* Installed capacity in Brazil in 2015. Data from (Ministério de Minas e Energia, 2016c)

The droughts that the country has suffered in the middle of the 2010 decade have exposed the heavy dependency of the country on hydropower (Corrêa da Silva, de Marchi Neto, & Silva Seifert, 2016) and vulnerability to hydrological conditions, a condition that may become worse with the current climate change previsions, increasing the energy vulnerability of the nation (Ruffato-Ferreira et al., 2017). It is noticeable as well that the participation of other renewable technologies has not been developed enough in a country as vast as Brazil with an enormous potential for wind and solar technologies development (M. G. Pereira et al., 2012), leaving a wide area of opportunity for further investments in this area, in which some technologies like hydro, biomass and onshore wind are competitive already and some others, for instance solar and offshore wind, still require government incentives (A. O. Pereira, Cunha da Costa, Costa, Marreco, & La Rovere, 2013).

The energy matrix of Brazil, as shown in Figure 9, relies heavily on hydropower, accounting for almost 62% of the electricity production of the country in 2015, followed by natural gas with a contribution of almost 14%. It is relevant the increase in the wind production of electricity, which passed from 12,210 GWh in 2014 to 21,626 GWh, an increase of 77.1%. The total participation of renewable technologies in the energy matrix was 75.5% (Ministério de Minas e Energia, 2016c). Electricity imports of the country are very important for the country, in 2015 they were 34,422 GWh, almost 6% of the total electricity consumption of the country. Proportionally, the electricity produced in the country in hydropower plants is higher than the installed capacity since this technology is used to cover the baseload demand while fossil-fueled power plants are run on to cover peak-load demand (Corrêa da Silva et al., 2016).

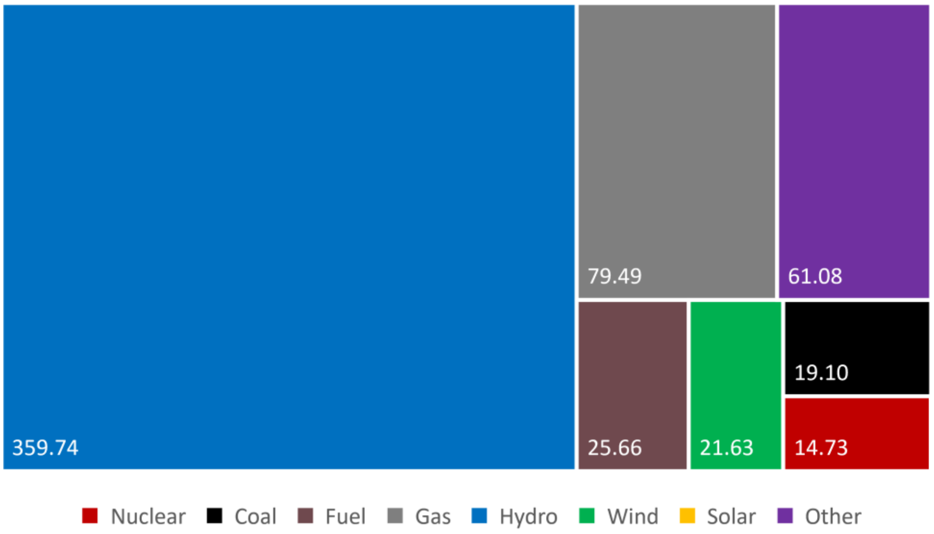

*Figure 9.* Electricity production in Brazil in 2015 in TWh. Data from (Ministério de Minas e Energia, 2016c)

The Brazilian electricity system is highly integrated with its neighbors, possessing not only international transmission lines but also binational hydropower plants. The most important development of this kind in the region is the Itaipu power plant, both the plant itself as well as the associated transmission lines, with a power of 14 GW (Ministério de Minas e Energia, 2016a). The interconnections, as it has said above, have helped Brazil to fulfill its energy needs and will continue to do so in an integrated South American energy market.

The Brazilian government is seeking to reduce its GHG emissions 37% and 43% by years 2025 and 2030, respectively, compared to year 2005 (Portal Brasil, 2015). The electricity consumption in the country is expected to grow 50.7% and achieve 940.8 TWh by 2024. By its part, electricity imports should be reduced at an annual rate of 6.5% towards 2024 (Ministério de Minas e Energia, 2016b). The hydropower dominance in the energy matrix will continue in a 2024-time horizon, with a participation of 65.8%, while other renewable energy technologies will pass from a contribution of 9.4% today to a 20.4% (Ministério de Minas e Energia, 2016b).

The participation of renewable energies in the total energy consumed in the country is expected to achieve 45.2% by 2024 while the aim of participation of renewables is to achieve 86% by 2024 in electricity generation (Ministério de Minas e Energia, 2016b), being, according to (Gils, Simon, & Soria, 2017), the expansion of solar and wind power a more cost-efficient option compared to the expansion of hydropower plants.

Regarding energy efficiency in the electrical system, Brazil has launched since 1985 the National Electricity Conservation Program, a Federal government program coordinated by the Ministry of Mines and Energy and implemented by Eletrobras and which promotes the efficient use of electrical energy. This program covers areas of education, information, and promotion in both the private and public sectors. In 2015, this program allowed the country to save 11,680 trillion kWh and avoided the emission of 1,453 billion tons of $CO_2$ equivalent (Eletrobras, 2016).

Within the Brazilian economy, a 1% increase of electricity consumption coming from renewable energy sources would increase the GDP by 0.20% (Corrêa da Silva et al., 2016), (Pao & Fu, 2013). So, an expansion of renewable energies would not only help to maintain low GHG emissions and boost economic growth, but also help the country's competitiveness and enhance its national energy security. It is imperative for the country to focus on investments and efforts on energy efficiency, technological improvements and renewable sources (Almeida Prado et al., 2016), so the government may dimension properly the country's energy needs considering the cultural and wealth differences among its population (Zurn, Tenfen, Rolim, Richter, & Hauer, 2017), and fulfill them in a more efficient way, avoiding being jeopardize by environmental factors, at the end, a vast and natural-resources rich country such as Brazil, should not have difficulties when it comes to energy terms.

## 4.2. Canada

Canada, a mature post-industrial economy, has large natural endowments of oil, natural gas, coal and hydropower potential. With its current power system structure, Canada is energy secure (Best et al., 2010). This condition is reached thanks to the vast resources the country possesses, its diversified energy mix, robust infrastructure, adequate market regulations supporting private investments and political stability (Langlois-Bertrand, 2010).

As it can be observed in Figure 10 and due to the large extension of the country and propitious geological conditions, hydropower installed capacity has a very strong presence in the Canada's energy mix, with 77 GW of installed capacity, followed by natural gas, which accounts 21 GW (National Energy Board, 2016a). Thanks to this hydropower prominence, Canada is the second largest electricity producer from this source in the world; in 2015 hydropower supplied 59.3% of the 631.7 TWh of consumed electricity in the country (Statistics Canada, 2016).

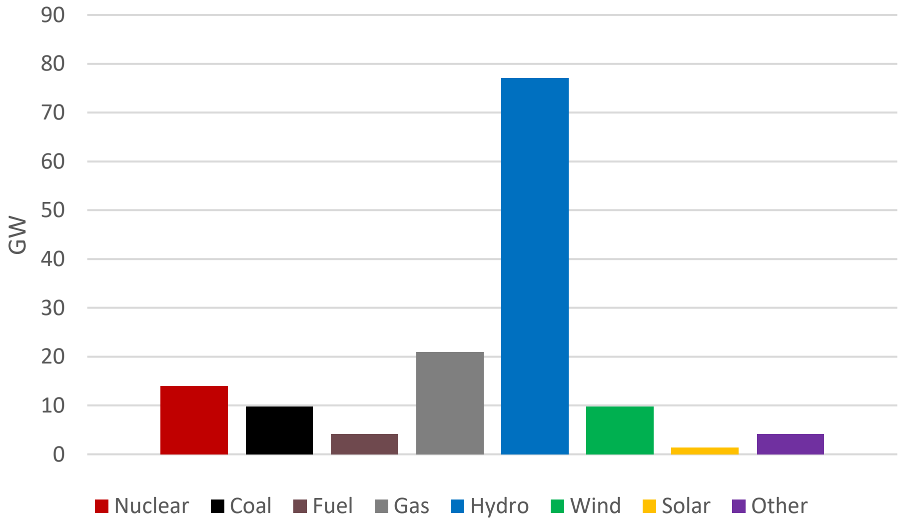

*Figure 10.* Installed capacity in Canada in 2014. Data from (National Energy Board, 2016a)

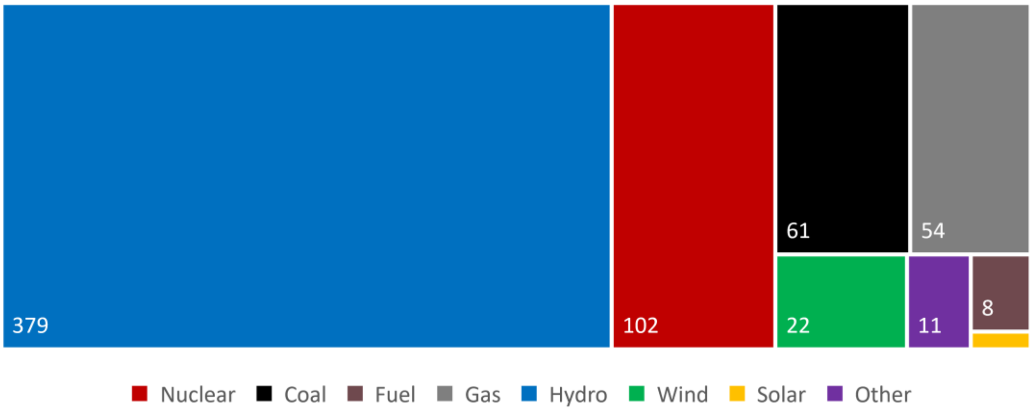

*Figure 11*. Electricity production in Canada in 2014 by energy source in TWh. Data from (Natural Resources Canada, 2016)

This country is the second largest producer of electricity from hydropower in the world (Natural Resources Canada, 2015), an evident fact in its energy mix shown in Figure 11. In 2015 its electricity production accounted 631.7 TWh, mostly from hydropower which represented a 59.3% of the total electricity consumption in the country (Statistics Canada, 2016). There are many reasons for Canada to rely so heavily on hydropower for its energy mix, such as its flexibility, relative affordability, lack of $CO_2$ emissions and cost stability (National Energy Board, 2016a) and is expected to reach 87 GW of installed capacity by 2040, while wind installed capacity will be increased to 19 GW and solar to 4.9 GW (National Energy Board, 2016a). By its part, the second major resource for the Canadian power system, natural gas, has the advantage of having low source prices, lower GHG emissions than other fossil fuel power plants as well as shorter construction times and the capacity will increase to 38 GW of installed capacity in the country (National Energy Board, 2016a).

The Canadian government has the aim of reducing its GHG emissions by 30% compared to year 2005 by 2030 (Office of the Parliamentary Budget Officer, 2016), a major task considering the current low-carbon power system the country possess, making it plausible that the country focuses more in buildings and transport.

With its current power system, Canada is energy secure (Best et al., 2010). This condition is reached thanks to the vast resources the country possesses, its diversified energy mix, robust infrastructure, adequate market regulations supporting private investments and political stability (Langlois-Bertrand, 2010). Nevertheless, there exist areas in which the country may perform better, such as energy intensity and environmental concerns (Best et al., 2010).

The Canadian Energy Strategy has focused its priorities on energy efficiency, delivering energy to the people, climate change, a lower-carbon economy, technology and innovation (International Energy Agency, 2015b). The three themes as well as the areas of cooperation of the strategy are summarized in Table 2:

**Table 2**
*Canada's Energy Security Strategy* (The Council of the Federation - Canada’s Premiers, 2015)

| | |
|---|---|
| Sustainability and conservation | 1. Promote efficiency and conservation<br>2. Transition to a lower carbon economy<br>3. Enhance energy information and awareness |
| Technology and innovation | 4. Accelerate development and deployment of energy research and technologies<br>5. Develop and implement strategies to meet needs<br>6. Facilitate the development of renewable/green/clean energy sources |
| Delivering Energy to people | 7. Develop and enhance a modern, reliable, environmentally safe and efficient energy networks<br>8. Improve the timeliness and certainty of regulatory approval decision-making processes while protecting the environment and public interest<br>9. Promote market diversification<br>10. Pursue formalized participation of provinces and territories in international energy discussions and negotiations |

In the upcoming years, new installations in the country will be mainly from natural gas, wind and hydropower technologies, while solar jointly with other renewable technologies will have a relatively minor participation increase in the future energy mix, through the time that the system will suffer reductions of coal, nuclear and oil-fired power plants (National Energy Board, 2016a).

Due to the federal political system of the country, there does not exist a national common target on renewable energies deployment, but are the provinces and territories themselves those in charge of establishing the targets (International Renewable Energy Agency, 2015).

The widespread use of clean fossil fuels represents a response to anthropogenic climate change (Markusson, Dahl Gjefsen, Stephens, & Tyfield, 2017) and in order to achieve a responsible expansion, the Canadian Government, through the Energy Safety and Security Act (Parliament of Canada, 2015), has established a frame for assessing environment protection measures for oil and gas operations. However, in a 2040 scenario, electricity generation will continue growing at an average rate of one per cent per year and natural gas will be the fastest growing fuel for generation, with an annual average rate of four per cent per year (National Energy Board, 2016a).

Due to policy incentives along with declining costs, non-hydro renewable technologies are expected to have important increases in the Canadian energy mix, in which wind contributes the most to this growth followed by solar, reaching five and three percent of the total installed capacity of the country by 2040 (National Energy Board, 2016a). In total, renewable energies are expected to account for 16 percent of the total installed capacity of the country but their contribution to the electricity production will be only eight percent because of their relatively low capacity factor compared to other technologies (National Energy Board, 2016a).

Because of its geographical location, the Canadian power system has interconnections with its southern neighbor, to which it exported a net amount of 59.5 TWh in 2015 (National Energy Board, 2016b), exports that are highly dependent on weather conditions and electricity markets of the United States (National Energy Board, 2016a). With this respect, the U.S. has issued a Clean Power Plan under the Obama administration and its purpose is to reduce GHG emissions from fossil fuel-fired power plants in the United States, the largest stationary source of emissions in the country (Environmental Protection Agency, 2015a). This plan contemplates the possibility of importing electricity from Canadian sources installed after 2012 in order to meet the emission reduction targets, a possibility that would mean an opportunity for the Canadian power system to be expanded, particularly for hydropower facilities. Besides energy policies of the United States, the Canadian power system behavior in the upcoming years will be highly dependent on technology, particularly the proper integration of renewable energies into the grid as well as sufficient storage. Nevertheless, under the Trump administration, such plan is under revision ("Trump signs executive order rolling back Obama-era energy regs," 2017), a factor adding a high level of uncertainty to the Canadian power system perspectives since the consumption of electricity by the United States will be a key variable for sizing the Canadian power system in the long term (Canadian Electricity Association, 2014).

Summarizing, Canada has enough resources not only to energetically satisfy its inner demand but also to export them. Besides the energy policies of the United States, the Canadian power system behavior in the upcoming years will be highly dependent on technology, particularly the proper integration of RE into the grid as well as sufficient storage. Currently, the country produces three quarters of its electricity from non-GHG-emitting sources and, due to its diversified, competitive secure and reliable energy supplies, Canada makes a contribution to global ES (International Energy Agency, 2015b), an example of success in energy matters for the region and the whole continent.

## 4.3. China

China has taken the planet's leadership in many areas, such as technology or economy, acquiring an indisputable international relevance and extending its influence area worldwide. The country has the objective of doubling its GDP by 2020 compared to 2010 (Yuan et al., 2013), decreasing its GHG emissions from 40 to 45% by the same yeas as of 2010 (Yuan, Hou, & Xu, 2012) and has the commitment of reducing them between 60 and 65% by 2030 (Zhao, Cai, Zhang, & Luo, 2017), objectives that imply important infrastructure and economic changes within the country.

China is already the largest energy producer in the world and it consumed 5,919.8 TWh of electricity in 2016 (National Energy Administration, 2017), 45% more than the United States. The installed capacity of the Asian country has overpassed as well the one of the United States Reaching 1,645.7 MW (National Energy Administration, 2017) and its structure may be observed in Figure 12:

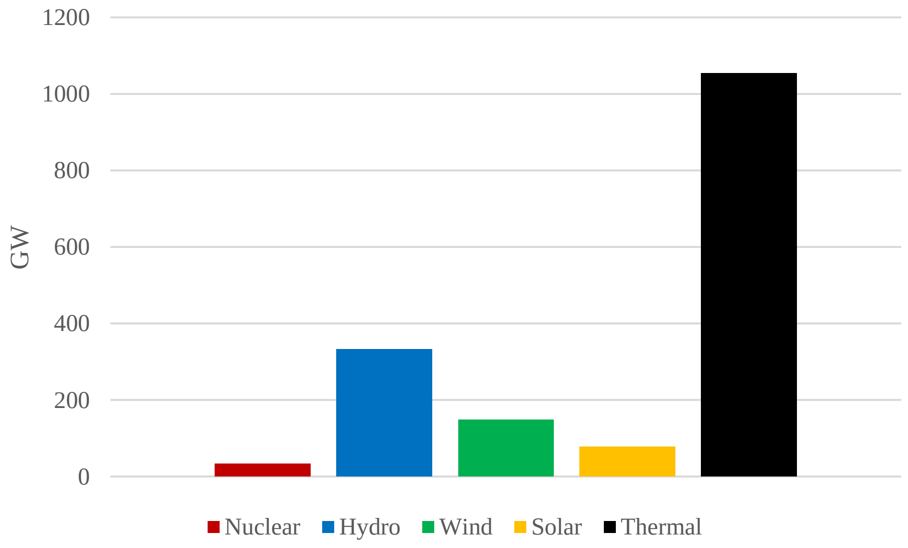

*Figure 12.* Installed power in China in 2016 (National Energy Administration, 2017)

The Chinese power mix is dominated by thermal energy, particularly coal power plants, that have taken the country to occupy the important international industrial position it has today, thanks to the fact that the country possesses the third largest coal reserves in the world and is the largest producer and consumer of this fuel (G. He, Zhang, Xu, & Lu, 2017). Actually, in the short-term and despite national efforts to reduce this tendency or to promote alternative clean fossil fuel technologies, coal will be the most important energy source of the country in the upcoming years (Niu, Song, & Xiao, 2017). The efficiency measures regarding the power sector are mostly focused on the improvement of coal power plants, limiting the national coal consumption to around 4.2 billion tons and the power plants with a capacity over 600 MW will have to reach an efficiency target of 300g of coal equivalent per kWh by 2020 (International Energy Agency, 2014).

Electricity produced in natural gas power plants is also expected to continue acquiring a more important role in the country due to the relative cleanness and efficiency of this technology compared to other fossil fuels which would help to reduce importantly air pollution (Xiao, Niu, & Guo, 2016).

Because of the expected expansion of the Chinese industry and services in the near future, the government’s strategy regarding the country’s energy mix includes an all-of-the-above approach to develop new energy installations. Hydropower plants with ecological conservation and a coastal nuclear power plant belt are projects currently taking place in the country, jointly with exploration of new oil and gas basins (National Development and Reform Commission, 2016). The Chinese strategy towards an energy transition includes, among other measures, the expansion of non-hydro renewable sources, particularly wind power (S. Zhang, Andrews-Speed, & Perera, 2015) through generous and sustained government support (Lam, Branstetter, & Azevedo, 2017). But also photovoltaic technologies will be supported and a strong boost of solar thermal power will take place in the country (National Development and Reform Commission, 2016). These series of policies place China as the largest country in terms of renewable energies investments in the world (Parkes, 2015). The deployment objectives of renewable energies are summarized in Table 3:

**Table 3**
*China renewable energy targets towards 2020* (International Energy Agency, 2016a)

| **Technology** | **Objective** |
|---|---|
| Hydropower | 380 GW |
| Onshore wind | 205 GW |
| Offshore wind | 5 GW |
| Solar PV | 110 GW |
| Solar thermal | 5 GW |
| Bioenergy | 15 GW |
| Geothermal | 530 MW |

The total penetration of clean energies in the Chinese energy mix is intended to be 15% by 2020 and moreover, the country has set a binding target of reducing its carbon intensity by 18% and its energy intensity in 15% by 2020 (U.S.-China Economic and Security Review Commission, 2017), objectives to be reached through energy efficiency, lower-emission technologies deployment and improvement of the energy supply mix, all in order to safeguard the energy security of China (National Development and Reform Commission, 2016).

As part of the national energy strategies, the development of new storage options is covered, particularly pumped storage hydro reaching 40 GW by 2020 and included in the targets of Table 3. The role of the storage facilities will be crucial for the Chinese power system, since this measure is expected to contribute to a more stable and secure operation of the power grid (Kong et al., 2017).

The electrical system in China is relatively complex, since 82% of the national coal deposits are concentrated in the north and southwest and 67% of the hydropower in the country is concentrated in the southwest, while 70% of the national electricity production is consumed in the central and coastal areas of China (Yonghua, 2007). This condition makes imperative for the country the development of a strong electrical infrastructure to deliver the low carbon transition (Yuan, Xu, Hu, et al., 2012) within an integrated planning, covering both physical power plants and efficiency use measures (Yuan, Xu, & Hu, 2012).

China has taken the route of both expanding its economy and reducing its GHG emissions intensity, which will require very important efforts of the country to simultaneously achieve those objectives, including decarbonizing the energy mix (J.-K. He, 2015) jointly with efficiency and technology improvements (Yang, Wang, & Shi, 2017).

### 4.4. Germany

Germany has the most ambitious plan for transforming its energy system and it has called it the *Energiewende.* Considering that it is the largest economy and energy producer and consumer in the continent, such change represents a very significant breakthrough, not only in the continent but in the world. The current national effort for reshaping the fossil-dominated energy system that Germany is carrying out, and that has greatly contributed to its prosperity (Fischer et al., 2016) is a major breakthrough. At the moment, this country has the most ambitious and comprehensive national plan to transform its energy sector (Quitzow et al., 2016), not only in the continent but among all industrial nations (Pescia & Graichen, 2015).

Fossil fuels are still the main source of the German electricity production, mainly coal with 49.8 GW of installed power, constituting 50% of the national production in 2016 (Fraunhofer-Institut für Solare Energiesysteme, 2016a). Despite the fact of the important installations of renewable energy technologies, particularly wind and solar power, which are 49.6 GW and 40.85 GW, respectively, summed only 27% of the total national production of electricity.

The current power system of Germany does still rely importantly on fossil fuels as shown in Figure 13, mainly coal and gas. There can be observed also a very important presence installed capacities of renewable energies, particularly wind and solar.

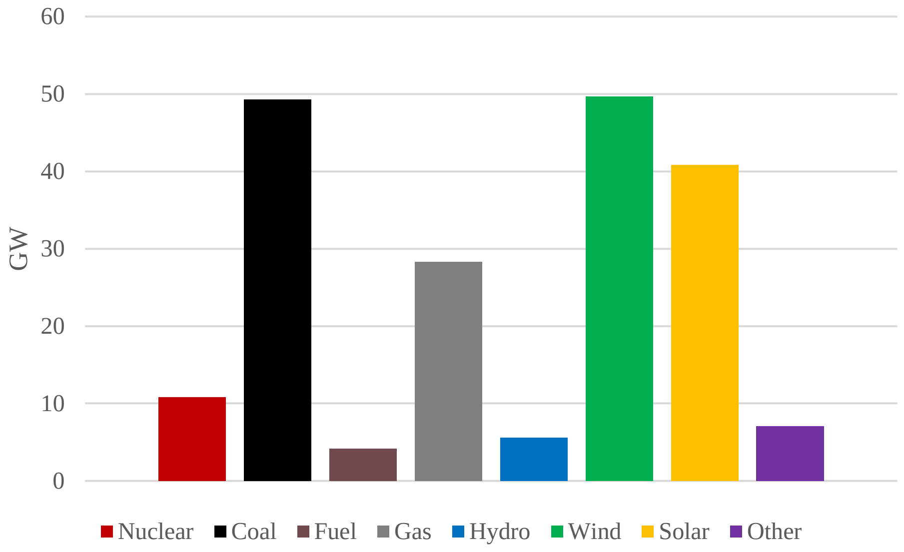

*Figure 13.* German power system in 2016. Data from (Fraunhofer-Institut für Solare Energiesysteme, 2016b)

But independently from the installed power and since renewable energies are, unlikely conventional sources, intermittent, the production of electrical energy in the country had a very different development, being dominated by coal as it can be seen in Figure 14, where it is also noticeable that renewable technologies play an important role in the total generation of electricity in the country, but still far from constituting even the majority of the electricity production. Renewable energies, solar, wind, hydro and biomass, produced almost 186 TWh, constituting 34% of the total electricity production of the country in 2016 (Fraunhofer-Institut für Solare Energiesysteme, 2016c).

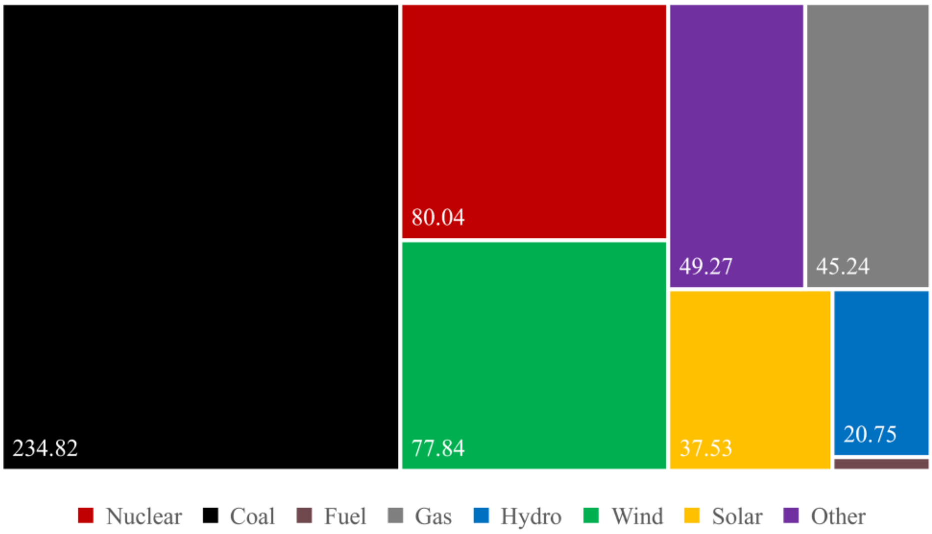

*Figure 14.* Electricity production in Germany 2016 by energy source in TWh. Data from (Fraunhofer-Institut für Solare Energiesysteme, 2016a)

Despite the fact that the country's strategies to transform its energy system cover a wide range of branches, from mobility to efficiency, the electricity sector is the forerunner and the main pillar of those strategies (Lenk, Pyc, & Steinke, 2015), being the focus of government energy policies. The country has the objective of transforming its power sector from a nuclear-and-coal-based model to a new one based on renewable energies in a four-decades time horizon (Agora Energiewende, 2013).

This vision of the future has received the name of the *Energiewende* (Energy transition) and covers a vast aspect of policies concerning the development and integration of renewable energies, a drastic depletion of GHG emissions (Henning & Palzer, 2015), improvement of energy efficiency and the phasing out of nuclear and coal power plant in the short- and mid-term, respectively (Hake, Fischer, Venghaus, & Weckenbrock, 2015), maintaining high competitiveness and security of energy supply (Schmid, Knopf, & Pechan, 2016).

Because of the weight of the country, the *Energiewende* has represented a new paradigm not only in the continent but in the whole world, placing Germany as the pioneer of transforming its energy system to a new one based on renewable energies (Hake et al., 2015) with the firm commitment of the nation to seek energy security and warrantee sustainable development (Quitzow et al., 2016). In order to achieve these purposes, the German energy transition is based on two pillars: renewable energies and efficiency (Bundesministerium für Bildung und Forschung, 2016). Through efficiency, both in the producer and consumer sides, it is expected that energy consumption in the country decreases constantly in the incoming years, while the economic growth will continue to expand. The two ultimate goals on each field are to reach at least 80% share of renewable energies in the gross electricity consumption by 2050 and to reduce 25% the electrical energy consumption compared to 2008 levels by year 2050 (Agora Energiewende, 2016), while the primary energy consumption shall be reduced 50% (Bundesministerium für Wirtschaft und Energie, 2016a). Reaching these objectives would lead the country to improve importantly its energy intensity at the time that electricity becomes the most important energy source in the country (Bundesministerium für Wirtschaft und Energie, 2016d).

One crucial measure promoted by the German government was the issue of the Renewable Energies Act (EEG), which was intended to allow the incipient of wind and solar technologies to enter in the energy market supported by fixed tariffs and a purchase guarantee (Bundesministerium für Wirtschaft und Energie, 2015). This policy had such an effectiveness, that, today, renewable energies constitute the most important source of electrical energy in the country. This law has had two revisions, one in 2014 and a second one in 2017. After the first revision it was decided that renewable energies should compete with conventional sources in a protected environment, while the second amendment, established that, since renewable energies have achieved a mature stage, they are ready to compete in equal conditions with conventional energies (Bundesministerium für Wirtschaft und Energie, 2017b).

The EEG 2017 has introduced some changes in the *Energiewende* targets. Those objectives regarding the consumption of electrical energy are summarized in Table 4:

**Table 4**
*Electrical energy objectives of the EEG* (Bundesministerium für Wirtschaft und Energie, 2016a)

| | | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Share of gross electricity consumption | Original target | >35% | >50% | >65% | >80% |
| | EEG 2017 target | | 2025:<br>40-45% | 2035:<br>55-60% | |

The EEG establishes as well deployment corridors to maintain the growth of renewable energies, focusing on wind and solar power plants, technologies that have led the energy transition and will continue doing so due to the fact that currently no other renewable technology is able to generate electricity in the quantity at the low-cost these technologies do (Agora Energiewende, 2013). Solar and wind power plants have a very strong presence all over the national geography and they will be expanded as it can be seen in Table 5:

**Table 5**
*Deployment corridors for installed capacity of solar and wind power plants under the EEG 2017*
(Bundesministerium für Wirtschaft und Energie, 2015)

| | | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Share of gross electricity consumption | Original target | >35% | >50% | >65% | >80% |
| | EEG 2017 target | | 2025:<br>40-45% | 2035:<br>55-60% | |

Such a boost of renewable energies in the power system require a deep restructuration of it. Because of the intermittent nature of renewable sources, a more flexible model of the electrical system is crucial (Pescia & Graichen, 2015). Currently, the flexibility needed for the integration of renewables is given by the existing conventional power sources but they will, as a part of the country's energy strategy, be drastically reduced or totally disappear, so relying on them is not possible. Two options remain, the one is to create energy storage facilities, or the second one is to improve an interconnected grid, not only within Germany but also with its neighbors, since they an interconnected grid may function as an indirect storage facility (Ess, Haefke, Hobohm, Peter, & Wünsch, 2012).

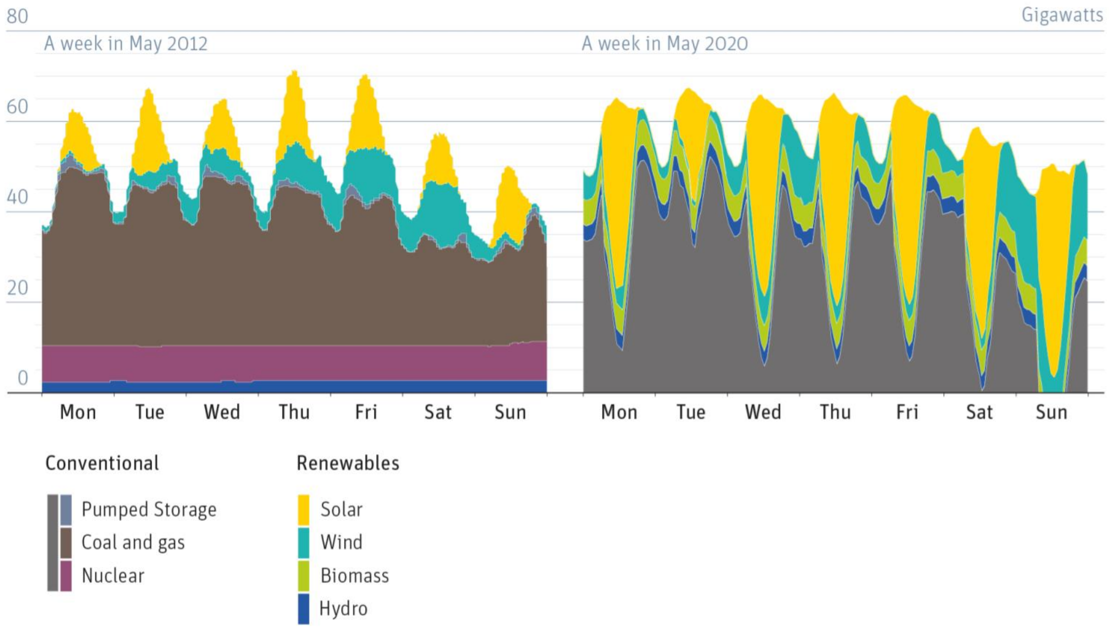

*Figure 15*. Estimated power demand over a week in 2012 and 2020, Germany (Morris & Pehnt, 2016) from (Quaschning, 2010)

A future prediction of the behavior of the energy demand in the power system in Germany is shown in Figure 15. Unlike in the present, a future system would disregard a baseload thanks to the penetration of renewable technologies, being able to produce energy totally from these sources for certain hours forcing conventional power plants feeding the residual load to turn off and after a couple of hours ramp up again. Thus, in a future scenario there will be no need of a baseload (Morris & Jungjohann, 2016) and instead, flexible power plants, energy storage and interconnections will be needed. This paradigm take the power system to have stand-by power plants which will be, unless government subsided, unable to operate economically (Hake et al., 2015) so a new regulatory frame must be issued in order to have all the necessary back-up power needed in case that renewable energies stop being available at a certain moment since flexibility will be the basis of the future electricity market (Bundesministerium für Wirtschaft und Energie, 2017a).

At a European level, there exist the plan to create an interconnected electrical market, the Energy Union (European Commission, 2016). This continental strategy is composed by five dimensions which are energy security, an integrated market, energy efficiency improvement, decarbonization and innovation on energy matters with the objective of transiting to a low-carbon, secure and competitive economy (European Commission, 2017).

Energy efficiency is crucial for the success of the *Energiewende* since the cleaner and cheapest energy is the one that never has to be produced (Bundesministerium für Wirtschaft und Energie, 2017a). In order to obtain meaningful results from efficiency policies, reductions on energy use have to be implemented on every branch of the economy, for instance buildings, transport, industry, households, etc. Companies that invest on efficiency technologies and optimization of processes may decrease their spending on energy, depending on the industry, from one to two thirds (Bundesministerium für Wirtschaft und Energie, 2017a) and (Agricola et al., 2012).

Reducing the use of energy by improving efficiency boost the economy generating more added value, creating more jobs and promoting innovation (Bundesministerium für

Wirtschaft und Energie, 2014). The current goals regarding energy efficiency on what concerns to primary energy consumption, energy productivity and electricity consumption in Germany within a 2050-time horizon are summarized in Table 6:

**Table 6**
*Energy efficiency objectives of Germany* (Bundesministerium für Wirtschaft und Energie, 2016a)

| | **2020** | **2050** |
|---|---|---|
| Primary energy consumption (compared with 2008) | -20% | -50% |
| Final energy productivity (2008-2050) | 2.1%/year | |
| Gross electricity consumption (compared with 2008) | -10% | -25% |

Nowadays, Germany is one of the countries with the highest energy productivity and the lowest energy intensity in the European continent (Bundesministerium für Wirtschaft und Energie, 2016b). The German government is aiming to reduce the energy intensity of the country's economy drastically in the upcoming years and a big part of that improvement is expected to be reached due to energy efficiency enhancement.

At a national level and with such high goals like those Germany is setting itself, energy efficiency is required not only from energy producers, but also from energy consumers. The producers are able to improve energy efficiency, which in their case is related to the energy required by power and heat generators, by replacing them by more efficient facilities or, in statistical terms, energy consumption declines if they are replaced by renewable energies (Bundesministerium für Wirtschaft und Energie, 2014). On the consumers' part, the improvement on efficiency is related to that of the devices they use as well as their sufficiency, which is basically less consumption of energy for providing the same services.

But energy consumption, according to the new model with an important presence of renewable energies, has new challenges referring to efficiency and a particular one is the time energy is consumed. The timing of energy consumption is relative to the match of the temporal pattern of demand to that one of the supply of electricity by renewable sources (Schmid et al., 2016). This is particularly applicable in an electrical system with an important penetration of solar power, in which the consumption of electricity should be promoted in such a way that it matches the time when the largest amount of renewable power is available, in order to avoid the use of conventional sources or feeding in out-of-the-borders to fulfill the residual load needs.

The goals of the Federal Government of Germany regarding energy efficiency are thus summarized in three major guidelines which are the distinctly and sustainable reduction of energy demand in all sectors ("Efficiency first" principle), the direct use of renewable energies, like solar thermal and geothermal technologies applied to fulfill heat needs, and the use of renewable energies for the remaining required energy consumption (Bundesministerium für Wirtschaft und Energie, 2016c).

In the upcoming years, in both medium and long term, it is expected that the energy consumption of Germany in absolute terms will drop further (Bundesministerium für Wirtschaft und Energie, 2016c) while the economic growth of the country will continue to growth helped, partially, precisely by the deployment of renewable energies (Blazejczak, Braun, Edler, & Schill, 2014). Electrical energy will become the most important source of energy in the German energy system (Bundesministerium für Wirtschaft und Energie, 2016d) and most of will proceed from renewable energy sources, particularly sun and wind.

The German power system is probably the one with the most important reforms currently being carried on in the world in which integration of renewables, efficiency and flexibility of the system are the main lines of the country's strategy to procure energy security.

## 4.5. France

France is the country with the largest participation of nuclear power in producing electricity (Nuclear Energy Institute, 2016) and has the second largest amount of installed nuclear power in the world (OECD, 2015) but, despite the fact that the government has lately made efforts to diminish its dependency on nuclear power reducing its use 7.9% for 2016 respecting 2015, the country does still rely strongly on this source to fulfill its energy needs.

The installed capacity of power system in France is largely dominated by nuclear power as shown in Figure 16. Renewable energies are also an important source of energy being hydro power the most important in the country. 63.13 GW is the installed capacity of nuclear power, followed by hydropower with 25.48 GW, the second most important source of electrical energy in the country in both, installed capacity and electricity produced, which has increased its presence in the French energy mix by 12% in 2016 (Réseau de transport d'électricité, 2016b).

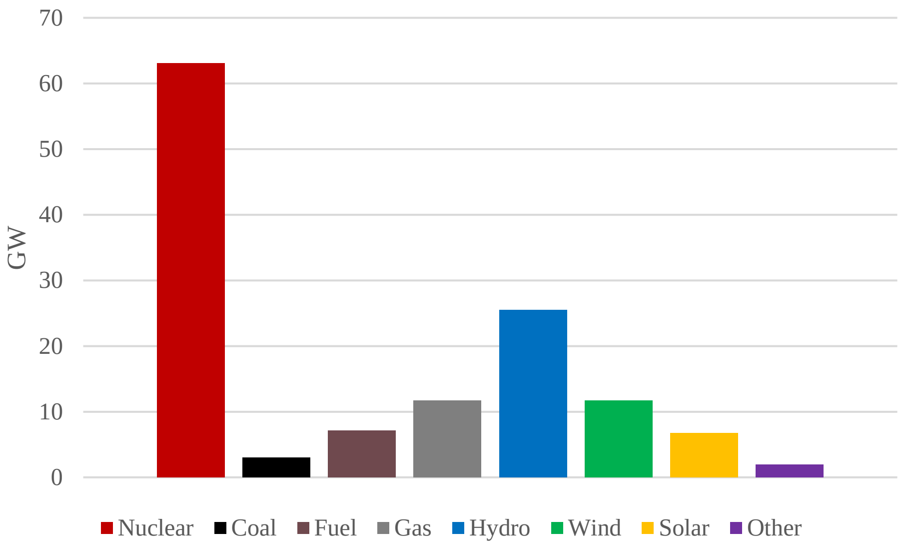

*Figure 16*. Power system of France in 2016. Data from (Réseau de transport d'électricité, 2016b)

Nuclear power and hydropower supplied more than 3/4 parts of the electricity consumed by France during year 2016 (Réseau de transport d'électricité, 2016b). In Figure 17 it is evident the strong presence of nuclear and hydro technologies in the France's electricity production.

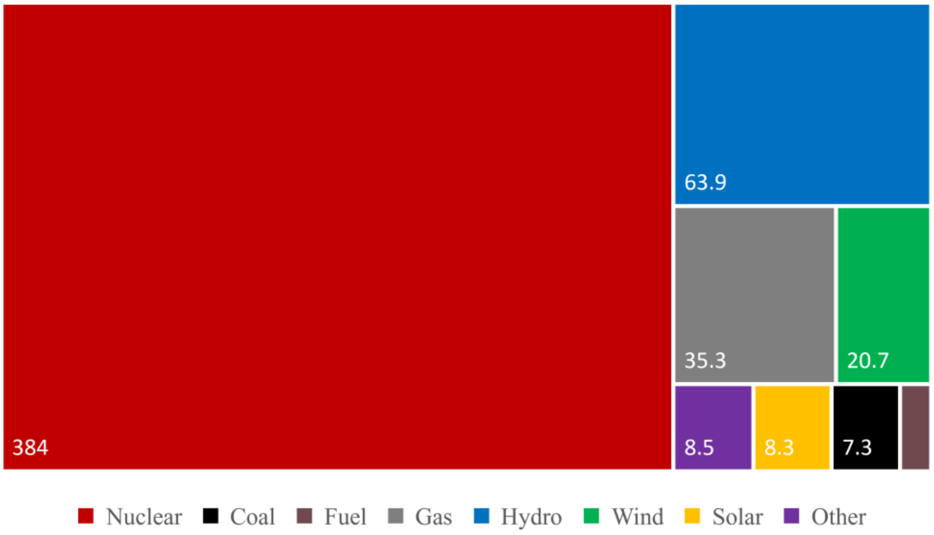

*Figure 17*. Electricity production in France in TWh. Data from (Réseau de transport d'électricité, 2016b)

The National Assembly and the Senate of France enacted the *law relative to the energy transition for the green growth (LTECV)* in 2015. This law has a long-term horizon purpose with objectives towards years 2030 and 2050 and its aim, jointly with its accompanying action plan, is to promote the mitigation of climate change and the preservation of the environment as well as reinforce the energy independence of the nation offering its enterprises and citizens energy access at a competitive cost (Ministère de l'Environnement de l'Énergie et de la Mer, 2016), so the ultimate goal is to boost the France's Energy Security.

The main objectives of the LTECV and summarized in Table 7, include the reduction of greenhouse gases by 40% for the period between 1990 and 2030, reducing the GHG emissions to one quarter for the period between 1990 and 2050; the reduction of the final consumption of energy by 50% for 2050 taking year 2012 as a reference with an intermediate goal of a 20% reduction by 2030; the reduction on consumption of fossil fuels by 30% for year 2030 as compared to 2012; the promotion of renewable energies by establishing a minimum consumption of 23% for 2020 and 32% for 2030 of the total final energy consumption and 40% of the total electricity production by the same year; the reduction of nuclear energy participation, one of the milestones in the current French power system, to a 50% of the national electricity production by 2025. The law also covers mitigation of energy poverty and promotes the creation of new jobs in the energy field, focusing on economic growth and sustainable development.

**Table 7**

*Objectives of the French Energy Transition Law for the Green Growth* (L'Assemblée nationale et le Sénat, 2015)

| | **Objective** | **Year** |
|---|---|---|
| GHG emissions reduction | -40% | 2030 [1] |
| | -75% | 2050 [1] |
| Final energy consumption | -20% | 2030 [2] |
| | -50% | 2050 [2] |
| Renewable energies share in final energy consumption | 23% | 2020 |
| | 32% | 2030 |
| Renewable energies share in electricity production | 40% | 2030 |
| Nuclear share of electricity production | 50% | 2025 |

[1] 1990 base

[2] 2012 base

In accordance and after the implementation of these measures, the electricity sector in France has diminished the use of coal and oil power plants to produce electricity while thanks to the installation of a new gas facility, the country has expanded its gas capacity as well as the electricity produced by these sources. All the renewable energy sources, hydro, wind and solar, have suffer a boost in installed capacity and in electricity production. The total consumption of electrical energy in the country decreased 2.8% in 2016 respecting to the previous year.

Unlike the other big economy of the European Union, like Germany, the French system will still rely in the future, even if the targeted 50% reduction objective is accomplished, on nuclear energy. This means that the flexibility of the system will be compromised because of the nature of the nuclear technology, that cannot be turned off if for instance there is a surplus on the production of renewable energies. Nowadays, the power system in France is able to adapt its production thanks mostly to the hydro and gas power plants, whose power is available practically instantaneously in case of need. In Figure 18 is shown the day of major electricity consumption in France in the winter 2016-2017:

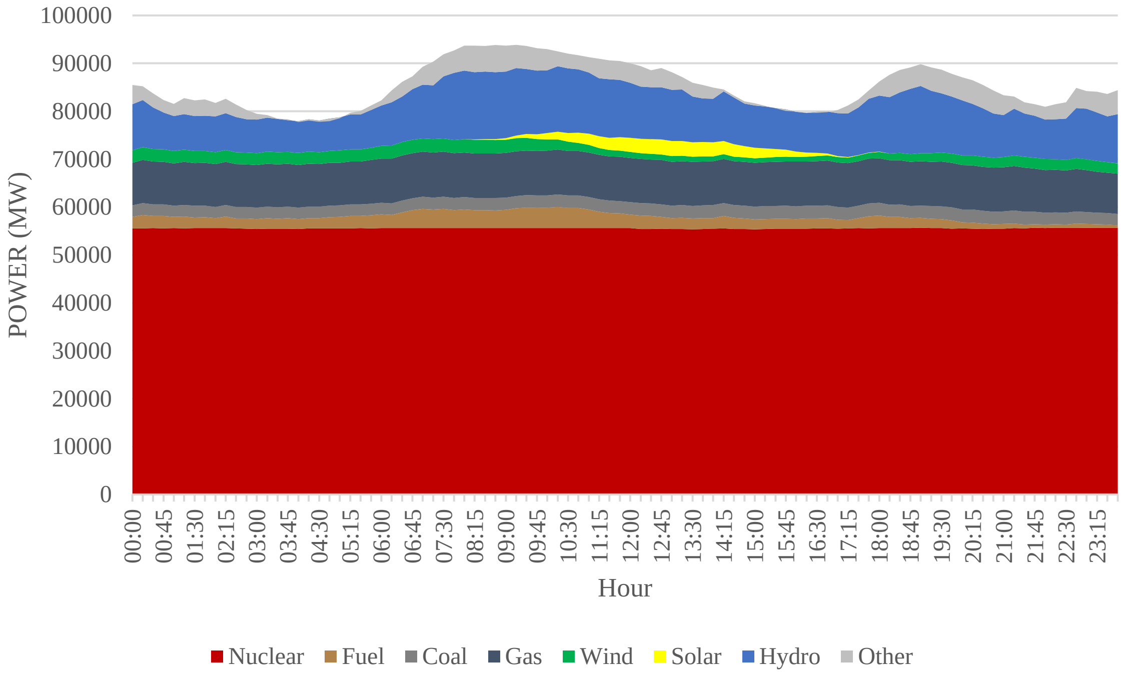

*Figure 18.* Detail of the electricity production in France by sector on January 20th, 2017. Own elaboration based on data from (Réseau de transport d'électricité, 2017)

France is, after Germany, the country that produced the most electrical energy in Europe in 2016 with a generation of 531.3 TWh (Réseau de transport d'électricité, 2016a), that represents a reduction of 2.8% compared to the previous year. This shows a clear result of the effectiveness of the applied energy policies in France, a figure that will be reflected in the country's energy intensity afterwards as a measure of its energy efficiency.

Regarding electrical energy exchanges in Europe in 2016, France exported a net amount of 39.1 TWh (Réseau de transport d'électricité, 2016b). France is a reliable partner for its neighbor countries mainly because of the important amount of nuclear power plants that the country possesses, making that energy available for the surrounding systems in case of need. But, since there exists the government aim of reducing the electricity production coming from nuclear power plants to a 50% of that of 2012, it is still uncertain how the interconnected European system will change in order to be adapted to this new paradigm, with one of the largest electricity producers in the continent cutting of partially but importantly the source of energy all its neighbors rely on. This means for the neighboring countries of France that they have to adapt as fast as possible to the new drastically French nuclear-power-reduced scenario, in a frame of a European coordinated energy policy (Malischek & Trüby, 2016).

Due to the very important presence of nuclear power in the energy mix, its depletion will, as it is intended, jointly with the boost of renewable energies, change drastically the form that France produces energy today. Nevertheless, changing the energy matrix of a country so dependent on one energy source requires great efforts in order to transit to a more environmentally-friendly scenario. The case of France shows that, regardless of the fact of not renouncing to its nuclear energy, the country commits itself to promote other forms of energy and to reduce its energy use. Some authors like (Morris & Pehnt, 2016; Quaschning, 2010) support the idea that nuclear energy is incompatible with a high penetration of renewable energies, so proving them wrong is a task that the French policy makers must contemplate for the future of their power system.

### 4.6. Mexico

The Mexican energy sector is one of the most important industries in the country in terms of its contribution to the national economy, as well as productive and social development of the country (Alpizar, Castro, Rodríguez, & Monroy, 2016). In 2013 Mexico faced a very significant change in its recent history: The Energy Reform. These series of amendments to the country's Constitution have been a breakthrough for the energy industry and all the related value chain, added to the fact that the energy sector has been considered a symbol of national sovereignty.

The drivers of the Mexican energy reform are the government's seek to finance the exploitation of hydrocarbons' reserves, to boost oil and gas exploration, to expand transmission and distribution networks and to improve oil, gas and power infrastructure (Alpizar et al., 2016).

The Constitutional Reform and the legal framework derived from it involve a structural change in the power sector structure (Alpizar et al., 2016). The Reform stipulates that the Nation will keep the planning and controlling of the national electrical system, as well as the transmission and distribution of electrical energy. Nevertheless, it allows the State to celebrate contracts with the private industry in order to finance, maintain, operate and expand the necessary infrastructure to offer the public services of transmission and distribution of electrical energy. Moreover, the private investment is now allowed to participate, together with the Electrical Federal Commission, in the generation of electrical energy, all under productivity and sustainability criteria (Gobierno de la República, 2014b).

All these series of amendments to the Constitution lead to the conclusion that a country that has plenty of resources due to its extension and geographical situation jointly with good physical conditions for their exploitation (Merchand, 2015) will now be able to use them to produce energy through private entities after decades of being controlled by State-owned monopolies.

This turning point brings a whole new horizon of possibilities for the country, being imperative to develop new schemes that will determine the future of the nation's energy security.

The purpose of this new paradigm in the energy sector of Mexico is to improve the energy access of the Mexicans, whether they are industries or particulars with the purpose of guarantee energy security in the country and, together with other government measures, boost the economic development of Mexico (Gobierno de la República, 2014a).

Towards 2040 and due to the exporting nature of its economy, Mexico is expected to be one of the fastest GDP expanding countries among the OECD members as well as one of the highest commercial energy consumption (U.S. Energy Information Administration, 2018c). Mexico is in the top five of the Americas' countries by both oil and natural gas reserves (Central Intelligence Agency, 2016a), (Central Intelligence Agency, 2016b), besides having a high potential of renewable energies, including solar, wind, biomass, hydropower and geothermal (Alemán-Nava et al., 2014).

But as it shown in Figure 19, the structure of the power system relies very heavily on fossil fuels in order to produce electricity, particularly natural gas in combined cycle power plants, that in year 2016 produced most of the half of the electricity in Mexico as it can be observed in Figure 20. Mexico, with a large production of natural gas, has had the one of the highest capacity factors worldwide on its gas-fired power plants independently of international prices of the source, against the tendency of most regions in the globe (U.S. Energy Information Administration, 2018c).

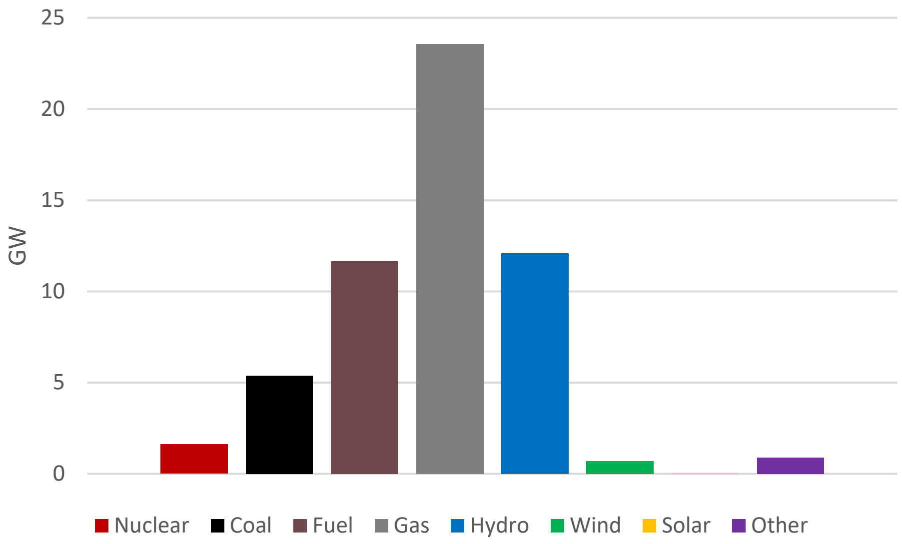

*Figure 19.* Installed capacity of the Mexican power system by technology. Data from (Comisión Federal de Electricidad, 2017a)

From the electricity produced in the country, the public electrical power plants accounted 55.4% of the total national amount, while independent producers accounted 29.2% and auto generation was 15.4% (Secretaría de Energía, 2016a).

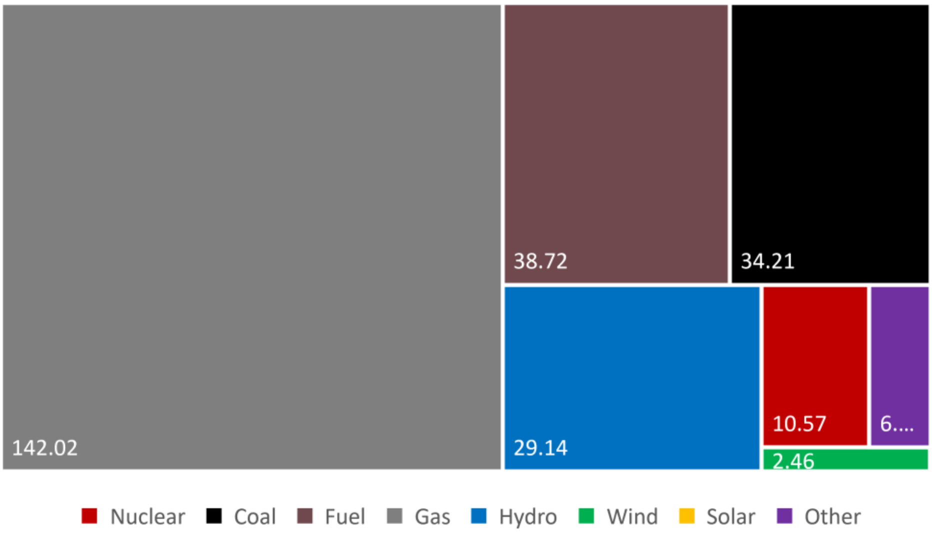

*Figure 20.* Electricity production in Mexico in 2016 by technology in TWh. Data from (Comisión Federal de Electricidad, 2017b)

The predominance of natural gas for producing electricity is evident but if to this number is added the fuel and coal electricity production, the fossil fuel participation in the country’s power sector is overwhelming accounting 81.68% of the electricity production in 2016.

The electric power generation sector is the main one consuming natural gas and it is expected to account for 75% of consumption growth until 2027, a 57% of the national demand (Feijoo, Huppmann, Sakiyama, & Siddiqui, 2016). It is also expected that the energy reform through the introduction of competition by the private sector facilitates the use of more advanced technologies for fossil fuels extraction and that new deposits should be detected faster (Alpizar et al., 2016).

An important synergy between the electricity sector reform and the one regarding the natural gas sector relies on the fact that if more regions within the country are able to access natural gas reserves, a new competitive power generation market provides an incentive to build gas-fired power plants and to inject this power into the market (Alpizar et al., 2016).

The average electricity prices in Mexico are 25% more expensive than in the United States, even being subsidized, a subside without they would be 73% even more expensive (Gobierno de la República, 2014a).

Due to the energy reform, which is expected to decrease electricity prices by 13% through substituting fuel oil power plants with natural gas power plants for electricity generation, would imply a 1.4-3.6% increase in manufacturing output and a 0.2-0.6% increase of the gross domestic product (Alvarez & Valencia, 2016). Additionally, natural gas use is expected to improve air quality by replacing generation from fuel (Alpizar et al., 2016).

In a 2029 scenario, the natural gas production in Mexico is expected to grow but the demand would do it at a faster rate, a difference compensated by imports, mostly from its northern neighbor (The National Energy Board Canada, Secretaría de Energía de México, & U.S. Energy Information Administration, 2015). An expansion of the Mexican gas market would reduce its dependency on pipelines imports from the United States and it is the energy reform jointly with the technological advances within the shale gas revolution, factors that will determine if the current north-to-south natural gas flow in North America will prevail or if Mexico decides to revert this pattern through self-sufficiency (Feijoo et al., 2016).

Mexico is a world climate change mitigation leading country with a Climate Change Law that enabled to stablish an institutional framework to set goals and to foster plans, programs and mechanisms regarding this issue as the country's adaptation to climate change (Grande-Acosta & Islas-Samperio, 2017). In 2030 the installed capacity of the country is expected to be 61% larger than the one installed today, being dominated by combined cycle power plants. By its part, in the electricity generated in the country there will be a participation of 59% of conventional sources and 41% of clean energies (Secretaría de Energía, 2016b).

The objectives of the country are to minimize the national GHG emission 30% by 2020 and 50% by 2050 compared to year 2000, while the energy transition law (Congreso General de los Estados Unidos Mexicanos, 2015) fixes a minimal participation of clean energies in the total electricity generation of 25% by 2018, 30% by 2021 and 35% by 2024.

About renewable energies, the market rules derived from the energy reform seek to promote energy efficiency and renewable technologies through new market incentives, auctions and a clean energy roadmap (Alpizar et al., 2016). The mechanism of the Reform to boost renewable energies is to issue "clean energy certificates" which will be bought by qualified users and suppliers and will be, in their turn, given to renewable energy generators. This scheme should guarantee the demand for the new renewable energy projects and assures income to finance their investments (Gobierno de la República, 2014a).

Mexico is one of the most attractive countries in the world to invest in photovoltaic solar power projects due to its high potential thanks to its location in the "solar belt" with a radiation exceeding 5 kWh per square meter per day and that in the case of Mexico it is concentrated in the north-west part of the country (Alemán-Nava et al., 2014). Nevertheless, the planning of the government does not include an important scheme to explode this potential, since the participation of solar technologies, either photovoltaic or thermal, are expected to contribute only in a 6% of the total electricity production of the country in a 2030 horizon (Secretaría de Energía, 2016b).

There exists also a potential need for deeper integration and, since the energy reform makes a clear reference to move Mexico's system toward neighboring systems to the North (Ibarra-Yunez, 2015), supported by the fact that the neighboring US electricity systems are mature and grids are rather deep and widespread (Ibarra-Yunez, 2015). Between Mexico and the United States exist 11 international electrical interconnections, while Mexico has 2 with Central America, one connecting the country with Belize and another one with Guatemala (Secretaría de Energía, 2016b).

Energy consumption in Mexico is geographically heterogeneous, being the northern part of the country the most energy-consuming region, while the south is the one that consumes the less energy (Rosas-Flores, 2017). It is also the north of Mexico the region with the most significant imports of US-American natural gas and, since the California peninsula is aisled from the rest of the country, it also imports important amounts of electricity from the United States. Moreover, the large energy consumption zones are not connected to the centers of high renewable energy potential (Gobierno de la República, 2014a). Thus, it is imperative for the Mexican government to enhance national interconnections in the country, so an energy union could be achieved inside the borders, prioritizing inner demand coverage with local resources before importing energy.

The Energy Reform in Mexico represents a watershed in for the country in many ways, since a critical economy sector for the country, has been modified deeply. The opening of private investors to participate in energy resources exploitation should relief the Mexican economy and create new opportunities for both, the companies and the people. Competition promotes improved performance in terms of greater electricity generation, generating capacity and improved labor productivity and capital utilization (Y.-F. Zhang, Parker, & Kirkpatrick, 2008), and all these, if managed appropriate, should improve the energy security of Mexico.

## 4.7. United States

The United States, an "energy hungry" country (Kaivo-oja, Vehmas, & Luukkanen, 2016) and the second largest energy producer and consumer in the world (U.S. Energy Information Administration, 2017d) has the firm objective of becoming an energy independent land and, by doing so, jointly with an increase on the country's energy productivity (U.S. Department of Energy, 2015a), to assure its energy security (Congress of the United States of America, 2007) and (Congress of the United States of America, 2012).

The National Security Strategy (The White House, 2015a) of the United States addresses the need of promoting diversification of energy fuels, sources and routes, besides encouraging indigenous sources of energy supply. Moreover, the strategy also contemplates the fact that, in order to achieve those goals, energy security and independence within the Americas are priority issues for the nation. An energy independence of the United States would be reached by diminishing energy use, promoting inland fuels and boosting alternative energy sources to fossil fuels (Greene, 2009).

The new paradigm of an energy independent United States due to increased access to oil and gas reserves thanks to new technologies (Worland, 2017) will change completely the energy world outlook. The energy consumption in the United States is projected to remain relatively flat with a slight increase of five percent for the period between 2016 and 2040 while the fuel mix is expected to change significantly (U.S. Energy Information Administration, 2017a). At the same time, energy intensity in the country is expected to continue decreasing as it has been doing since the last for decays in a 2040 horizon (Institute for 21st Century Energy, 2016).

Regarding electricity, the tendency in the country is a further growth in the upcoming years, yet at a slower rate than before due to the use of more efficient equipment follow new efficiency standards and a less-energy-intense economy trend (U.S. Energy Information Administration, 2017a).

The Environmental Protection Agency (Environmental Protection Agency, 2015a) projects that coal and natural gas will remain the two most important sources of electricity generation in the United States in the mid-term, with a participation of 27% and 33% on power generation, respectively, and the expansion of natural gas in the power system will be a dominant tendency independently of the expansion of renewable energies (Tsai & Gülen, 2017). Figure 21 shows the current structure of the power mix of the United States, in which is yet noticeable the important presence of fossil fuels, mainly natural gas but also a very strong presence of coal-fired power plants. This energy matrix would affect energy security of the country, shrinking the diversity of energy sources to produce electricity in the country (Institute for 21st Century Energy, 2016).

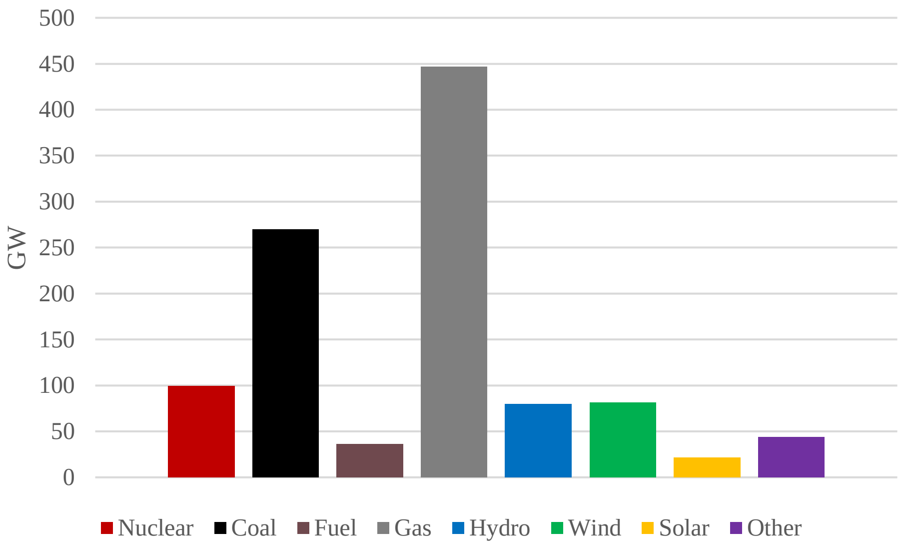

*Figure 21*. Installed power in the United States by the end of 2016. Data from (U.S. Energy Information Administration, 2017b)

The use of natural gas, the least carbon-intense fossil fuel (U.S. Energy Information Administration, 2018c) led by demand from industrial and power sectors, is expected to increase importantly in the upcoming years, a tendency followed also by renewable energies, which will suffer the largest percentage expansion due to a capital costs fall and government policies promoting their use and integration to the power grid (U.S. Energy Information Administration, 2017a). Meanwhile, petroleum is expected to remain stable in its consumption while coal is the fuel that will see the largest decrease in its consumption partially due to the implementation of the Clean Power Plan, which would take this technology to one-third of the current generation (U.S. Energy Information Administration, 2018c), giving way to natural gas and renewable technologies (U.S. Energy Information Administration, 2017a).

About renewable technologies, wind and solar will take the lead instead of hydro, being the predominant sources of this kind in the power energy mix of the country following the Clean Power Plan and tax credits supporting the use of renewable technologies (U.S. Energy Information Administration, 2017a). It is precisely thanks to the this plan that renewable energy technologies generation in the United States would increase by 2030 roughly 396 billion kWh (58%) compared to the reference case (U.S. Energy Information Administration, 2018c). Wind power is expected to increase importantly in mid- and long-term scenarios, in such a way that it would supply 10% of end-use electricity demand by 2020, 20% by 2030 and 35% by 2050, which would require 113, 224 and 404 GW of installed power in the respective years (U.S. Department of Energy, 2015b).

The United States relies hardly on fossil fuels to fulfill its energy needs at it can be seen in Figure 22. Here the presence of natural gas and coal dominate abruptly in the generation mix of the country, a tendency that, depending on following or not the current federal strategies, would remain in the upcoming years or may be reverted in favor of renewable generation.

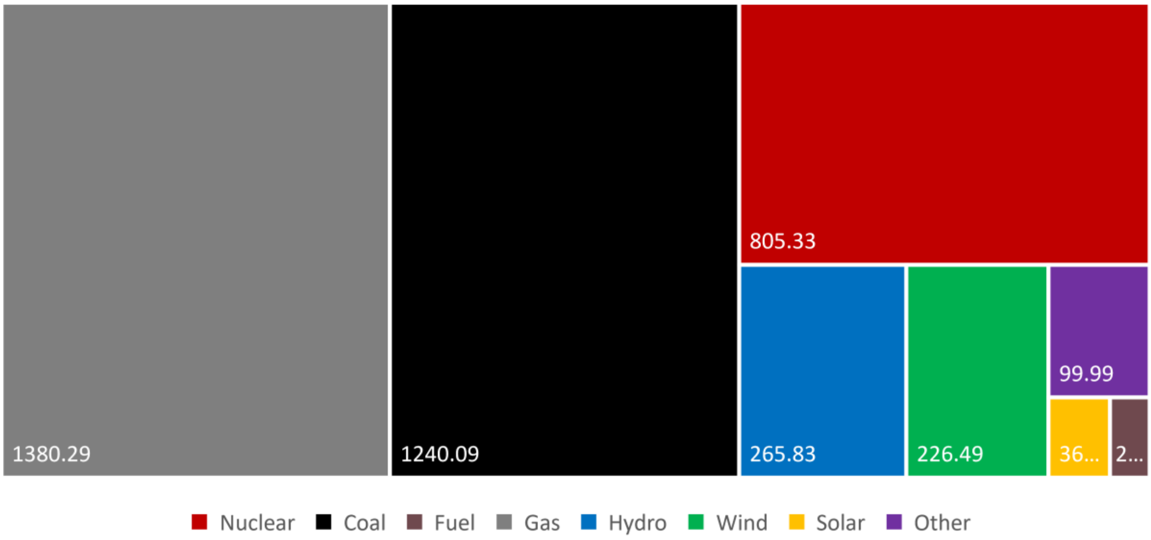

*Figure 22.* Electricity production in the United States in 2016 by energy source in TWh. Data from (U.S. Energy Information Administration, 2017c)

The country reaches 447 GW of natural gas power plants, the largest fuel present in the power mix, which produced 34% of the 4,078 TWh generated in the country in

2016, followed by coal power plants, which sum 270 GW of installed power and contributed with 30% of the electricity production (U.S. Energy Information Administration, 2017b).

There are several strategies followed by the United States' Government to make an energy transition to a cleaner and lower polluter US-American energy system, which includes an integral development, deployment and efficient use of all-of-the-above forms of energy resources while strengthening the country's energy infrastructure (U.S. Department of Energy, 2014).

The U.S. Congress released the Energy Policy Modernization Act (Congress of the United States of America, 2015) which focused on energy security, promotes conservation, improves accountability, increases the country's energy supply, improves energy infrastructure, and enhances energy efficiency (Gattie, 2017).

Federal government had the aim of reducing its GHG emissions from 26 to 28% by 2025 compared to 2005 levels (The White House, 2015b). By its part, the participation of renewable energies in the energy mix is a matter that as a Federation, corresponds to each one of the states in the union. Nowadays, 29 states, Washington D.C. and three territories have adopted renewable energies standards, while specific goals have been issued and adopted by eight states and one territory (Durkay, 2016).

Canada, the United States and Mexico have agreed to achieve a 50% share of clean power generation by 2025 at a North American level, objective to be achieved through the development and deployment of clean energy technologies, energy innovation and efficiency measures (The White House, 2016). Due to the amount of energy, this initiative would require the largest effort coming from the United States, since it is the most energy consuming country in the region.

Recently, the United States government has suffered a dramatic shift regarding energy regulations policies, since the Clean Power Plan (CPP) is harnessed by the current issued policies from the White House (“Trump signs executive order rolling back Obama-era energy regs,” 2017). The CCP intended to reduce carbon pollution from coal power plants, supposedly 32 percent below 2005 levels by 2030 in the power sector (Environmental Protection Agency, 2015d) and would spur a reduction of 7 percent on electricity demand by the same year (Environmental Protection Agency, 2015b) while maintaining energy reliability and affordability in a federal and state level cooperation frame (Environmental Protection Agency, 2015c). Nevertheless, this plan would cost $39 billion a year and would increase energy prices for most of the states in the union in the upcoming years (The White House, 2017b) and (Harrison et al., 2014).

President Trump released a Presidential Executive order on Promoting Energy Independence and Economic Growth. The objective of this executive order is to promote national energy resources avoiding regulations that encumber energy production, constrain economic growth and prevent job creation, all in order to ensure United States’ geopolitical security (Donald J. Trump, 2017). The order covers the promotion of every single energy source of the country, even if it is a fossil one or not, in order to be exploded and contribute to the country’s energy security.

Shale gas is one of the pillars of energy policy in the United States in this century, since the development of the necessary technologies and regulations to its use have modeled the Washington’s national and foreign energy policies (Kobek, Ugarte, & Aguilar, 2015). This tendency has led to the so called “shale gas revolution”, a revolution that will be embraced by the current White House administration (The White House, 2017a) and which consists of an outstanding development of in production technology and a considerable increase in production volume of this source of energy (Bilgili, Koçak, Bulut, & Nedim Sualp, 2016). Today, the United States, sustained by the shale gas production, is the largest natural gas producer in the world and the manufacturing expansion of the country has accelerated due to this energy revolution (Arezki, Fetzer, & Pisch, 2017). Moreover, shale gas represents an opportunity to strengthen energy security by reducing the energy dependence of the United States (Wang & Li, 2017), at the time it would help to lower natural gas prices, enhance employment and competitive industrial power and, if compared to other fossil fuels, decrease GHG emissions (Bilgili et al., 2016).

Energy security in the country has then been enhanced due to unconventional fossil fuels extraction, helped by the boost of new technologies like fracking, a slight reduction on fossil fuels consumption and thus a reduction on fuels imports (De Luis López, 2017). In the United States’ energy security interests as well as relief for the economy, the government is seeking to boost domestic energy production (The White House, 2017a).

Regarding efficiency, the United States’ Government is aimed to double energy productivity of the country –the ratio of economic output per unit of energy use (Atalla & Bean, 2016)- by 2030 and, by doing so, contributing to economic growth (U.S. Department of Energy, 2015a) and the reduction on imports from today’s 19% to a 7% in 2030, which would directly be translated into energy security enhancement (Rhodium Group, 2013). The roadmap for energy productivity will rely on governments, business, utilities, institutions and individuals to achieve its goals. It is though imperative for the continuation and full implementation of this strategy the consent of the current federal administration which may, or not, keep it until the fulfillment of its objectives.

The United States is currently in a deep transformation, in the technology, energy and political spheres. When it comes to energy, the shale revolution and the expansion of renewables are the main entities that will shape the future energy system of the country but, unlike the last federal administration, the Trump’s one is intended to promote a deeper use of indigenous sources, independently if their nature, seeking to reach energy independence and security. The current administration of the White House should try to balance its ambitious energy policies with global political ideologies in order to avoid uncertainty in the power sector and try to keep the energy leadership of the United States (Gattie, 2017).

### 4.8. Chapter review

There does not exist a single strategy for enhancing energy security of a country, instead, every nation stablishes its own approach in the matter according to its own possibilities, needs and interests. Nevertheless, international regimes, such as the fight against global warming, tend to shape energy policies globally. Energy security does mean different things for different people, but the fact is that, among the studied countries, they all share the intention of achieving security of energy supply according to their own understanding of the concept, as well as their inherent possibilities. In this line and as stated by (Schaffitzel, Jakob, Soria, Vogt-Schilb, & Ward, 2020), commons strategies, such as the increase of energy prices in order to foster development programs, to reduce public deficits and incentivize transitions to low-carbon energy systems, might benefit all the countries deciding to apply them.

Among the covered countries, the most important discrepancies on their energy scopes regarding energy security are based on the fact that they possess different resources as a result of distinct geographical and geological situations. Although all of them plan to develop renewable technology installations for electricity production and, simultaneously, enhancing their energy efficiency while reducing their GHG emissions, their goals on each topic are different, primarily due to their despair current status, projections and priorities. Those countries lacking of conventional energy sources tend to rely highly on renewable energies since, among other reasons, those are the only available sources within their borders. Economies possessing large reserves of fossil fuels are willing to use them as much as they can in order to fulfill their energy needs; nevertheless, most of them also plan to substitute their conventional power plants gradually for cleaner technologies.

Countries in North America possess large amounts of energy resources, both fossil and renewable ones, which, jointly with the fact that the economies in the region are expected to continue expanding in the upcoming years, take these nations to take the approach of capitalizing on every form of their energy sources for procuring energy security within their borders.

The largest economy in the continent, the United States, has developed an all-of-the-above strategy for procuring its energy security, an effective way of becoming energy independent through the exploitation of all of its indigenous energy sources to the extent of possible. The country has no priority on shifting to a mostly-renewable energy mix, since the large reservoirs of fossil fuels it possesses, shale in particular, guarantee energy access in the country even in the long-term. Nevertheless, the United States has some of the largest renewable energy installations in the world, and it is a pioneer on technology development for both fossil fuels exploitation and renewable energies use. Additionally, several efficiency measures are currently taking place in the country, all in order to improve national energy productivity as a key measure for the betterment of energy security within its borders.

Canada and Brazil have similar approaches concerning their energy transitions; since both have an important share of renewable energy in their total electricity production thanks to hydroelectric power plants, their strategies consist basically of partially moving this hydropower electricity production to other renewable energy forms, particularly wind and solar power plants, along with improvements on efficiency.

Mexico, by its part, depends mainly on natural gas for producing electricity, while it plans to increase the presence of renewable energies, and moreover, the country is eager to exploit its fossil conventional sources as a primary measure for improvement on energy security.

In Latin America in general, more aggressive targets on international interconnections would boost the integration of renewable energies at a regional level.

European economies promote importantly the use of renewable energies, a totally understandable aim since fossil fuels are practically absent in the region. This fact has taken the countries in the continent to launch important energy transition paths that, besides covering renewable energies deployment, include improvement measures on energy efficiency and flexibility. Moreover, shifts on their energy mix are also covered in their respective strategies.

France, a today's heavily dependent nation on nuclear energy, plans to limit the presence of nuclear power in its electricity mix, while Germany, the largest economy in Europe, has taken the lead in the continent transforming its power system through the Energiewende, which intends to shift its heavy dependence on coal to renewables, particularly wind and solar, while totally phasing out its nuclear plants by 2022, and it includes a very ambitious renewable energies deployment accompanied by energy efficiency measures. Nonetheless and despite the fact that these are very important steps for their respective energy transitions, these countries will still rely heavily on conventional and foreign fuels in the mid- and long-terms, so efficiency, diversification of fuels and sources as well as interconnections are also imperative for guaranteeing their energy security.

By its part, China, as the most important country in terms of electric energy production and consumption, plays a central role in the international energy policy scenario. The Asian country follows a similar path as the one of the United States. Despite the relevant future penetration of renewable technologies, the country is as well keen to draw upon unconventional fossil fuels to enhance its security of energy supply. China has the aim of decarbonizing and expanding its energy mix with the largest renewable energy installations in the world, while it will also still rely importantly on fossil fuels in the mid- and long-terms for fulfilling its energy needs. The corresponding strategies of all of the covered countries are summarized in Table 8, in which it is shown their objectives regarding GHG emissions, final energy consumption, energy productivity, electricity consumption, renewable energies and nuclear energy. Argentina’s objectives in the matter, that will be covered in chapter 6, have also been included in the summary, so it is easier to make a comparison with the rest of economies.

**Table 8**

*Summary of national energy objectives and year of accomplishment*

| | | | Argentina | | | | Brazil | | | | Canada | | | | China | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Year | Target | Value | Unit | Year | Target | Value | Unit | Year | Target | Value | Unit | Year | Target | Value | Unit |
| GHG | | Base | - | - | - | kt of CO2 equivalent | 2005 | - | 863,894.87 | kt of CO2 equivalent | 2005 | - | 729,747.17 | kt of CO2 equivalent | 2005 | | 0.79 | kg of CO2 emissions per USD |
| | | Current status | 2017 | - | 322,000.00 | | 2012 | - | 1,027,739.00 | | 2017 | - | 713,838.21 | | 2014 | | 0.59 | |
| | | Objectives | 2030 (Compared to BAU scenario i.e. 592) | -15% | 503,000.00 | | 2020 | -37% | 544,253.77 | | 2030 | -30% | 510,823.02 | | 2020 | -40% to -45% | 0.46 | |
| | | | | | | | 2025 | -50% | 431,947.44 | | | | | | 2030 | -60% to -65% | 0.30 | |
| Final energy consumption | | Base | ND | | | | ND | | | | ND | | | | | - | | Mtoe |
| | | Current status | | | | | | | | | | | | | 2016 | - | 2000 | |
| | | Objectives | | | | | | | | | | | | | 2020 | | <5000 | |
| | | | | | | | | | | | | | | | 2030 | | <6000 | |
| Energy productivity | | Base | ND | | | | ND | | | | ND | | | | 2015 | | 3682.37 | Current USD/toe |
| | | Current status | | | | | | | | | | | | | 2016 | | 3765.35 | |
| | | Objectives | | | | | | | | | | | | | 2020 | >15% (2020) | 4234.72 | |
| Gross electricity consumption | | Base | ND | | | | ND | | | | ND | | | | ND | | | |
| | | Current status | | | | | | | | | | | | | | | | |
| | | Objectives | | | | | | | | | | | | | | | | |
| Renewable energies | In primary energy consumption | Current status | ND | | | | 2017 | - | 123.64 | Mtoe | 2017 | - | 50.57 | Mtoe | 2016 | 9% | 266.48 | Mtoe |
| | | Objectives | | | | | 2024 | | 45% | | 2025 | | 50% (at a Noth American level) | | 2020 | 15% | 750 | |
| | | | | | | | | | | | | | | | 2030 | 20% | 1200 | |
| | In gross electricity consumption | Current status | 2017 | 23% | 33.40 | TWh | 2017 | 79% | 465.63 | TWh | Provincial / territorial objectives | | | | 2016 | 25% | 1650 | TWh |
| | | Objectives | 2018 | | 8% | | 2024 | | 86% | | | | | | 2030 | 50% | 4765.2 | |
| | | | 20.25 | | 25% | | | | | | | | | | | | | |
| Nuclear energy | | Current status | ND | | | | ND | | | | ND | | | | ND | | | |
| | | Objectives | | | | | | | | | | | | | | | | |

ND: not determined

**Table 8 (cont.)**

*Summary of national energy objectives and year of accomplishment*

| | | | Germany | | | | France | | | | Mexico | | | | United States | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Year | Target | Value | Unit | Year | Target | Value | Unit | Year | Target | Value | Unit | Year | Target | Value | Unit |
| GHG | | Base | 1990 | | 1,219,680.87 | kt of CO2 equivalent | 1990 | | 529,212.63 | kt of CO2 equivalent | 2000 | - | 544,660.10 | kt of CO2 equivalent | 2005 | - | 6,599,005.62 | kt of CO2 equivalent |
| | | Current status | 2017 | | 891,426.25 | | 2017 | | 439,420.41 | | 2015 | - | 699,564.27 | | 2017 | - | 5,742,622.75 | |
| | | Objectives | 2020 | -40% | 731,808.52 | | 2030 | -40% | 317527.58 | | 2020 | -30% | 381,262.07 | | 2020 | -17% | 5,477,174.66 | |
| | | | 2030 | -55% | 548,856.39 | | | | | | | | | | | | | |
| | | | 2040 | -70% | 365,904.26 | | | | | | | | | | | | | |
| | | | 2050 | -80% to 95% | 60,984.04 | | 2050 | -75% | 132303.16 | | 2050 | -50% | 272,330.05 | | 2025 | -28% | 4,751,284.05 | |
| Final energy consumption | | Base | 2008 | - | 226.90 | Mtoe | 2012 | - | 155.3 | Mtoe | ND | | | | ND | | | |
| | | Current status | 2016 | - | 223.90 | | 2016 | - | 152.2 | | | | | | | | | |
| | | Objectives | 2020 | -20% | 181.52 | | 2030 | -20% | 124.24 | | | | | | | | | |
| | | | 2050 | -50% | 113.45 | | 2050 | -50% | 77.65 | | | | | | | | | |
| Energy productivity | | Base | 2008 | | 13195.32 | Current USD/toe | ND | | | | 2016 | - | 5821.00 | Current USD/toe | 2014 | | 7925.88 | Current USD/toe |
| | | Current status | 2016 | | 14557.18 | | | | | | | | | | 2016 | | 8634.27 | |
| | | Objectives | 2008-2050 | 2.1% /year | 31586.47 | | | | | | 2016-2030 | 1.9% / year | 7575.93 | | 2030 | Double (2014) | 15851.76 | |
| | | | | | | | | | | | 2031-2050 | 3.7% / year | 15108.89 | | | | | |
| Gross electricity consumption | | Base | 2008 | - | 619 | TWh | ND | | | | ND | | | | ND | | | |
| | | Current status | 2017 | - | 598.7 | | | | | | | | | | | | | |
| | | Objectives | 2020 | 10% | 557 | | | | | | | | | | | | | |
| | | | 2050 | 25% | 464 | | | | | | | | | | | | | |
| Renewable energies | In primary energy consumption | Current status | 2016 | 13% | 29.50 | Mtoe | 2016 | 10% | 24.58 | Mtoe | 2017 | - | 16.11 | Mtoe | 2016 | - | 156.23 | Mtoe |
| | | Objectives | 2020 | 18% | 32.67 | | 2020 | 23% | 28.58 | | 2025 | 50% (at a Noth American level) | | | 2025 | 50% (at a Noth American level) | | |
| | | | 2030 | 30% | 47.65 | | 2030 | 32% | 24.85 | | | | | | | | | |
| | | | 2040 | 45% | 61.26 | | | | | | | | | | | | | |
| | | | 2050 | 60% | 68.07 | | | | | | | | | | | | | |
| | In gross electricity consumption | Current status | 2016 | 29% | 187.83 | TWh | 2016 | 18% | 100.26 | TWh | 2017 | 16% | 51.54 | TWh | State Objectives | | | |
| | | Objectives | 2020 | >35% | 194.95 | | | | | | 2018 | | 25% | | | | | |
| | | | 2030 | >50% | 263 | | 2030 | 40% | 243.36 | | 2021 | | 30% | | | | | |
| | | | 2040 | >65% | 321.75 | | | | | | 2024 | | 35% | | | | | |
| | | | 2050 | >80% | 371.2 | | | | | | 2050 | | 50% | | | | | |
| Nuclear energy | | Current status | 2016 | 13% | | TWh | 2016 | 73% | | TWh | ND | | | | ND | | | |
| | | Objectives | 2022 | 0% | 0 | | 2035 | 50% | 250-325 | | | | | | | | | |

ND: not determined

## 5. Multidimensional index

Several composed indicators focused on studying energy security have been constructed; some of the most widespread indexes in the literature have been summarized by (Ang et al., 2015; Kruyt et al., 2009; Martchamadol & Kumar, 2013; Narula & Reddy, 2015). The indicators that have been reviewed for the construction of the proposed index in this paper are presented in Table 9:

**Table 9**
*Reviewed publications on energy security*

| Author/Institution | Name of Indicator/Index | Energy Source | Dimensions | No. of Indicators |
|---|---|---|---|---|
| Asia Pacific Energy Research Centre | Energy Security Indicators | Primary Energy | Availability; accessibility; acceptability; affordability | 16 |
| International Atomic Energy Agency | Energy Indicators for Sustainable Development | Primary Energy | Social; economic; environmental | 31 |
| World Energy Council | World Energy Trilemma Index | Primary Energy | Energy security; energy equity; environmental sustainability | 35 |
| Global Energy Institute | International Index of Energy Security Risk | Primary Energy | Global fuels; fuel imports; energy expenditures; price and market volatility; energy use intensity; electric power sector; transportations sector; environmental; R&D | 29 |
| Sovacool and Mukherjee | Energy Security Index | Primary Energy | Availability; affordability; technology development and efficiency; environmental sustainability; regulation and governance | 20 |
| Martchamadol and Kumar | Aggregated Energy Security Performance Indicator | Primary Energy | Social; economic; environmental | 25 |
| Kruyt et al. | Security of Supply Indicators | Primary Energy | Availability; accessibility; acceptability; affordability | 22 |
| Scheepers et al. | Supply/Demand index | Primary Energy | Essential energy demand needs; primary energy sources; energy conversions and transport | 19 |
| Jansen et al. | Long-term energy security indicators | Primary Energy | Diversification of energy sources in the energy supply; diversification of imports with respect to imported energy sources; long-term political stability in import regions; the resource base in regions of origin | 4 |

As Table 9 shows, the covered indexes generally deal with primary energy security of supply; as a result, they are unsuitable for specifically evaluating energy security of the power system. Due to the growing significance of the power sector, the present situation calls for the development of an index that focuses on the security of the supply of electrical energy.

### 5.1. Dimensions, categories and indicators

Due to the polysemic nature of the energy security concept (Chester, 2010), it can be covered from different approaches, which leads energy security to possess different defining factors that depend on the specific analysis to be conducted (Månsson et al., 2014).

The approach that has led to the conception of the composed index is the one presented in Figure 23, in which, within the context of energy transitions and for the purpose of evaluating energy security in the power system, a multidimensional index has been designed, namely Power System Security Index (PSIx), with which it is possible the track the evolution of a single country in two different time frames, or to compare different countries at a given time.

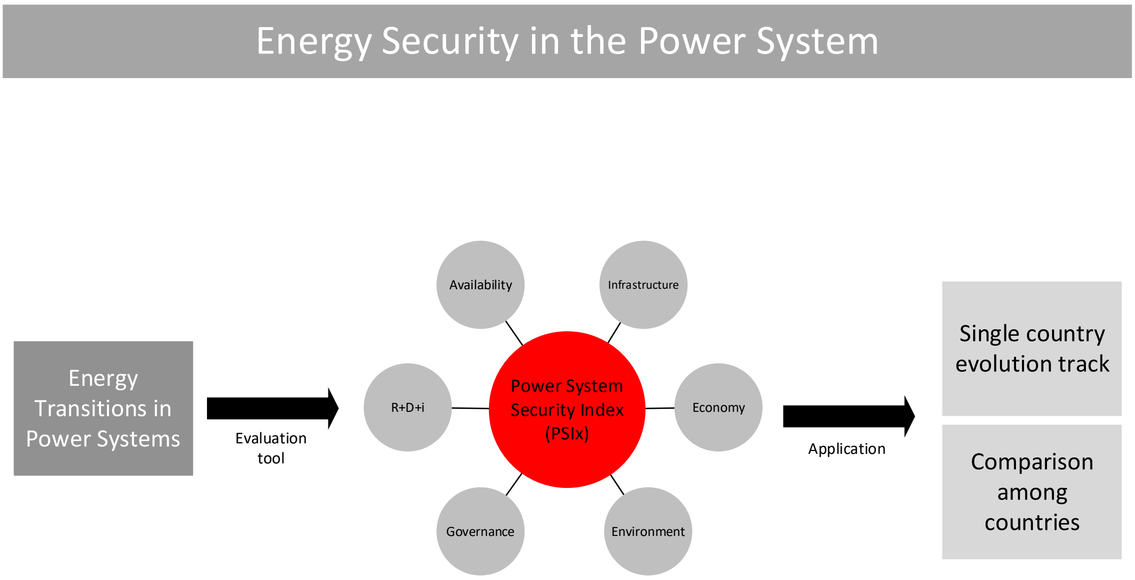

*Figure 23.* Scope of the PSIx (Fuentes, Villafafila-Robles, & Lerner, 2020)

According to the definition stated in section 3.1, six dimensions do characterize the energy security concept in the present work, namely availability, infrastructure, economy, environment, governance and research, development and innovation (R+D+i). Each one of these dimensions possesses multifold indicators grouped, in turn, into different categories. The structure of the PSIx is presented in Figure 24, where the dimensions, categories and indicators are shown. Each dimension, category and indicator possess an alphanumeric code for its identification throughout the document.

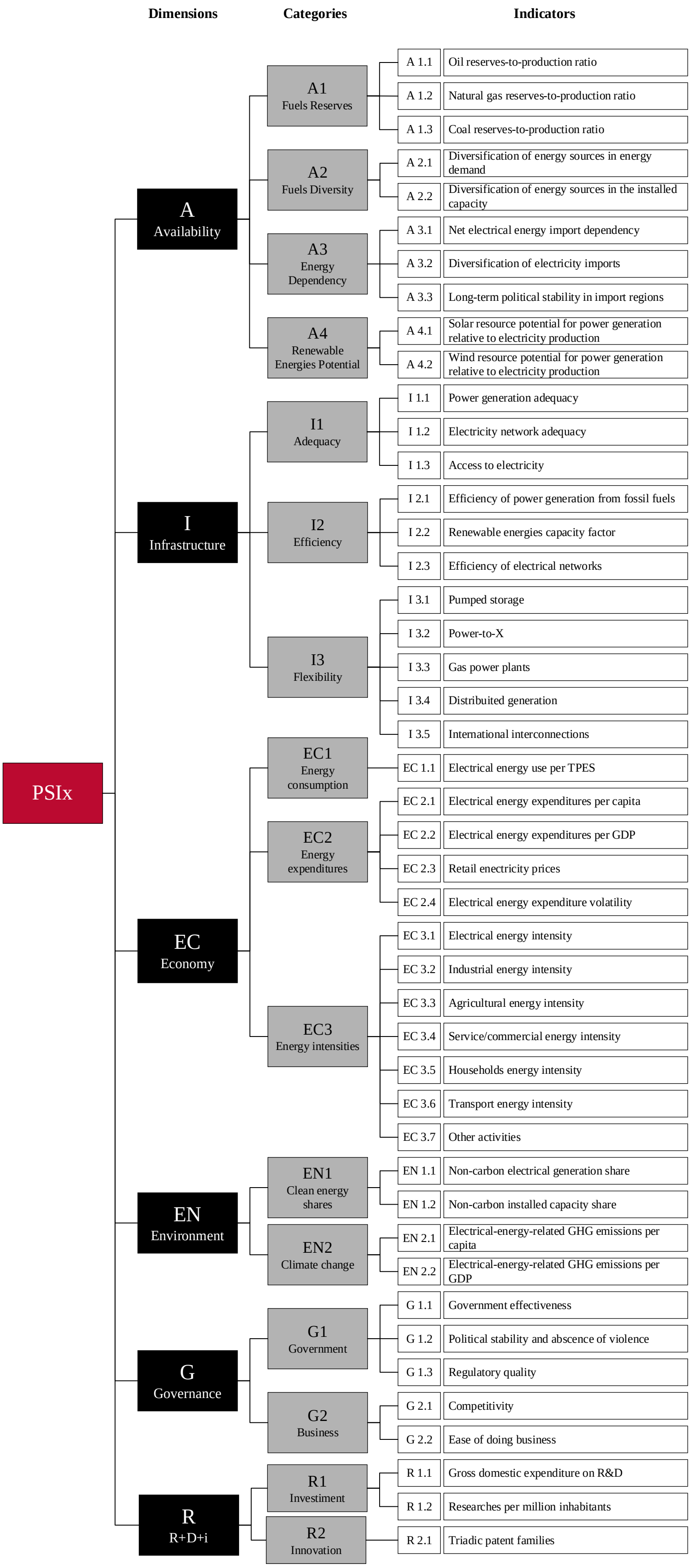

*Figure 24.* Energy Security Index structure (Fuentes et al., 2020)

### 5.1.1. Availability (A)

Availability is the dimension that appears the most in literature (Kruyt et al., 2009), and it is directly related to energy independence (Sovacool, Mukherjee, Drupady, D ’agostino, & Kuan, 2011). It refers to the geological existence of an energy resource within a determined area, as well as the degree of their replacement by alternative energy resources (Chang & Yong, 2007; Tongsopit, Kittner, Chang, Aksornkij, & Wangjiraniran, 2016). Moreover, this dimension covers the promotion of diversified energy technologies and energy sources (Sovacool et al., 2011). Four categories constitute the availability dimension: fuels reserves, fuels diversity, energy dependency and renewable energies potential:

- Fuels reserves (A1)

  This category covers the existence of a certain type of fuel relative to its production within national borders. This measure indicates the left years of the fuel at current production levels, as proposed by (Kruyt et al., 2009). Since this category deals with the depletion rates of energy fuels, only conventional ones are included on it.

  - Oil reserves-to-production ratio (A1.1)

    This indicator measures the availability of crude oil reserves respect to the oil production of an economy during a given year, which constitutes a basis for estimating future energy supplies, a key aspect of sustainability (International Atomic Energy Agency, 2005):

$$A1.1 = \frac{r_a}{s_a} \tag{1}$$

where:

$r_a$ = crude oil reserves

$s_a$ = crude oil production

The higher the indicator results, the higher its reserves-to-production ratio is, resulting in less risk associated to crude oil reserves, meaning a higher availability of oil supplies.

- Natural gas reserves-to-production ratio (A1.2)

On a yearly basis, this indicator measures the amount of remaining natural gas reserves respect to its production:

$$A1.2 = \frac{r_b}{s_b} \qquad (2)$$

where:

$r_b$ = proven natural gas reserves

$s_b$ = natural gas production

- Coal reserves-to-production ratio (A1.3)

On a yearly basis, this indicator measures the amount of remaining coal reserves respect to its production.

$$A1.3 = \frac{r_c}{s_c} \qquad (3)$$

Coal reserves-to-production ratio (A1.3)

$r_c$ = proven coal reserves

$t_c$ = coal production

- Fuels diversity (A2)

It covers how different types of fuels are integrated in the electrical energy matrix in both, installed capacity and the consumed energy. In this category both conventional and renewable technologies are included.

  - Diversification of energy sources in electrical energy demand (A2.1)

Obtained from (Jansen, Van Arkel, & Boots, 2004), this indicator consists of a modified Shannon diversity index to denote the portfolio of sources related, in this case, to electricity generation.

$$A2.1 = -\sum_{i} (p_i \ln p_i) \tag{4}$$

where:

$i$ = 1…M: energy source index in the electricity matrix with M distinguished sources.

$p_i$ = share of energy source $i$ in the total electricity generation matrix.

M sources throughout this document are eight in number: oil, gas, coal, nuclear, hydro, wind, solar and others. Others includes geothermal, tide, wave, ocean, chemical heat and other non-specified sources of electricity production, as proposed by (International Energy Agency, 2016b).

  - Diversification of energy sources in installed capacity (A2.2)

This indicator is equally a modified Shannon diversity index, here applied to the electrical installed capacity of the studied country in order to determine its diversity.

$$A2.2 = -\sum_{i}(q_i \ln q_i) \tag{5}$$

where:

$i$ = 1…M: energy source index in the installed capacity matrix with M distinguished sources.

$q_i$ = share of energy source i in the total installed capacity matrix.

- Energy dependency (A3)

The exposure of a country to rely on alien sources to supply its energy needs is examined under this category. This series of measures is particularly important, due to the fact that a higher reliability and diversity from energy import regions mean a lower risk to energy security (Global Energy Institute, 2017).

  - Net electricity import dependency (A3.1)

Indicator that measures the extent to which an economy depends on a third country for satisfying its own electrical energy needs. It is defined as the ratio of net electrical energy imports respect to the total consumed electricity in a given year.

$$A3.1 = \frac{e_z}{e_y} \tag{6}$$

where:

$e_z$ = net imported electricity

$e_y$ = consumed electricity

- Diversification of electricity import regions (A3.2)

This indicator shows how diversified is the electricity dependence on foreign countries.

$$A3.2 = -\sum_k (r_k \ln r_k) \tag{7}$$

with:

$r_k$ = share of electrical energy imported from k region

$k$ = 1…O import regions index, with O regions distinguished

- Long-term political stability in import regions (A3.3)

From (Jansen et al., 2004), this indicator relates long-term political stability in regions of origin to the Shannon diversity index, and it does it through the use of the UNDP Human Development Index (HDI) as a the measure for socio-economic stability in the long-term.

$$A3.3 = -\sum_i \left(c_{3,i} p_i \ln p_i\right) \tag{8}$$

with:

$$c_{3,i} = 1 - m_i \left(1 - \frac{S_i^{m^*}}{S_i^{m^*,max}}\right) \tag{9}$$

$$S_i^{m^*} = -\sum_j \left(h_j m_{ij} \ln m_{ij}\right) \tag{10}$$

$h_j$ = extent of political stability in region j

$S_i^{m^*}$ = Adjusted Shannon index of import flows of resource $i$ for political stability in the regions of origin

$S_i^{m^*,max}$= maximum value of Shannon index of import flows of resource $i$, (-ln(1/N)).

- Renewable energies potential (A4)

Under this category the potentials of solar and wind energy sources for electricity production are measured. Other renewable energy sources, are not included since their presence in the electricity matrix of most economies is still incipient. For the particular case of hydropower, its potential relies on the development of infrastructure, being hence its inclusion within this category not worth quantifying.

  - Solar resource potential for power generation relative to electricity production (A4.1)

Possible (theoretical) power generation from solar source relative to the national produced electricity in a given year is measured by this indicator:

$$A4.1 = \frac{e_{gen,p,s}}{e_{gen}} \tag{11}$$

where:

$e_{gen,p,s}$ = potential of electricity generation from solar sources

$e_{gen}$ = total national electricity generation

  - Wind resource potential for power generation relative to electricity production (A4.2)

Possible (theoretical) power generation from wind source relative to the national produced electricity in a given year.

$$A4.2 = \frac{e_{gen,p,w}}{e_{gen}} \quad (12)$$

where:

$e_{gen,p,w}$ = potential electricity generation from wind sources

$e_{gen}$ = total national electricity generation

### 5.1.2. Infrastructure (I)

This dimension measures the reliability of the power system, understood as the ability to access energy resources in order to provide a stable and uninterrupted supply of electrical energy; in some studies, it is referred as accessibility (Holley & Lecavalier, 2017; Kruyt et al., 2009),. Three categories make up the infrastructure dimension, which are adequacy, efficiency and flexibility.

- Adequacy (I1)

  This category covers the sufficiency of power generation plants and electrical networks in order to guarantee access to electrical energy to the population. Additionally, the population with access to that energy is included.

  - Power generation adequacy (I1.1)

    Capacity of power generation exceeding the peak demand level of the last available year.

$$I1.1 = \frac{P}{D_{peak}} \quad (13)$$

$P$ = power generation capacity

$D_{peak}$ = peak demand

- Electrical network adequacy (I1.2)

  Sum of domestic and import capacity compared to peak home demand.

$$I1.2 = \frac{P_{trans}}{D_{peak}} \tag{14}$$

$P_{trans}$ = transformer capacity

$D_{peak}$ = peak demand

- Access to electricity (I1.3)

  Percentage of people with access to electrical energy.

$$I1.3 = \frac{pl_e}{pl} \tag{15}$$

$pl_e$ = population with access to electricity

$pl$= total population

- Efficiency (I2)

It deals with power generation plants as well as electrical networks, evaluating how these facilities are able to achieve their maximum productivity for procuring electrical energy supply.

- Efficiency of power generation from fossil fuels (I2.1)

  Electricity generation efficiency at the present state of the technology. Gross production of electricity from fossil fuel power plants relative to fossil fuel inputs. (Btu content of a kWh of electricity = 3,412 Btu (U.S. Energy Information Administration (EIA), 2017))

$$I2.1 = \frac{e_{gen,f}}{e_{gen,f,max}} \tag{16}$$

$e_{gen,f}$= electrical energy generation from fossil-fuel-based installations

$e_{gen,f,max}$= maximum possible electrical energy generation from fossil-fuel-based installations

- Renewable energies capacity factor (I2.2)

The taken definition is the one proposed by (United States Nuclear Regulatory Commission, 2017) , which defines this issue as the "ratio of net electricity generated in a considered time, to the energy that could have been generated at continuous full-power operation during the same period"

$$I2.2 = \frac{e_{gen,r}}{e_{gen,r,max}} \tag{17}$$

$e_{gen,r}$= electrical energy generation from renewable sources

$e_{gen,r,max}$ = maximum possible electrical energy generation from renewable sources

- Efficiency of electrical networks (I2.3)

The ratio between the quantity of energy lost during transport and distribution and the electricity consumption.

$$I2.3 = \frac{e_l}{e_c} \tag{18}$$

$e_l$ = electricity injected to the power lines

$e_c$ = electricity consumed by final users

- Flexibility (I3)

It measures the capacity of the power system to cope with variability in both generation and demand, so that the system is able to remain resilient, one of the greatest challenges energy sectors face globally (China National Renewable Energy Centre, 2019). Flexibility category encompasses power-to-X facilities, gas power plants, distributed generation and international electrical interconnections.

  - Pumped storage (I3.1)

The indicator measures the low-cost solution (International Energy Agency, 2015a) for the provision of flexibility of the power system, relative to the total electrical installed capacity.

$$I3.1 = \frac{S_{pump}}{P} \tag{19}$$

$S_{pump}$ = pumped-storage capacity

$P$ = power generation capacity

  - Power-to-X (I3.2)

This indicator summarizes enabling technologies aimed to store electrical energy into other forms, i.e. gases, fuels and chemicals (Schnuelle et al., 2019), and compares it to the total installed capacity of the country.

$$I3.2 = \frac{PtX}{P} \tag{20}$$

$PtX$ = Power-to-X installed capacity

$P$ = power generation capacity

- Gas power plants (I3.3)

The indicator of installed gas-fueled power plants is of particular interest due to the flexibility that these installations provide for the integration of renewable energies, thanks to the compatibility of both technologies.

$$I3.3 = \frac{P_{gas}}{P} \tag{21}$$

$P_{gas}$ = gas-fired power plants capacity

$P$ = power generation capacity

- Distributed generation (I3.4)

It accounts the percentage of distributed generation capacity compared to the total installed capacity of a country.

$$I3.4 = \frac{P_{dis}}{P} \tag{22}$$

$P_{dis}$ = distributed generation capacity

$P$ = power generation capacity

- International interconnections (I3.5)

In terms of flexibility, electrical interconnections between countries do enhance the reliability of the electrical system, since it can count on the electricity supply of a neighboring economy for fulfilling the national energy needs at certain times and under certain conditions. Moreover, electrical interconnections provide a way of selling electrical energy to third countries, which can be translated into benefits for the exporting country.

$$I3.5 = \frac{L_{int}}{P} \tag{23}$$

$L_{int}$ = international interconnections capacity

$P$ = power generation capacity

### 5.1.3. Economy (EC)

The economic dimension, or affordability, is intended to measure the price of energy for a series of technologies (Tongsopit et al., 2016). Its relevance resides in the fact that volatility and high energy prices have strong repercussions on the economy, competitiveness of industries and trade balance (Global Energy Institute, 2017). In this dimension, energy consumption, expenditures and energy intensities are covered:

- Energy consumption (EC1)

  As well as the rest of categories, it is focused on electrical energy. The category is composed by one single indicator.

  - Electrical energy use per TPES (EC1.1)

    The indicator consists of the comparison of electrical energy consumption contrasted with the total primary energy consumption at national level.

$$EC1.1 = \frac{e_c}{TPES} \tag{24}$$

$e_c$ = electricity consumption

$TPES$ = total primary energy supply

- Energy expenditures (EC2)

Under this category it is measured how much money is paid for the electrical energy supply, contrasted with national income, as well as the volatility of the prices of electricity.

  - Electrical energy expenditures per capita (EC2.1)

Through this indicator, the costs of electrical energy are contrasted with the total population of the country and, as well as indicator EC2.1, it is intended to measure the exposure of consumers to price shocks, as proposed by (Global Energy Institute, 2018).

$$EC2.1 = \frac{x_e}{pl} \tag{25}$$

$x_e$ = electrical energy expenditures

$pl$ = total population

  - Electrical energy expenditures per GDP (EC2.2)

The ratio of energy expenditures compared to the total gross domestic product measures also the exposure of consumers to energy prices. The lower the costs and exposure do represent a lower risk to energy security (Global Energy Institute, 2018).

$$EC2.2 = \frac{x_e}{GDP} \tag{26}$$

$x_e$ = electrical energy expenditures

$GDP$ = gross domestic product

- Retail electricity prices (EC2.3)

This indicator, jointly with EC2.4, assesses the susceptibility of a national economy and consumers to large swings in energy prices. A lower volatility represents a lower risk to energy security (Global Energy Institute, 2018).

$$EC2.3 = \frac{c_e}{e_u} \tag{27}$$

$c_e$ = cost of electricity

$e_u$ = electrical energy unit

- Electrical energy expenditure volatility (EC2.4)

This indicator, based on the proposal developed by (Global Energy Institute, 2018), is measured as the absolute average change in retail prices on electricity over the previous and the current year and compared to the total gross domestic product of the current year.

$$EC2.4 = \frac{x_e - x_{e-1}}{GDP} \tag{28}$$

$x_e$ = electrical energy expenditures

$x_{e-1}$ = electrical energy expenditures of the previous year

$GDP$ = gross domestic product

- Energy intensities (EC3)

Energy intensities are used as proxy measures to indicate how efficient is a country to generate economic growth per unit of used energy. It will be, according to (International Atomic Energy Agency, 2005), divided by sectors, this in order to have a benchmark of energy efficiency. This category is a particularly relevant issue for the scope if this work, since efficiency helps to improve energy security by reducing energy needs due to favorable changes in energy technologies, systems and practices (Ang et al., 2015).

- Electrical energy intensity (EC3.1)

This indicator is aimed to assess the use of electrical energy in relation to economic output and energy efficiency, as proposed by (Global Energy Institute, 2018). Lower amounts of electricity for the production of goods and services are translated into a lower risk for energy security.

Indicators from EC3.2 to EC3.7 split energy intensity of a country by different sectors of the economy.

$$EC3.1 = \frac{e_c}{GDP} \tag{29}$$

$e_c$ = electricity consumption

$GDP$ = gross domestic product

- Industrial energy intensity (EC3.2)

The indicator measures the aggregate energy use of the industrial sector per corresponding value added.

$$EC3.2 = \frac{e_{c,1}}{GDP_1} \tag{30}$$

$e_{c,1}$ = electricity consumption by industrial activities

$GDP_1$ = gross domestic product of industrial activities

- Agricultural energy intensity (EC3.3)

Final energy use per unit of agricultural value added.

$$EC3.3 = \frac{e_{c,2}}{GDP_2} \tag{31}$$

$e_{c,2}$ = electricity consumption by agricultural activities

$GDP_2$ = gross domestic product of agricultural activities

- Services/commercial energy intensity (EC3.4)

In order to monitor trends in energy usage in the tertiary sector, this indicator consists of the ratio of final energy use with respect to the service and commercial value added.

$$EC3.4 = \frac{e_{c,3}}{GDP_3} \tag{32}$$

$e_{c,3}$ = electricity consumption by service/commercial activities

$GDP_3$ = gross domestic product of service/commercial activities

- Households energy intensity (EC3.5)

This indicator is used as a proxy figure to estimate the consumption of electricity by households in a given economy, and it consists of the ratio of electricity consumed for domestic purposes relative to the total population of a country.

$$EC3.5 = \frac{e_{c,4}}{pl} \tag{33}$$

$e_{c,4}$ = household electricity consumption

$pl$ = total population

- Transport energy intensity (EC3.6)

Transport, as a major user of energy, particularly of oil, is a key player in national consumption of such fuel. The indicator, which measures the amount of energy per quantity of vehicles, and as proposed by (Global Energy Institute, 2018), gives an idea of how much energy is used for moving both goods and people.

$$EC3.6 = \frac{e_{c,5}}{vh} \tag{34}$$

$e_{c,5}$ = electricity consumption by transport

$vh$ = number of vehicles

- Other activities energy intensity (EC3.7)

Economic activities not included in the previous categories are summed up under this indicator, measuring as well their use of energy respect to their contribution to the national GDP.

$$EC3.7 = \frac{e_{c,o}}{GDP_o} \tag{35}$$

$e_{c,o}$ = electricity consumption by other activities

$GDP_o$ = gross domestic product of other activities

### 5.1.4. Environment (EN)

The impact on the environment has acquired a very high importance for energy policy makers in this century, particularly GHG emissions. This tendency has translated into strict restrictions to conventional energy technologies, which has spurred several countries to transform their power systems. In this line, the aspects of the environmental dimension are intended to measure the repercussion of technologies on the environment, so they do not represent a menace for sustainable development. Electricity shares of non-carbon sources and emissions associated to climate change are the categories of this dimension:

- Electricity shares (EN1)

  This category covers the share of non-carbon power plants in the total installed capacity, as well as the share of their generation in the national production in a national basis.

  - Non-carbon electrical generation share (EN1.1)

    This indicator, expressed in percentage, indicates the presence of non-carbon sources in the national energy matrix. The indicator, proposed by (International Atomic Energy Agency, 2005), surges as the international priority of promoting electricity generation from non-carbon sources as a measure for achieving sustainable development.

$$EN1.1 = \frac{e_r}{e_p} \tag{36}$$

$e_r$ = electricity produced by renewable sources

$e_p$ = electricity production

  - Non-carbon installed capacity share (EN1.2)

The indicator measures the presence of non-carbon electricity generation facilities in national installed capacities.

$$EN1.2 = \frac{P_r}{P} \tag{37}$$

$P_r$ = Installed capacity of renewable energy facilities

$P$ = total installed power

- Climate change (EN2)

It deals with greenhouse gases (GHG) emissions per capita and per GDP, including carbon dioxide, methane and nitrous oxide, as a measure of impact in the environment of energy-related activities.

  - Electrical-energy-related GHG emissions per capita (EN2.1)

$$EN2.1 = \frac{GHG}{pl} \tag{38}$$

$GHG$ = greenhouse gases emissions

$pl$ = total population

  - Electrical-energy-related GHG emissions per GDP (EN2.2)

$$EN2.2 = \frac{GHG}{GDP} \tag{39}$$

$GHG$ = greenhouse gases emissions

$GDP$ = gross domestic product

### 5.1.5. Governance (G)

Governments are responsible of effectively planning infrastructure development in order to ensure long-term energy security (Ang et al., 2015). They are, as well, pledge to establish lasting relationships with other countries, so it is possible to assure energy supplies in a political-stable scenario, reasons to consider governance as a fundamental component of energy security. Government and business environment conform this dimension:

- Government (G1)

  Under this category, data related to the government development is covered, including not only its performance but also the political stability product of it and the regulatory quality, as well as the absence of violence, measures necessary for the proper functioning of the energy system. These figures are directly taken from (The World Bank, 2019d) and in the index are formed by the following indicators:

  - Government effectiveness (G1.1)

    This indicator, proposed by (The World Bank, 2019b), does assess perceptions on public and civil services' quality, and their independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.

  - Political stability and absence of violence/terrorism (G1.2)

    The indicator measures perceptions on the possibility of political instability and/or politically-motivated violence, including terrorism within a given territory.

  - Regulatory quality (G1.3)

    This indicator assesses perceptions of the ability of a national government to formulate and implement sound policies and regulations that allow and foster private sector development.

- Business (G2)

  The economic environment of the country is considered in this category, as much as investments are the lifeblood of the energy system (International Energy Agency; & International Renewable Energy Agency, 2017). The indicators of this category are gotten directly from (World Economic Forum, 2019) and (The World Bank, 2019a), respectively.

  - Competitivity (G2.1)

    The Global Competitiveness Index, developed by (World Economic Forum, 2019), does assess national competitiveness, i.e. set of institutions, policies and factors that determine the level of productivity.

  - Ease of doing business (G2.2)

    The ease of doing business index measures the regulatory environment of an economy in such a way that it is conductive to business operation (The World Bank, 2019a).

### 5.1.6. Research, development and innovation (R)

Research, development and innovation (R+D+i) play a central role in energy security since these improve the capacity to adapt and respond to disruption challenges through innovation (Sovacool et al., 2011). This dimension has the aim of, as proposed by (Institute for the 21st Century Energy, 2016), measuring new energy technologies and the development of intellectual capital as a factor to assess risks on energy security. The categories composing this dimension are investment and innovation, whose indicators are obtained directly from (The World Bank, 2019c).

- Investment (R1)

Gross domestic expenditure on R+D+i and the proportional number of researchers respect to the population are the variables used for dimensioning this category.

  - Gross domestic expenditure on R+D+I (R1.1)

    This indicator measures the total expenditure on R+D+i performed by all resident companies, research institutes, universities and government laboratories in a country.

  - Researchers per million inhabitants (R1.2)

    The indicator measures active researchers per 1 million people employed.

- Innovation (R2)

Triadic patent families' number of a country is used as a proxy variable used for measuring the innovation level of a given country in an annual basis.

  - Triadic patent families (R2.1)

    It is defined as a set of patents registered in various countries in order to protect the same invention. These offices are, according to the definition elaborated by (OECD, 2018), the European Patent Office, the Japan Patent Office and the United States Patent and Trademark Office.

The individual indicators along with their respective objective, are presented in Table 10, while in the corresponding units of each variable are summarized in Table 11:

**Table 10**
*Indicators' objectives. Reprinted from* (Fuentes et al., 2020)

| ID | Formula | Objective | ID | Formula | Objective |
|---|---|---|---|---|---|
| A1.1 | $A1.1 = \frac{r_a}{s_a}$ | Maximize | EC2.2 | $EC2.2 = \frac{x_e}{GDP}$ | Minimize |
| A1.2 | $A1.2 = \frac{r_b}{s_b}$ | Maximize | EC2.3 | $EC2.3 = \frac{c_e}{e_u}$ | Minimize |
| A1.3 | $A1.3 = \frac{r_c}{s_c}$ | Maximize | EC2.4 | $EC2.4 = \frac{x_e - x_{e-1}}{GDP}$ | Minimize |
| A2.1 | $A2.1 = -\sum_i (p_i \ln p_i)$ | Maximize | EC3.1 | $EC3.1 = \frac{e_c}{GDP}$ | Minimize |
| A2.2 | $A2.2 = -\sum_i (q_i \ln q_i)$ | Maximize | EC3.2 | $EC3.2 = \frac{e_{c,1}}{GDP_1}$ | Minimize |
| A3.1 | $A3.1 = \frac{e_z}{e_y}$ | Minimize | EC3.3 | $EC3.3 = \frac{e_{c,2}}{GDP_2}$ | Minimize |
| A3.2 | $A3.2 = -\sum_k (r_k \ln r_k)$ | Maximize | EC3.4 | $EC3.4 = \frac{e_{c,3}}{GDP_3}$ | Minimize |
| A3.3 | $A3.3 = -\sum_i (c_{3,i} p_i \ln p_i)$ | Maximize | EC3.5[3] | $EC3.5 = \frac{e_{c,4}}{pl}$ | Minimize |
| A4.1 | $A4.1 = \frac{e_{gen,p,s}}{e_{gen}}$ | Maximize | EC3.6 | $EC3.6 = \frac{e_{c,5}}{vh}$ | Minimize |
| A4.2 | $A4.2 = \frac{e_{gen,p,w}}{e_{gen}}$ | Maximize | EC3.7 | $EC3.6 = \frac{e_{c,o}}{GDP_o}$ | Minimize |
| I1.1 | $I1.1 = \frac{P}{D_{peak}}$ | Maximize | EN1.1 | $EN1.1 = \frac{e_r}{e_p}$ | Maximize |
| I1.2 | $I1.2 = \frac{P_{trans}}{D_{peak}}$ | Maximize | EN1.2 | $EN1.2 = \frac{P_r}{P}$ | Maximize |
| I1.3 | $I1.3 = \frac{pl_e}{pl}$ | Maximize | EN2.1 | $EN2.1 = \frac{GHG}{pl}$ | Minimize |
| I2.1 | $I2.1 = \frac{e_{gen,f}}{e_{gen,f,max}}$ | Maximize | EN2.2 | $EN2.2 = \frac{GHG}{GDP}$ | Minimize |
| I2.2 | $I2.2 = \frac{e_{gen,r}}{e_{gen,r,max}}$ | Maximize | G1.1 | Direct value | Maximize |
| I2.3 | $I2.3 = \frac{e_l}{e_c}$ | Maximize | G1.2 | Direct value | Maximize |
| I3.1 | $I3.1 = \frac{S_{pump}}{P}$ | Maximize | G1.3 | Direct value | Maximize |
| I3.2 | $I3.2 = \frac{PtX}{P}$ | Maximize | G2.1 | Direct value | Maximize |
| I3.3 | $I3.3 = \frac{P_{gas}}{P}$ | Maximize | G2.2 | Direct value | Maximize |
| I3.4 | $I3.4 = \frac{P_{dis}}{P}$ | Maximize | R1.1 | Direct value | Maximize |
| I3.5 | $I3.5 = \frac{L_{int}}{P}$ | Maximize | R1.2 | Direct value | Maximize |
| EC1.1 | $EC1.1 = \frac{e_c}{TPES}$ | Maximize | R2.1 | Direct value | Maximize |
| EC2.1 | $EC2.1 = \frac{x_e}{pl}$ | Minimize | | | |

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[3] Proxy measure. Household energy intensity is considered to be domestic electrical consumption per capita.

**Table 11**

*Variables' units. Reprinted from* (Fuentes et al., 2020)

| Variable | Description | Units | Variable | Description | Units |
|---|---|---|---|---|---|
| $r_a$ | Crude oil reserves | b | $e_l$ | Electricity supplied to the power lines | kWh |
| $s_a$ | Crude oil production | b | $e_c$ | Electricity consumption | kWh |
| $r_b$ | Natural gas reserves | cu m | $PtX$ | Power-to-X installed capacity | MW |
| $s_b$ | Natural gas production | cu m | $P_{gas}$ | Installed capacity of gas-fired power plants | MW |
| $r_c$ | Coal reserves | ton | $P_{dist}$ | Installed capacity of distributed generation facilities | MW |
| $s_c$ | Coal production | ton | $L_{int}$ | International interconnections | MW |
| $p_i$ | Share of energy source $i$ in the total electricity generation matrix | - | $TPES$ | Total primary energy supply | MWh |
| $q_i$ | Share of energy source $i$ in the total installed capacity matrix | - | $x_e$ | Electrical energy expenditures | USD |
| $e_z$ | Net imported electricity | kWh | $GDP$ | Gross domestic product | USD |
| $e_y$ | Net consumed electricity | kWh | $e_{c,1}$ | Electricity consumption by industrial activities | kWh |
| $r_k$ | Share of electrical energy imported from k region | % | $GDP_1$ | Gross domestic product of industrial activities | USD |
| $c_3$ | Correction factor for pi, political stability | - | $e_{c,2}$ | Electricity consumption by agricultural activities | kWh |
| $e_{gen}$ | Total electricity generation | kWh | $GDP_2$ | Gross domestic consumption of agricultural activities | USD |
| $e_{gen,p,s}$ | Potential for power generation from solar sources | MW | $e_{c,3}$ | Electricity consumption by service/commercial activities | kWh |
| $e_{gen,p,w}$ | Potential for power generation from wind sources | MW | $GDP_3$ | Gross domestic product of service/commercial activities | USD |
| $P$ | Power generation capacity | MW | $e_{c,4}$ | Household electricity consumption | kWh |
| $D_{peak}$ | Peak demand | MW | $e_{c,5}$ | Electricity consumption by transport | kWh |
| $pl$ | Total population | people | $vh$ | Number of vehicles | - |
| $pl_e$ | Population with access to electricity | people | $e_{c,o}$ | Electricity consumption by other activities | kWh |
| $e_{gen,f}$ | Produced electricity from fossil-fuel-based installations | kWh | $GDP_o$ | Gross domestic product of other activities | USD |
| $e_{gen,f,max}$ | Maximum possible produced electricity from fossil-fuel-based installations | kWh | $c_e$ | Cost of electricity | USD/kWh |
| $e_{gen,r}$ | Produced electricity from renewable energy installations | kWh | $e_u$ | Electrical energy unit | kWh |
| $e_{gen,r,max}$ | Maximum possible produced electricity from renewable energy installations | kWh | $e_r$ | Electricity produced by renewable sources | kWh |
| $S_{pump}$ | Pumped-storage capacity | MW | $e_p$ | Electricity production | kWh |
| $e_{gen,max}$ | Maximum generation energy | kWh | $P_r$ | Installed capacity of renewable energy facilities | MW |
| $P_{trans}$ | Transformers power | MW | $GHG$ | Greenhouse gases emissions | ton |

# 6. The case of Argentina

Argentina is the barycenter of the electrical market in the southern cone (Wiegers, 1996). The current Argentinean electrical system depends heavily on hydrocarbons, but the country is entitled to reshape it through the fulfillment of ambitious targets, particularly the expansion of renewable energy sources and their decentralized integration to the electrical grid, as well as the implementation of several efficiency measures.

The last decade of the 20th century was characterized by favorable conditions for new power installations in Argentina, which include availability of natural resources, a mature technology, a suitable regulatory frame and a friendly macroeconomic environment (Abadie & Lerner, 2012). These conditions took the energy matrix of the country to become more dependent on thermal energy plants, particularly those using natural gas as fuel, relegating nuclear and renewable energies to a second place. Moreover, one of the most severe economic crises of Argentina in recent history took place between years 2001 and 2002, leading to an abrupt change in energy consumption, all within a frame established by a government regime with an abruptly different scope about energy production compared to the one presided by Mauricio Macri.

The austral country has plenty of energy resources suitable to be exploited, both fossil and renewable, conventional and unconventional ones. Argentina possesses very important proven reservoirs of fossil fuels: 2,017 million barrels of oil and 355 billion cubic meters of natural gas (OPEC, 2019), placing the country as one of the leaders in the Latin America in terms of energy potential.

Natural gas is the pillar of the Argentinean energy system, reason why the country is intended to expand its gas ducts, both nationally and internationally, this in order to increase its capabilities of gas trade. Additionally, federal and local governments plan to develop unconventional gas field projects, being the most important one the *Vaca Muerta* unconventional gas field, which shall increase importantly the country's availability of this fuel (Ministry of Energy and Mining, 2017a). This dependence of the country on natural gas leaves an important area of improvement for enhancing diversification of the energy system.

Argentina has a very strong presence of gas-fueled power plants, including plants based on combined cycle, turbo-gas and turbo-vapor technologies. Most of the installed plants allow the use of, besides natural gas, fuel oil or gas oil for electricity generation, increasing even further the system's flexibility. Figure 25 shows the installed power of the country by technology.

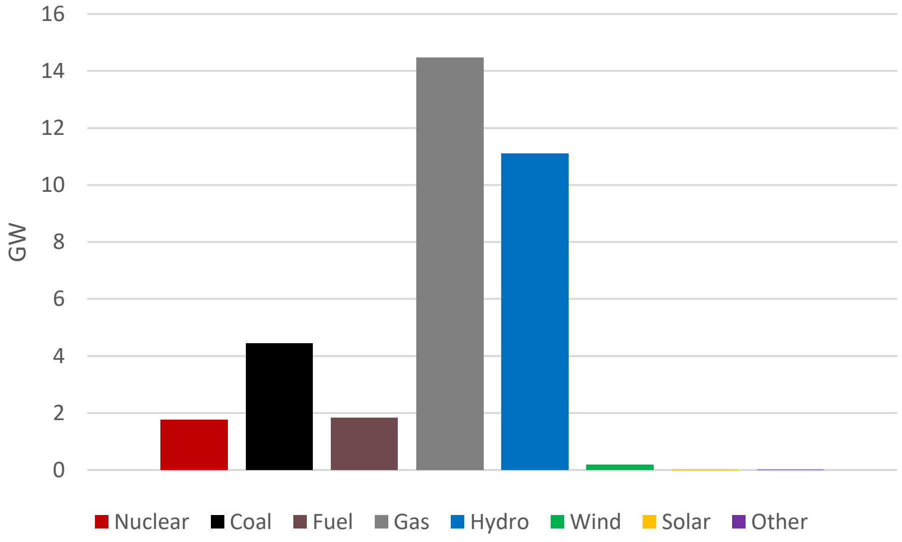

*Figure 25.* Installed power in Argentina by technology in 2015. Data from (Comisión Nacional de Energía Atómica, 2016)

By its part, electricity generation in the country, shown in Figure 26, follows the same pattern as the installed capacity, being the preponderant sources of energy the natural gas power plants, specifically those of combined cycle. As the developing country that it is, it is expected that energy consumption in the country increases in the upcoming years; electrical energy demand will go from 135 TWh to 170 TWh (Ministry of Energy and Mining, 2016).

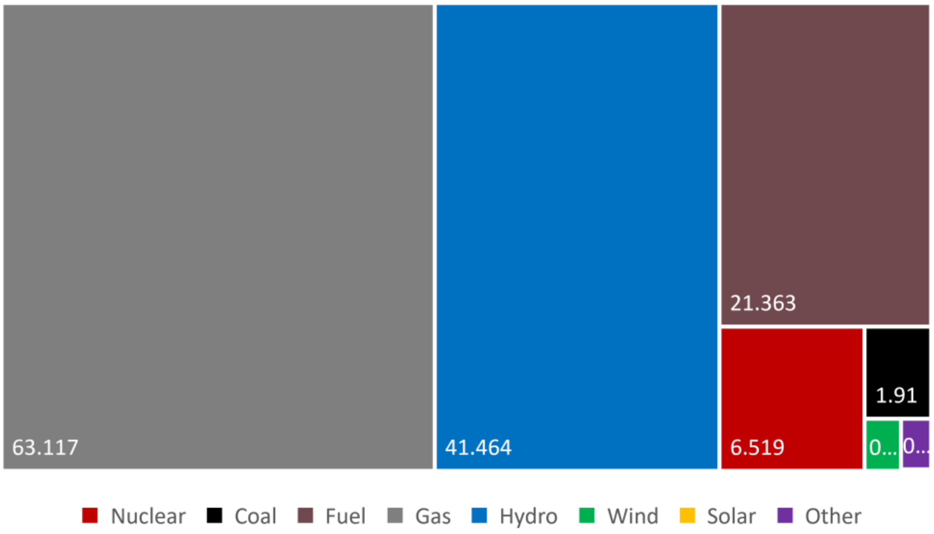

*Figure 26.* Electricity generation by source in Argentina in 2015 in TWh. Data from (Compañía Administradora del Mercado Mayorista Eléctrico S.A., 2016)

Argentina has electrical interconnections with most of its neighbors, besides several binational hydropower plants. In 2017 the country exported 69.2 GWh, of which 69.1 had Brazil as destination; the rest was exported to Chile. Electrical imports, by their part, accounted for 733.9 GWh, from which 474.0 GWh were imported from Uruguay, 153.6 GWh from Brazil, 70.4 GWh from Paraguay and 36.9 GWh from Chile (CAMMESA, 2018). International electrical interconnections play an important role in the day-to-day supply of electricity in the country. Thus, the Argentinean power system's flexibility is strong, but there is still room for improvement in a high-renewable-energy-penetration scenario.

Despite the fact that Argentina has one of the largest potentials for the development of wind and solar energies in the region (Garcia-Heller, On Espinasa, & Paredes, 2016), those technologies achieved only a 0.4% participation of the total electricity production in the country in 2015 (Compañía Administradora del Mercado

Mayorista Eléctrico S.A., 2016). The southern part of the country has some of the better wind power densities in the continent for electricity production, while the solar irradiation in the northeast is ideal for generation of electricity from photovoltaic installations. Hydropower is currently the most important renewable source of energy in the Argentinian energy mix, representing the 70% of the renewable production of electricity.

According to the standards proposed by (Scheepers, Seebregts, de Jong, & Maters, 2007), the infrastructure of the electrical system is considered to be adequate, both the installed capacity and the electrical network, and their efficiency is similar to other countries in the region (OLADE, 2019). Moreover, the country has implemented the necessary measures to achieve a very high percentage of people with access to electricity: 98.79% (OLADE, 2019).

Driven by the local energy transition, particularly by the introduction of renewable energies and due to their non-homogenous nature, it is fundamental to enhance flexibility of the power system. Several measures can be implemented for this purpose, such as energy storage, power-to-x, the expansion of gas-fueled power plants, the broadening of distributed generation and the reinforcement of national and international interconnections.

The Argentinean federal administration is committed to improve the efficiency of energy consumption and, with this aim, it has created a series of programs with which it is expected that the country reduces 5.9% its final energy consumption by year 2025, compared to the current tendency (Ministry of Energy and Mining, 2017a).

In order to promote energy efficiency, the Argentinian federal administration, through the Ministry of Energy and Mining, has created a series of programs with which it is expected that the country reduces its consumption by 5.9% of the final energy consumption in the country by 2025, compared to the current tendency (Ministry of Energy and Mining, 2017b), and move from 170 TWh of consumption to 158 TWh through efficiency measures (Ministry of Energy and Mining, 2017a).

Economically, the country has gone through adverse conditions during the last decades. The current inflation is 43.7% (IMF, 2019) and the GDP is expected to contract by 1.82% in 2019 (OECD, 2019). The complicated economic situation is extended to the prices of energy, which have increased jointly with raises in the costs of energy production, directly associated to foreign currencies. Despite the economical stumble, energy intensities have had a mixed development. Agricultural, commercial and transport sectors have improved compared to year 2009, while industrial, household and other activities have decreased their electrical energy productivity.

The current federal government addresses the promotion of renewable energies in the country as a strategic objective for mitigating climate change and improving the nation’s energy security (Ministry of Energy and Mining, 2016). In this line, it has issued the long-term target of achieving 20% of electrical energy consumption coming from renewable sources by 2025 (Law 27191, 2015); it is also committed to promote distributed generation of energy produced from renewable sources and its integration to the electrical network (Law 27424, 2017). A reduction of 15% of GHG emissions in a business as usual scenario towards 2030 is the current national objective and that reduction may be augmented to a 30% if necessary foreign aid is provided to the country (República Argentina, 2015).

Governance and business environment are, in general and according to international entities, such as (The World Bank, 2019d; World Economic Forum, 2017), large areas of opportunity in the country. The middling development in these dimensions is not endemic for Argentina, but it is a common trend in the region. Political stability, control of corruption and government effectiveness, are some aspects that the country needs to improve, this in order to create an adequate environment to attract investments and boost the national economy in general, and the energy industry in particular.

Finally, R+D+i in Argentina are currently in disadvantageous conditions, partially due to economic reasons which have shrunk their advancement, but also because they have not been established as priorities under the recent administrations. Just like governability and business environment, the country could improve R+D+i in order to create favorable conditions for attracting investment and get qualified personnel for the development and implementation of energy projects, which would, in turn, translate into improvements of national energy security.

It can be seen that the current federal administration of Argentina has the aim of transforming the country's energy mix towards greener alternatives as well as developing new interconnections and boost the use of local resources for fulfilling its energy needs. Despite the fact that the objectives of the country regarding energy efficiency and renewable energy sources penetration are not as aggressive as other countries in Latin America, the current series of strategies in the country, if implemented adequately, may place Argentina as a new more investment-attractive economy with a stronger security of energy supply.

## 6.1. Mathematical model

### 6.1.1. Normalization

As indicators use different measurement units and scales, it is necessary to create a frame that allows adding them up in the composite index (Ang et al., 2015; Martchamadol & Kumar, 2013). The application of the composed index will be carried out through gathering and subsequently comparing large amount of data from different nature and from different sources, data which ranges from fossil fuel reserves to expenditures on research, development and innovation. Hence, it is necessary the establishment of rules that allow a precise management of such information.

In order to make the values comparable in this work, two different forms of normalization are used depending on the nature of the variable to be measured: distance to a reference and historical evaluation. Both used formulas are mathematically identical, but they differ in terms of the definition of their denominators:

- Distance to a reference: The first normalization technique to be applied in the index consists of measuring the distance to a base value of an indicator. This distance can be applied either to a maximum or minimum figure, depending on the nature of the indicator in each situation; a maximum value is intended to be reached in cases such as population with access to electricity, while a minimum value is desirable in, for instance, electrical import dependency. Equation (40) illustrates this approach:

$$I_{qc}^{t} = \frac{x_{qc}^{t}}{x_{qb}^{t}} \tag{40}$$

where the normalized value of the $q$th indicator $I_{qc}^{t}$, associated to a $c$ country at a $t$ time, is given by the ratio of the indicator $x_{qc}^{t}$ to the maximum value given by $x_{qb}^{t}$. Indicators scored under this method are those belonging to the A, I, EN, G, and R dimensions.

- Historical evaluation: The second normalization scope will be used to evaluate historical data, mainly related to economic indicators; this measurement will be performed through percentage of annual differences over years. This technique is described as follows:

$$I_{qc}^{t} = \frac{x_{qc}^{t}}{x_{qc}^{t_0}} \tag{41}$$

where the normalized value of the $q$th indicator $I_{qc}^{t}$ is given by the ratio of the indicator $x_{qc}^{t}$ to the value of the same country but a different time, $t_0$. Indicators contained in the EC dimension are evaluated according to this second scope.

Within the availability dimension, reserves-to-production maximum ratios were established by the median value of international ratios in order to neglect extreme values. The maximum diversification of sources is obtained by assuming optimal conditions in the power system.

Adequacy values in the infrastructure dimension are taken from (Scheepers et al., 2007) and are set as 20% over the peak demand values. Efficiency in power plants and transmission lines is reflected directly as a percentage in the index.

The factors belonging to the economic dimension are evaluated by historical data. For establishing a time basis that serves as a benchmark for this dimension, the year 2002 was chosen. During this year, as detailed in Section 6, values corresponding to the most severe financial crisis in Argentina in its recent history are reflected. Taking this year as a basis establishes a common starting point for the evaluation of the development of the country in energy-related matters.

For the environmental dimension, a GHG-emissions-free and 100% renewable energy system is considered the ideal system to be reached.

The data used in the governance dimension come from sources which present them as percentages, already measuring the performance of the nation within its different categories.

The R+D+i category's maximum values are obtained from the world-leading country for each indicator under this dimension.

The minimum value of each indicator is set to 0, while the maximum value is considered to be the unit, as well as the most desirable value for each indicator. In the case that the objective of an indicator is its minimization, according to what is indicated in Table 10 and in order to keep the value of 1 as the target, the value of this particular indicator is subtracted from the unit; therefore, it is ensured that the unit is the desired and maximum value in both cases, maximization and minimization. For the specific case of the EC dimension, the base year will be considered to be the unit, in order to track the performance of the country from this benchmark.

### 6.1.2. Weighting and aggregation

The benchmarking frame developed by the normalization method makes it so that the weights of the indicators, as stated by (OECD, 2008), have a significant effect on the overall composite indicator. The selected model for the PSIx is the equal weight model, consisting of assigning the same value to the weight of each variable within the index. Since dimensions and categories possess different numbers of indicators, their weights are also different: A accounts for 22.22%, I for 24.4%, EC for 26.67%, EN for 8.89%, G for 11.11%, and R for 6.67% of the total weight of the composed index.

Two approaches have been applied for the aggregation of variables. The first one is a non-compensatory aggregation technique among indicators of different categories; this in order to avoid compensability of indicators belonging to categories of distinct dimensions. The second approach is taught to be applied to indicators within a specific category, and it consists of the geometric aggregation described by Equation (3):

$$CI_c = \prod_{q=1}^{Q} x_{q,c}^{w_q} \tag{42}$$

where $q = 1, \ldots, Q$ are the series of indicators $x_{q,c}^{w_q}$ with the assigned weight $w_q$ and belonging to the same category. This method, geometrical aggregation, aims to incentive the enhancement of indicators with particularly low scores (OECD, 2008), a desirable characteristic for ensuring the security of energy systems.

## 6.2. Results

The outcomes of each one of the indicators after applying the PSIx tool to the case of Argentina are summarized in Table 12 and Table 13. Following the described background in section 6, year 2002 was chosen as a reference for contrasting the current status of the security of the power system of the country, and for tracking its development.

In Table 12 the quantitative results of the indicators are reflected, as well as their change between years 2002 and 2017. Table 13 shows the results for categories and dimensions of the index, also contrasting the evolution of the country in the selected time frame, as well as the corresponding weights of the dimensions and the PSIx scores.

**Table 12**
*Outcomes of the PSIx for the Argentinean case* (Fuentes et al., 2020)

| Dimension | Category | ID | Indicator | 2002 | 2017 | Change |
|---|---|---|---|---|---|---|
| Availability | Fuels reserves | A1.1 | Oil reserves-to-production ratio | 0.41 | 0.47 | 16.01% |
| | | A1.2 | Natural gas reserves-to-production ratio | 0.65 | 0.54 | -17.07% |
| | | A1.3 | Coal reserves-to-production ratio | 1.00 | 1.00 | 0.00% |
| | Fuels diversity | A2.1 | Diversification of energy sources in electrical energy demand | 0.44 | 0.37 | -15.27% |
| | | A2.2 | Diversification of energy sources in the electrical installed capacity | 0.38 | 0.40 | 5.33% |
| | Energy dependency | A3.1 | Net electrical energy import dependency | 0.90 | 0.93 | 3.27% |
| | | A3.2 | Diversification of electricity imports | 0.31 | 0.71 | 128.19% |
| | | A3.3 | Long-term political stability in import regions | 0.21 | 0.55 | 157.38% |
| | Renewable energies potential | A4.1 | Solar resource potential for power generation relative to electricity production | 1.00 | 1.00 | 0.00% |
| | | A4.2 | Wind resource potential for power generation relative to electricity production | 1.00 | 1.00 | 0.00% |
| Infrastructure | Adequacy | I1.1 | Power generation adequacy | 1.00 | 1.00 | 0.00% |
| | | I1.2 | Electricity network adequacy | 0.71 | 0.87 | 21.93% |
| | | I1.3 | Access to electricity (% of population) | 0.96 | 0.99 | 2.79% |
| | Efficiency | I2.1 | Efficiency of power generation from fossil fuels | 0.65 | 0.68 | 4.62% |
| | | I2.2 | Renewable energies capacity factor | 0.36 | 0.42 | 16.09% |
| | | I2.3 | Efficiency of electrical networks | 0.85 | 0.85 | 0.14% |
| | Flexibility | I3.1 | Pumped storage | 1.00 | 1.00 | 0.00% |
| | | I3.2 | Power-to-X | 0.00 | 0.27 | 100.00% |
| | | I3.3 | Gas power plants | 1.00 | 1.00 | 0.00% |
| | | I3.4 | Distributed generation | 0.00 | 0.18 | 100.00% |
| | | I3.5 | International interconnections | 1.00 | 1.00 | 0.00% |
| Economy | Energy consumption | EC1.1 | Electrical energy use per total primary energy consumption | 1.00 | 1.00 | 0.00% |
| | Energy expenditures | EC2.1 | Electrical energy expenditures per capita | 1.00 | 0.51 | -49.37% |
| | | EC2.2 | Electrical energy expenditures per GDP | 1.00 | 0.75 | -24.65% |
| | | EC2.3 | Retail electricity prices | 1.00 | 0.20 | -79.74% |
| | | EC2.4 | Electrical energy prices volatility | 1.00 | 0.68 | -31.57% |
| | Energy intensities | EC3.1 | Electrical energy intensity | 1.00 | 1.00 | 0.00% |
| | | EC3.2 | Industrial energy intensities | 1.00 | 1.00 | 0.00% |
| | | EC3.3 | Agricultural energy intensities | 1.00 | 0.56 | -43.54% |
| | | EC3.4 | Service/commercial energy intensities | 1.00 | 1.00 | 0.00% |
| | | EC3.5 | Household energy intensities | 1.00 | 0.55 | -45.07% |
| | | EC3.6 | Transport energy intensities | 1.00 | 1.00 | 0.00% |
| | | EC3.7 | Other activities | 1.00 | 1.00 | 0.00% |
| Environment | Electricity shares | EN1.1 | Non-carbon electrical energy production share | 0.56 | 0.35 | -37.47% |
| | | EN1.2 | Non-carbon installed capacity share | 0.45 | 0.37 | -17.92% |
| | Climate change | EN2.1 | Electrical-energy-related GHG emissions per capita[1] | 1.00 | 1.00 | -0.06% |
| | | EN2.2 | Electrical-energy-related GHG emissions per GDP | 1.00 | 1.00 | 0.00% |
| Governance | Government | G1.1 | Government Effectiveness | 0.47 | 0.60 | 25.64% |
| | | G1.2 | Political Stability and Absence of Violence/Terrorism | 0.22 | 0.53 | 140.00% |
| | | G1.3 | Regulatory quality | 0.19 | 0.41 | 113.26% |
| | Business | G2.1 | Competitiveness index | 0.31 | 0.57 | 87.43% |
| | | G2.2 | Ease of doing business index | 0.58 | 0.58 | 0.22% |
| R&D | Investment | R1.1 | Gross domestic expenditure on R&D | 0.09 | 0.13 | 47.28% |
| | | R1.2 | Researchers per million inhabitants (Per 1000 employed) | 0.12 | 0.18 | 49.30% |
| | Innovation | R2.1 | Triadic patent families | 0.00 | 0.00 | 17.78% |

[1] Changes are not shown in the indicator due to decimal places position

Argentina shows mixed values in the different covered dimensions, categories and individual variables.

In what respects to indicators, the largest improvements are observed in A3.2, A3.3, both related diversification of imports, I3.4, and G1.2 and G1.3, both related to governability. On the other hand, EC2.3, EC2.1 and EC3.5 are the indicators that present the largest setbacks in the analyzed time frame for Argentina.

The category with the largest improvement is G1 followed by A3, while EC2 is the one with the weakest development.

In dimensions, the country scores clearly higher in areas such G and A, with also important improvements in I and R. In contrast, EC and EN are the dimensions that present a negative behavior for the country during the covered time.

**Table 13**
*PSIx score in the case of Argentina* (Fuentes et al., 2020)

| ID | Category | 2002 | 2017 | Change | ID | Dimension | Weight | 2002 | 2017 | Change | Score 2002 | Score 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | Fuels reserves | 0.26 | 0.25 | -3.79% | A | Availability | 0.22 | 0.00 | 0.01 | 420.73% | 0.29 | 0.02 |
| A2 | Fuels diversity | 0.17 | 0.15 | -10.75% | | | | | | | | |
| A3 | Energy dependency | 0.06 | 0.36 | 506.48% | | | | | | | | |
| A4 | Renewable energies potential | 1.00 | 1.00 | 0.00% | | | | | | | | |
| I1 | Adequacy | 0.68 | 0.86 | 25.33% | I | Infrastructure | 0.24 | 0.14 | 0.21 | 52.42% | | |
| I2 | Efficiency | 0.20 | 0.24 | 21.62% | | | | | | | | |
| I3 | Flexibility | 0.00 | 0.05 | 100.00% | | | | | | | | |
| EC1 | Energy consumption | 1.00 | 1.00 | 0.00% | EC | Economy | 0.27 | 1.00 | 0.02 | -98.36% | | |
| EC2 | Energy expenditures | 1.00 | 0.05 | -94.71% | | | | | | | | |
| EC3 | Energy intensities | 1.00 | 0.31 | -68.98% | | | | | | | | |
| EN1 | Electricity shares | 0.25 | 0.13 | -48.68% | EN | Environment | 0.09 | 0.25 | 0.13 | -48.71% | | |
| EN2 | Climate change | 1.00 | 1.00 | -0.06% | | | | | | | | |
| G1 | Government | 0.02 | 0.13 | 543.06% | G | Governance | 0.11 | 0.00 | 0.04 | 1108.02% | | |
| G2 | Business | 0.18 | 0.33 | 87.86% | | | | | | | | |
| R1 | Investment | 0.01 | 0.02 | 119.88% | R | R+D+i | 0.07 | 0.00 | 0.00 | 158.99% | | |
| R2 | Innovation | 0.00 | 0.00 | 17.78% | | | | | | | | |

Despite the fact that Argentina has improved importantly in areas such as availability of sources and governability, as it is shown in Figure 27, its detriment in the economic dimension take the country to present a general setback in its energy security score, going from 0.29 to 0.02.

*Figure 27.* Argentina development comparison

Within A dimension and thanks to its large energy resources, the country presents an outstanding development. Both fossil fuels basins and renewable sources potential strengthen remarkably the energy security of Argentina. In spite of notable outcome numbers on diversification of energy sources, it is an area in which the country could run larger improvements, mainly because of its dependence on natural gas for electricity generation, which shrinks its diversity of fuels for electricity production. The abundance of energy resources is also translated into a low dependency on electrical energy imports. The country presents an outstanding behavior on renewable energies potential, this thanks to its very favorable conditions in what respects to solar and wind sources.

Both installed capacity and the electric transport network are adequate for the country's energy needs according to the standards proposed by (Scheepers et al., 2007), reflected also in the high percentage of the population with access to electrical energy. Efficiency of power plants and of electrical networks are appropriate compared to other countries in the region. Adequacy and efficiency of the electrical infrastructure have, moreover, been improved during the covered time frame. In the other hand, the flexibility of the system can still be boosted, by deploying power-to-x installations and increasing distributed generation, a measure that the current government is already working on through different public policies. Gas-fueled power plants have been included in the PDIx as sources of flexibility in the power system as a specific indicator, not only because they are highly compatible with renewable energy sources, but also because this kind of plants currently generate most of the electricity in Argentina; such condition takes the electricity market price to be determined by the behavior of natural gas price. In a further stage, more sources could be incorporated.

The economy dimension is the one which has suffered the highest shrinkages. One of the main reasons that explain this situation, is that prices of electricity in Argentina are suffering a constant increase caused by subsidy cuts, at the time that national GDP has not been increased considerably, taking indicators of expenditures on electricity to suffer an important downturn. By their part, energy intensities, in general, show also a setback, partially also due to the contraction of the national GDP, unable to be overpassed by efficiency measures conducted to reduce energy consumption. Exemptions to this tendency are industrial, commercial and transport energy intensities.

Since the energy mix is dominated by natural gas and hydro power plants, GHG emissions of the country are relatively low compared to other expanding economies. Nevertheless, the expansion of gas-fueled power plants is translated into more emissions than those associated to the use of renewable technologies. In this line, a reduction of 15% of GHG emissions in a business as usual scenario towards 2030 is the current national objective, and that reduction can be augmented to a 30% if necessary foreign aid is provided to the country (Argentine Republic, 2015).

Argentina's governability is placed in an improvable position, since, it scores 0.6, 0.5, and 0.4 in government effectiveness, political stability, regulatory quality and rule of law indicators, respectively. Notwithstanding, the country has achieved an enormous progress in each category, improving in 26%, 140% and 123% in every indicator compared to year 2002 (The World Bank, 2019d). This has taken the country to present an increase of 1108.02% in the G dimension; it should be noted that the geometric aggregation system gives more importance to improvements on weak indicators, reason that takes the country to have such a high score in governance. It must be noted that the Argentinian case is atypical; in year 2002 the country was in an unprecedented political transition, in which several people occupied the presidency within a few days which, besides the external debt default, took the country to reach a peak of governance instability, a situation that was overpassed by year 2017.

The business environment of Argentina represents also room for improvement, since the country scores 57.7 out of 100 in the Global Competitiveness Index (World Economic Forum, 2017), and 58.8 out of 100 in the Ease of Doing Business Ranking (The World Bank, 2018).

For year 2016, the country expended 0.53% of its GDP expenditures on R+D+i, it accounted 3.004 researchers per 1,000 employed people and summed 10.945 triadic patent families for the same year (OECD, 2019). Despite the fact that these numbers position Argentina over its neighbor countries in the R dimension, internationally the country can still improve importantly in this matter.

Strengths and weaknesses of Argentina are therefore clear, while their large energy resources and solid infrastructure represent its most valuable assets in energy terms, the economical and governability spheres are the largest areas of opportunity of the country.

Despite the fact that the PSIx has been thought as a tool applicable to different economies, some limitations have been identified for achieving such purpose under certain circumstances. The selected method of equal weights, does assign the same importance to all the indicators and, therefore, establishes the same importance to categories with a large number of variables, which might be translated into a disequilibrium among dimensions. Benchmark values for determining maximum values in A dimension represent room for improvement in the index design, since these values have been selected arbitrarily. Furthermore, for different economies, some dimensions or categories could be of particular interest for their national energy security, but in the present study such condition has not been considered.

# 7. The case of Latin America and the Caribbean

Latin America is an energy rich region, not only in fossil fuels reservoirs, but also in renewable energies potential. At the same time, some nations in the region do not possess strong economies, taking them to undermine their electricity systems, independently of their possession or not of fuels basins. Due to the diversity of circumstances, it results pertinent to evaluate how policies of different countries in the region are translated into improvements on energy security in their respective power systems.

The main source for obtaining information about the countries' energy systems is the Latin America and the Caribbean Energy Information System, developed by the Latin America and the Caribbean Energy Organization (OLADE, 2019).

## 7.1. Mathematical model

### 7.1.1. Imputation of missing data

Some economies, particularly the smallest ones, have not provided complete datasets on energy information, either to international entities or through their own responsible authorities, which is translated into missing values for the indicators within the composed index. Therefore, it is necessary to complete these values by means of a suitable analytical method.

As defined by (Little & Rubin, 2002), missing data are unobservable values, which, if observed, would have a meaningful implication in the analysis. According to (Rubin, 1976), there are three types of missing values depending on their predictability of not-appearing in the studied dataset, i.e. missing completely at random (MCAR), missing at random (MAR) and not missing at random (NMAR). MCAR values are independent of the variable of interest or any other observed variable; MAR values are independent of the variable of interest, but other variables in the dataset condition their missingness while, by their part, NMAR values are dependent on the missing data.

The indicators containing missing values are I1.2, I3.1, I3.3, EC2.4, EC3.3, EC3.6, EC3.7, G2.1, R1.1, R1.2, R2.1. Two indicators possess NMAR values, since the availability of data is scarce for every country, not only those gathered by international institutions, but also those collected by each responsible national entity. These indicators are I3.1 and I3.3. It is inferred that these values are unavailable in most cases due to, precisely, the scarcity of data. Moreover, these indicators are relatively new compared to the rest of them, and policies of the covered countries do not consider them as priorities yet, therefore, their measurement at national level is, in most cases, rather low or inexistent.

For the NMAR values present in the index, an implicit modeling method has been selected for completing the corresponding datasets, i.e. hot deck imputation. This method is used to impute missing values within a data matrix by using available values from the same matrix with similar figures (Joenssen & Bankhofer, 2012). The countries are considered to have a similar behavior in the deployment of power-to-x and distributed generation installations. For these two specific indicators, in case of missing values, they are set to cero, considering, therefore, that the measured value is negligible for its study.

The rest of the indicators with missing values correspond, in general, to small economies, particularly to those located in the Caribbean. In order to achieve a more reliable imputation, the countries of the index have been divided in four categories, depending on the size of their economies and their geographical locations, this with the purpose of considering them more equal in energy terms. These categories are:

A. Big continental economies: Argentina, Brazil, Chile, Colombia, Mexico and Peru
B. Small continental economies: Bolivia, Ecuador, Guatemala, Paraguay, Uruguay and Venezuela
C. Caribbean and the Guianas: Barbados, Cuba, Grenada, Guyana, Haiti, Jamaica, Dominican Republic, Suriname and Trinidad & Tobago
D. Central America: Belize, Costa Rica, El Salvador, Honduras, Nicaragua and Panama

In order to impute the missing values of indicators, an explicit method, based on a formal statistical model, was selected, specifically the unconditional mean imputation method. This approach consists of the substitution of missing values by means of the sample series. Consequently, such procedure leads to estimates similar to those found by weighting, provided the sampling weights are constant within weighting classes (Little & Rubin, 2002).

### 7.1.2. Normalization

Regardless of their units and scales and with the target of render the variables comparable, it is necessary to determine a normalization method for the gathered data, which is done through the design of a frame that allows the addition of their values within the composite index (Ang et al., 2015; Martchamadol & Kumar, 2013). The data aimed to analyze different countries can be normalized in the same way that it was done for the case of a single-country study. Both approaches, distance-to-a-reference and historical evaluation are therefore kept for performing the analysis of Latin American economies.

### 7.1.3. Multivariate analysis

With the objective of assessing the underlying structure of the gathered data, a multivariate analysis has been conducted. This approach is also helpful for assigning weights to the indicators, a crucial step for, according to (Decancq & Lugo, 2012), determining their influence within the index, as well as their trade-off values.

Among the different methodological techniques present in literature, a data-driven approach has been selected, since it depends entirely on the data themselves. A factorial analysis approach, specifically the principal component analysis, has been chosen, since this statistical approximation allows the determination of interrelations among a great number of variables, at the time that it also allows to explain their behavior in terms of their subjacent common dimensions (Hair, Anderson, Tatham, & Black, 1999).

The treated variables have not been considered initially neither dependent nor independent from each other, therefore and, according to (OECD, 2008), an interdependency study can be executed. As the methodology dictates, the statistical study must cover all the variables simultaneously, so an underlying structure and can be identified for the whole set of indicators. For performing the principal components analysis, a covariance matrix of the data has been employed, containing 44 indicators for the 27 analyzed countries within the composed index.

For analyzing the correlations of the indicators, an item analysis was performed and the most significant values of the resulting correlation matrix is shown in Table 14. The matrix confirms the existence of a subjacent structure among the gathered data. In the table the most significant correlations among the variables, those equal to or above 0.70, are highlighted.

**Table 14**
*Correlation matrix showing the most significant correlations among variables* (Fuentes, Villafafila-Robles, Rull-Duran, & Galceran-Arellano, 2021)

| | A1.3 | A2.1 | A3.2 | I1.1 | I1.3 | I2.2 | I3.1 | I3.3 | I3.4 | EN1.1 | EN2.1 | G1.1 | G1.3 | G2.1 | R1.1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A2.2 | 0.16 | **0.97** | | | | | | | | | | | | | |
| A3.3 | 0.00 | 0.11 | **1.00** | | | | | | | | | | | | |
| I1.3 | 0.24 | 0.03 | 0.20 | **0.83** | | | | | | | | | | | |
| I2.3 | 0.03 | 0.13 | 0.00 | 0.69 | **0.73** | 0.10 | | | | | | | | | |
| I3.3 | 0.53 | 0.07 | 0.28 | -0.04 | 0.12 | -0.01 | **0.82** | | | | | | | | |
| EC1.1 | -0.21 | -0.22 | -0.18 | **-0.76** | -0.63 | -0.12 | -0.19 | -0.15 | -0.24 | | | | | | |
| EN1.1 | 0.06 | 0.51 | 0.45 | 0.11 | 0.20 | **0.76** | -0.15 | -0.12 | **0.75** | | | | | | |
| EN1.2 | 0.20 | 0.33 | 0.45 | 0.11 | 0.12 | **0.70** | -0.07 | -0.01 | 0.64 | **0.90** | | | | | |
| EN2.2 | -0.04 | 0.33 | 0.44 | -0.16 | 0.02 | 0.45 | -0.05 | 0.02 | 0.64 | **0.75** | **0.71** | | | | |
| G1.3 | 0.14 | 0.07 | -0.09 | 0.36 | 0.41 | 0.03 | 0.04 | 0.01 | 0.05 | 0.15 | -0.20 | **0.78** | | | |
| G2.1 | 0.30 | 0.23 | 0.02 | 0.51 | 0.63 | 0.19 | 0.16 | 0.14 | 0.25 | 0.29 | -0.13 | **0.76** | **0.80** | | |
| G2.2 | 0.02 | 0.21 | 0.16 | 0.41 | 0.45 | 0.13 | 0.02 | 0.06 | 0.30 | 0.24 | 0.04 | 0.69 | **0.79** | **0.87** | |
| R1.1 | **0.78** | 0.17 | 0.00 | 0.09 | 0.21 | 0.15 | 0.47 | 0.56 | 0.05 | 0.09 | -0.04 | 0.30 | 0.38 | 0.53 | |
| R1.2 | **0.74** | 0.14 | 0.08 | 0.06 | 0.19 | 0.16 | 0.64 | **0.72** | 0.10 | 0.09 | -0.01 | 0.28 | 0.30 | 0.43 | **0.95** |

With the purpose of evaluating the internal consistency of the analyzed data, the Cronbach's alpha parameter was employed and, since its value overpasses the benchmark of 0.7, specifically 0.7347, it is considered that the analyzed data measures the same characteristic, namely energy security in the power system, in the case of the present study.

The methodology proposed by (Jolliffe, 2002) has been selected for determining the principal components of the gathered data; for such purpose, the correlation matrix does serve as a basis. A principal component analysis is defined as:

$$\boldsymbol{z} = \boldsymbol{A}'\boldsymbol{x}^{*} \tag{43}$$

where $\boldsymbol{A}$ consists of columns formed by the eigenvectors of the correlation matrix, while $\boldsymbol{x}^{*}$ is composed by the arrangement of standardized variables. The objective of this approach is to identify the principal components of the standardize version of $\boldsymbol{x}^{*}$ with regard to $\boldsymbol{x}$, where $\boldsymbol{x}^{*}$ possesses $j$th element $x_j/\sigma_{jj}^{1/2}$, $j = 1, 2, \dots, p$, $x_j$ is the $j$th element of $\boldsymbol{x}$, and $\sigma_{jj}$ is the variance of $x_j$. Therefore, the covariance matrix for $\boldsymbol{x}^*$ is the correlation matrix for $\boldsymbol{x}$, while the principal components of $\boldsymbol{x}^*$ are determined by equation (43).

For the selection of the factors to be considered as relevant for a further analysis, and which do give rise to the determination of principal components, an a-priori criterion has been chosen, i.e. it will be considered that those factors that contribute for explaining 90% of the variance of the data are those that will be kept.

After the execution of the principal component analysis, the variance values of the principal components with a considerable influence were obtained and they are sown in Table 15. They are 10 of the total sample of 44 values, which explain 91.2% of the variance of the dataset:

**Table 15**
*Values of the factors of the covariance matrix* (Fuentes et al., 2021)

| **Factor** | **Eigenvalue** | **Proportion** | **Accumulated** |
|---|---|---|---|
| 1 | 0.54515 | 0.277 | 0.277 |
| 2 | 0.37498 | 0.191 | 0.468 |
| 3 | 0.18972 | 0.097 | 0.565 |
| 4 | 0.17292 | 0.088 | 0.653 |
| 5 | 0.14021 | 0.071 | 0.724 |
| 6 | 0.11698 | 0.06 | 0.783 |
| 7 | 0.08296 | 0.042 | 0.826 |
| 8 | 0.07199 | 0.037 | 0.862 |
| 9 | 0.0537 | 0.027 | 0.889 |
| 10 | 0.04414 | 0.022 | 0.912 |

The scree plot of the total number of factors vs. their corresponding eigenvalues in a descending order is shown in Figure 28. It can be observed the considerable high value of the first two components, while from the 15th value the curve presents practically a flat behavior.

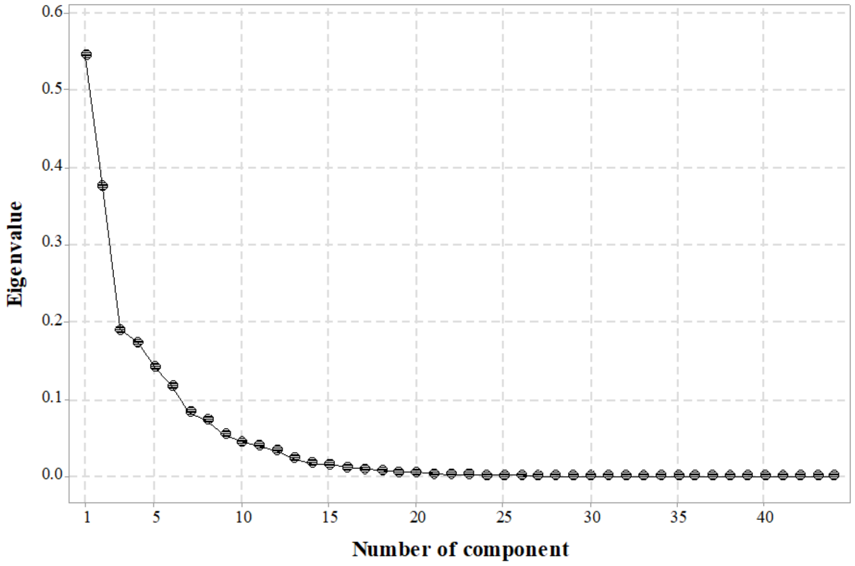

*Figure 28.* Data scree plot (Fuentes et al., 2021)

The first two principal components, named PC1 and PC2 and which account for 46.8% of the total variance in the data, are presented in Table 16, jointly with the PSIx variables and the corresponding factorial loads or eigenvectors. The load values higher than 0.25 are highlighted, as they are considered significant for each component.

**Table 16**
*Eigenvectors of the first two principal components* (Fuentes et al., 2021)

| Variable | PC1 | PC2 | Variable | PC1 | PC2 | Variable | PC1 | PC2 | Variable | PC1 | PC2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A1.1 | **0.27** | **0.44** | I1.2 | -0.13 | 0.16 | EC2.2 | 0.04 | -0.03 | EN1.2 | **-0.28** | 0.16 |
| A1.2 | **0.29** | **0.36** | I1.3 | -0.01 | 0.08 | EC2.3 | 0.01 | -0.01 | EN2.1 | 0.00 | 0.00 |
| A1.3 | 0.08 | **0.46** | I2.1 | -0.05 | -0.04 | EC2.4 | -0.06 | 0.11 | EN2.2 | -0.07 | 0.03 |
| A2.1 | -0.15 | 0.12 | I2.2 | -0.12 | 0.07 | EC3.1 | 0.00 | 0.00 | G1.1 | 0.04 | 0.05 |
| A2.2 | -0.15 | 0.11 | I2.3 | 0.00 | 0.05 | EC3.2 | 0.03 | 0.04 | G1.2 | 0.02 | -0.12 |
| A3.1 | 0.04 | -0.01 | I3.1 | 0.00 | 0.00 | EC3.3 | 0.01 | 0.06 | G1.3 | -0.03 | 0.03 |
| A3.2 | **-0.32** | 0.09 | I3.2 | **0.29** | **0.43** | EC3.4 | 0.02 | -0.11 | G2.1 | -0.01 | 0.04 |
| A3.3 | **-0.24** | 0.07 | I3.3 | 0.00 | 0.00 | EC3.5 | 0.07 | 0.02 | G2.2 | -0.04 | 0.02 |
| A4.1 | 0.03 | -0.01 | I3.4 | **-0.52** | **0.27** | EC3.6 | 0.00 | 0.00 | R1.1 | 0.01 | 0.05 |
| A4.2 | -0.09 | 0.04 | EC1.1 | 0.05 | -0.07 | EC3.7 | 0.00 | 0.00 | R1.2 | 0.00 | 0.05 |
| I1.1 | -0.01 | 0.04 | EC2.1 | 0.02 | -0.07 | EN1.1 | **-0.38** | 0.18 | R2.1 | 0.00 | 0.00 |

To picture these results graphically, Figure 29 is shows the loading plot of the data:

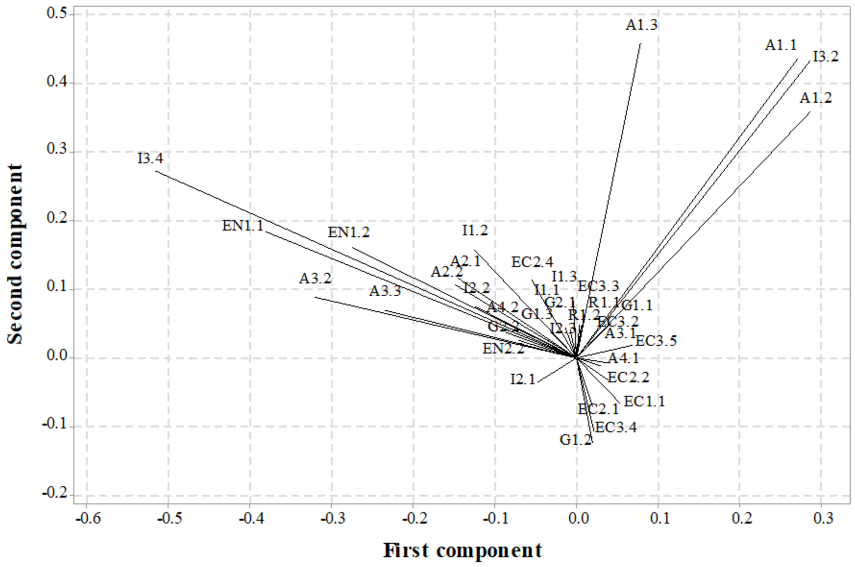

*Figure 29.* Loading plot for the first two principal components (Fuentes et al., 2021)

PC1 has a large positive influence of loads coming from variables belonging to the availability dimension, particularly A1.1 and A1.2, which measure reserves-to-production ratios of oil and gas fuels, respectively. Therefore, it can be inferred that this component is an indicator related the availability of energy sources. On the contrary, indicators I3.4 of international electrical interconnections, and availability indicators related to the diversification of sources have a strong negative load in the component. It can be deduced that while the larger the ratio of production of fossil fuels compared to the reserves, the lower the diversification of other sources of energy. By its part, PC2 has a considerable load of values corresponding to the infrastructure dimension, jointly with other availability indicators.

### 7.1.4. Weighting and aggregation

Despite the fact that the relative importance of different indicators for sustainable energy development vary from country to country, depending on country-specific conditions, national energy priorities, sustainability development criteria and their inherent objectives (International Atomic Energy Agency, 2005), it is necessary to establish a groundwork that assigns weights as importance coefficients to the indicators of the PSIx, so the analyzed countries can be evaluated, compared and ranked within a common framework.

A data-driven approach has been determined for assigning weights to the PSIx indicators. For that aim, the outcomes obtained through the principal component analysis in section 7.1.3, result highly advantageous, since they offer a statistical approach for comparing the variables of the index and, since a large amount of data is being analyzed, the risk of double-weighting the indicators of the index is avoided (Gan et al., 2017).

From the correlation matrix, also presented in section 7.1.3, new intermediate composites have been obtained by selecting the indicator with the highest correlation to each significant factor, whose value is expressed by:

$$\widetilde{w}_j = arg \max_i \left( \frac{a_{ij}^2}{\sum_{k=1}^{m} a_{ik}^2} \right) \tag{44}$$

In which:

j $= 1, \dots, m$: index indicators

$i$: analyzed country

$a_{ij}$: factor load for country $i$ of $j$ indicator

Therefore, the weight of each $j$th variable is obtained as follows:

$$w_j = \frac{\tilde{w}_j \left( \frac{\sum_{k=1}^{m} a_{ik}^2}{\sum_{j=1}^{m-q} \sum_{k=1}^{m} a_{ik}^2} \right)}{\sum_{j=1}^{m} \tilde{w}_j \left( \frac{\sum_{k=1}^{m} a_{ik}^2}{\sum_{j=1}^{m-q} \sum_{k=1}^{m} a_{ik}^2} \right)} \tag{45}$$

In which $q$ is the last significant factor to be considered for the analysis according to the scope described in section 7.1.3.

Table 17 shows the weights assigned to each indicator of the index according to the described methodology. As a result of such procedure, several indicators lack of a significant value, with only 18 variables being considered as significant. Furthermore, from the original six dimensions of the index, only three result of statistical interest, which are Availability, Infrastructure and Economy, summarizing a weight of 0.24, 0.44 and 0.32, respectively.

**Table 17**
*Weights assigned to each indicator* (Fuentes et al., 2021)

| Dimension | Variable | Domain weight | Weight of the respective factor | Weight score (ωi) | Resulting weight (Σωi=1) | Dimension weight (Σωi=1) |
|---|---|---|---|---|---|---|
| Availability | A1.1 | 0.1247 | 0.0040 | 0.0005 | 0.0024 | 0.24 |
| | A1.2 | 0.3407 | 0.0370 | 0.0126 | 0.0604 | |
| | A1.3 | 0.2108 | 0.0910 | 0.0192 | 0.0918 | |
| | A3.1 | 0.1339 | 0.0020 | 0.0003 | 0.0013 | |
| | A3.2 | 0.2381 | 0.0710 | 0.0169 | 0.0809 | |
| Infrastructure | I2.1 | 0.1902 | 0.0010 | 0.0002 | 0.0009 | 0.44 |
| | I2.3 | 0.2634 | 0.0010 | 0.0003 | 0.0013 | |
| | I3.2 | 0.1964 | 0.0220 | 0.0043 | 0.0207 | |
| | I3.4 | 0.2664 | 0.2770 | 0.0874 | 0.4187 | |
| | | 0.2277 | 0.0600 | | | |
| Economy | EC1.1 | 0.1822 | 0.0170 | 0.0031 | 0.0148 | 0.32 |
| | EC2.1 | 0.2477 | 0.0710 | 0.0176 | 0.0842 | |
| | EC2.2 | 0.3906 | 0.0420 | 0.0164 | 0.0786 | |
| | EC2.3 | 0.2854 | 0.0080 | 0.0023 | 0.0109 | |
| | EC2.4 | 0.2246 | 0.0270 | 0.0061 | 0.0290 | |
| | EC3.2 | 0.1747 | 0.0050 | 0.0009 | 0.0044 | |
| | | 0.0180 | 0.0030 | | | |
| | EC3.3 | 0.5825 | 0.0170 | 0.0099 | 0.0474 | |
| | EC3.4 | 0.3893 | 0.0200 | 0.0078 | 0.0373 | |
| | EC3.5 | 0.5186 | 0.0060 | 0.0031 | 0.0149 | |

While it is true that, according to the impossibility theorem of (Arrow, 1963), there does not exist a perfect aggregation method, it is necessary design a frame that fits the needs of the desired scope for the PSIx application. In this process, the utilization of rules implying additive or multiplicative principles, i.e. linear or geometric aggregation methods, could be possible. Even though, the use of any of these techniques implies that weights become able to be substituted by themselves, meaning that a poor development on one variable might be compensated by an over standing development in another one. The compensability property leads linear and geometric aggregation methods to minimize the importance of the associated indicators. It is, thus, necessary the use of a method which does not allow or restrain compensability according to the scope of the built index.

As stated by (OECD, 2008; Podinovskii, 1994), for weights to be construed as importance coefficients, a non-compensatory frame must be adopted in the aggregation process. The non-compensatory multi-criteria approach (MCA), is the selected method, since it restrains compensability by setting arrangements between two or more legitimate goals.

The elasticity of substitution between indicators $j$ and $j'$, understood, according to (Decancq & Lugo, 2012), as how much one variable has to give up of one achievement to get an extra unit of a second indicator while keeping the level of energy security, is expressed by:

$$\delta_{jj'} = \frac{1}{(1-\beta)} \tag{46}$$

From this expression, it is noticeable that the smaller the value of $\beta$, the smaller the allowed substitutability between indicators. Depending on if the values correspond to the same dimension or not, the value of $\beta$ is considered distinctly in the aggregation process. For intra-dimensional indicators, the value assigned to $\beta$ is set to 1, therefore $\delta \rightarrow \infty$, meaning that all the indicators of one particular dimension are completely substitutable with each other. On the other hand, it is desired that the possibility of substitutions among indicators of different dimensions is zero, so $\beta$ is set to $-\infty$ and the elasticity of substitution $\delta$ is null.

With the purpose of assigning scores to each dimension, the one-digit classification, shown in Table 18, has been established:

**Table 18**
*Dimensions grading system* (Fuentes et al., 2021)

| Performance | Grade |
|---|---|
| X > 90 | 1 |
| 80 ≤X< 90 | 2 |
| 70 ≤ X< 80 | 3 |
| 60 ≤ X< 70 | 4 |
| 50 ≤ X< 60 | 5 |
| 40 ≤ X< 50 | 6 |
| 30 ≤ X< 40 | 7 |
| 20 ≤ X< 30 | 8 |
| 10 ≤ X< 20 | 9 |
| X< 10 | 0 |

The score on each dimension is determined by evaluating the development of each individual country. Since there is no inter-dimensional substitutability, there will be a grade for each relevant dimension within the index.

## 7.2. Results

From section 7.1.3 and with most of the variance in the data gathered, the score plot, shown in Figure 30, allows to cluster the analyzed countries depending on their results. It can be observed that all the big economies in the continent, the A group according to the classification presented in section 7.1.1, are located in the upper part of the graph, deducing, therefore, that their infrastructure is more developed than other countries, compared, for instance, with the case of the Caribbean countries and the Guianas. By their part, Central American countries can be easily grouped due to their closeness in the plot; hence, their energy security, according to the first two principal components, can be considered to be very alike to each other. The plot shows that the geographical location of the covered countries does have a strong influence on the development of their power systems, as well as the size of the respective economies.

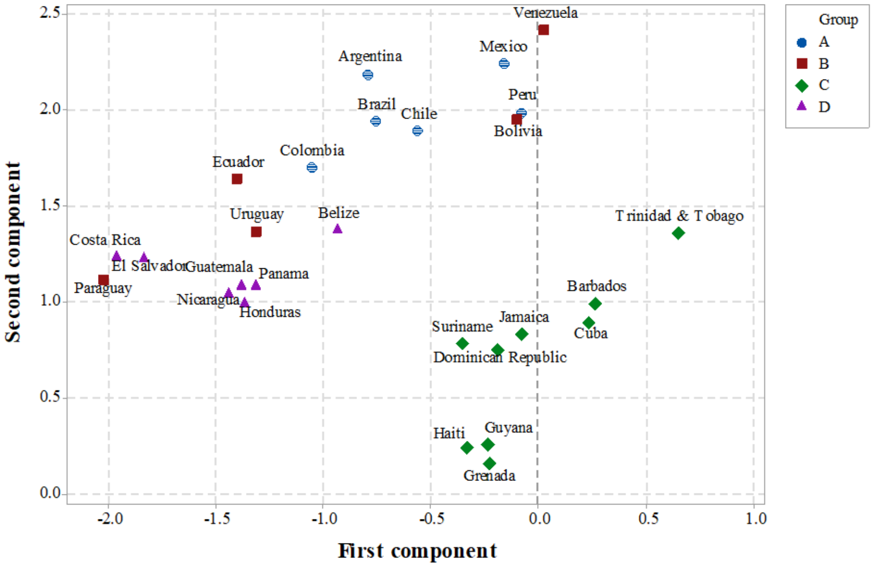

*Figure 30.* Score plot of the first two components (Fuentes et al., 2021)

The resulting outcomes from the evaluation of countries in the Latin America and the Caribbean region, are summarized in Table 19, where the results of each dimension are shown, as well as the overall score of the index. The score of each country is determined by the multiplication of the performance on each dimension times its respective weight, as indicated in Table 18.

**Table 19**
*Resulting scores of the composed index for countries of Latin American and the Caribbean* (Fuentes et al., 2021)

| | | **A** | **I** | **EC** | **Score** | | | **A** | **I** | **EC** | **Score** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st | Argentina | 3 | 1 | 0 | 0.67 | 15th | Mexico | 5 | 5 | 0 | 0.40 |
| 2nd | Ecuador | 7 | 1 | 0 | 0.58 | 16th | Venezuela | 4 | 7 | 0 | 0.33 |
| 3rd | Costa Rica | 8 | 1 | 8 | 0.55 | 17th | Peru | 8 | 8 | 8 | 0.24 |
| 4th | El Salvador | 7 | 1 | 0 | 0.54 | 18th | Brazil | 5 | 0 | 0 | 0.24 |
| 5th | Paraguay | 7 | 1 | 0 | 0.54 | 19th | Trinidad & Tobago | 8 | 0 | 8 | 0.15 |
| 6th | Colombia | 7 | 1 | 0 | 0.54 | 20th | Cuba | 8 | 0 | 8 | 0.15 |
| 7th | Panama | 0 | 1 | 8 | 0.50 | 21st | Barbados | 0 | 0 | 8 | 0.13 |
| 8th | Nicaragua | 0 | 1 | 0 | 0.49 | 22nd | Grenada | 0 | 0 | 8 | 0.07 |
| 9th | Bolivia | 8 | 2 | 0 | 0.49 | 23rd | Guyana | 0 | 0 | 8 | 0.07 |
| 10th | Uruguay | 0 | 1 | 0 | 0.48 | 24th | Suriname | 0 | 0 | 0 | 0.06 |
| 11th | Honduras | 0 | 1 | 0 | 0.47 | 25th | Dominican Republic | 0 | 0 | 0 | 0.04 |
| 12th | Guatemala | 0 | 1 | 0 | 0.47 | 26th | Jamaica | 0 | 0 | 0 | 0.04 |
| 13th | Chile | 6 | 4 | 8 | 0.45 | 27th | Haiti | 0 | 0 | 0 | 0.03 |
| 14th | Belize | 0 | 1 | 0 | 0.44 | | | | | | |

It can be observed that the countries within the region have mixed values in their energy security performance. The country with the highest overall score is Argentina, mainly due to its performance on infrastructure and availability dimensions, and despite the fact that it does not have an outstanding development in the economic dimension. Indeed, the country has very important reserves of fossil fuels, it has a noticeable energy self-sufficiency and, additionally, its electrical interconnections provide an important flexibility capacity to the Argentinean power system. On the other hand, Haiti is the country with more areas of improvement, being weak in all the three evaluated dimensions; the Caribbean country has no fossil fuels in its territory, has a feeble energy infrastructure and it possesses a fragile and inefficient economy.

By dimension, most of the studied countries have an improvable behavior in availability, with Venezuela, Argentina, Brazil and Mexico being the countries best positioned, in this order. In infrastructure, the gap among countries with relatively good energy infrastructure and those lacking of it is deep, with Argentina, Colombia, Ecuador, Paraguay, Uruguay and the Central American nations as the best performers in this dimension. By its part, no country has shown an outstanding performance in the economic dimension, on the contrary, most of them have a mediocre behavior; Barbados, Chile, Costa Rica, Cuba, Grenada, Guyana, Panama, Peru and Trinidad and Tobago are the countries that performed the best in this dimension.

# 8. Conclusions

Energy transitions are reshaping the global energy system. Despite the fact that every single country determines its own transition according to its own possibilities, needs and interests, some measures are extensive to transitions of all regions of the planet, such as the decarbonization of the energy system, performed throug3h the expansion of renewable sources and improvements on energy efficiency. Energy transitions have taken the power sector to become a center piece of modern infrastructures in general and of energy systems in particular. Electrification of energy systems has hence become a priority in the international energy agenda and, therefore, guaranteeing a secure electrical energy supply is crucial for guaranteeing sustainable development.

Due to the diversity of policies aimed to enhance energy security, and with the aim of helping policy makers in their task of issuing strategies focused in reaching sustainable development, an evaluation tool, based in a composite indicator has been developed through the present thesis. The tool, called PSIx, allows the assessment of energy security in the power system from a multidimensional approach; the dimensions that conform this approach are namely, availability, infrastructure, economy, environment, government and R+D+i. These dimensions, to which several indicators are assigned and are, in turn, grouped into different categories, allow the identification of areas in which the country, or series of countries, in question develop adequately and in which areas there exists room for improvement.

PSIx is intended for two types of comparisons, i.e. the tracking of the development of a single country and the evaluation of several economies in the same reference time. Therefore, PSIx constitutes a comprehensive frame in which strategies addressed to enhance energy security in the power system can be evaluated according to their effectiveness for achieving that purpose.

Argentina, a developing economy with plenty of natural resources, albeit passing through an adverse economic situation, does perform particularly well in availability and infrastructure dimensions of the PSIx, helped by its abundant indigenous energy resources, as well as a diversified and interconnected electrical system. The economic dimension represents the weakest point of the country since, due to the contraction of the national GDP, energy productivity of the country has been harmed in several areas, while the implemented efficiency measures have not been enough to compensate this fact. By their part, governance and R+D+i are areas in which Argentina develops weakly as well, making it necessary to enhance them in order to attract financing for developing energy projects addressed to facilitate the national energy transition.

Latin America and the Caribbean is a very diverse region in energy terms, in which countries range from possessing some of the largest fossil fuel reserves in the world, to others with a large-scale energy poverty. The analysis of their strategies on how efficient they are for procuring energy security results, hence, particularly useful for the enhancement of power systems in the continent.  Three of the six dimensions result of statistical relevance i.e. availability, infrastructure and economy. It results pertinent to notice that this does not mean that the rest of the dimensions are not important for energy security, but that variance of data among countries is explained mostly by those dimensions considered statistically significant. The evaluated countries, as expected, perform very distinctly in the relevant dimensions of the index. Countries that possess considerable fuel reservoirs have higher evaluation results in the energy availability dimension. There exists a wide division between countries with an adequate electrical infrastructure and those that lack of it, mainly due to the existence of international interconnections and the presence of gas-fueled power plants, which, additionally, are measures that greatly enhance the flexibility of the electrical network. No country presents distinguished results on the economic dimension, on the contrary, they all have rather lackluster performances. The country with the highest overall score is Argentina, followed by Ecuador and Costa Rica. The first two countries, Argentina and Ecuador, have important fossil fuels reservoirs, while Costa Rica has a completely renewable energy matrix. The case of Paraguay, occupying the fourth position in the ranking, is a net electricity exporter thanks to its large hydropower plants. These countries are very well interconnected with their neighbors, while Ecuador and Paraguay have experienced important improvements on their economies lately.

The developed multi-dimensional index constitutes a comprehensive frame in which strategies addressed to enhance energy security in the power system can be evaluated, according to their effectiveness for achieving that purpose. Through its application in both, the case of Argentina and the case of Latin America and the Caribbean, and after the subsequent statistical analysis, it can be confirmed that this tool can, through the enhancement of energy security on national energy systems, help policy makers to assess energy strategies aimed to reach sustainable development. Future work shall include the application of the index to other regions at a supranational level, in order to assess the suitability of policies aimed to improve energy security, as well as the incorporation of more indicators aimed to achieve a sustainable energy system.

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# Appendix A

## Publications

Fuentes, S.; Villafafila-Robles, R.; Rull-Duran, J.; Galceran-Arellano, S. (2021). Composed Index for the Evaluation of Energy Security in Power Systems within the Frame of Energy Transitions—The Case of Latin America and the Caribbean. Energies, 14, 2467. https://doi.org/10.3390/en14092467 [SCImago Journal Rank (SJR): 2.702 (2019)]

Fuentes, S., Villafafila-Robles, R., & Lerner, E. (2020). Composed Index for the Evaluation of the Energy Security of Power Systems: Application to the Case of Argentina. Energies, 13(15), 3998. https://doi.org/10.3390/en13153998 [SCImago Journal Rank (SJR): 2.702 (2019)]

Fuentes, S., Villafafila-Robles, R., & Olivella-Rosell, P. (2019). International Tendencies on Energy Security: A review on National Energy Policies in the Electrical Sector. EnerLAC, III (1). Retrieved from http://enerlac.olade.org/index.php/ENERLAC/article/view/75/77

Fuentes, S., Villafafila-Robles, R., Olivella-Rosell, P., Rull-Duran, J., & Galceran-Arellano, S. (2020). Transition to a greener Power Sector: Four different scopes on energy security. Renewable Energy Focus, 33. https://doi.org/10.1016/j.ref.2020.03.001

[SCImago Journal Rank (SJR): 0.483 (2019)]

# Appendix B

## Attended conferences

- Berlin Energy Transition Dialogue. Federal Government of Germany. Berlin, Germany (2017).
- Berlin Energy Transition Dialogue. Federal Government of Germany. Berlin, Germany (2018).
- III Semana de la Energía. Latin American Energy Organization, Inter-American Development Bank, Ministry of Energy and Mining of Uruguay. Montevideo, Uruguay (2018).
- Berlin Energy Transition Dialogue. Federal Government of Germany. Berlin, Germany (2019).