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Smart Energy Planning in the Midst of a Technological and Political Change towards a 100% Renewable System in Mexico by 2050

Daniel Icaza-Alvarez [1,2,*], Nestor Daniel Galan-Hernandez [3], Eber Enrique Orozco-Guillen [3] and Francisco Jurado [1]

1 Department of Electrical Engineering, University of Jaen, 23700 Linares, Spain; fjurado@ujaen.es
2 GIRVyP Group Reserch, Faculty of Electrical Engineering, Catholic University of Cuenca, Cuenca 010111, Ecuador
3 Department of Energy Engineering, Polytechnic University of Sinaloa, Mazatlán 82199, Mexico; ngalan@upsin.edu.mx (N.D.G.-H.); eorozco@upsin.edu.mx (E.E.O.-G.)
* Correspondence: dicazaa@ucacue.edu.ec

Abstract: This study presents a 100% renewable and diversified system taking advantage of the available energy potential of renewable energies in Mexico with a view to a planned energy transition in cooperation with the environment. The processes of change that are experienced worldwide in favor of the planet make us reflect and propose alternatives that break traditional schemes in the production of energy (for which reason Mexico cannot deviate from its current model). It is here that this research becomes a transcendental and important reference for decision-making and the transformation of the energy sector in Mexico. The current electrical system relies on fossil fuels that need to be replaced by renewable energy sources (and it is necessary to satisfy growing demands in the long term). The methodological process is carried out with the use of the 100% renewable energy market design tool EnergyPLAN, which puts the concept of intelligent energy into practice by 2050. Finally, after analyzing the results, it is concluded that a good energy mix for 2050 is 30% solar photovoltaic, 25% wind, 14.5% hydraulic, 13.8% CSP plants, and 16.7% other technologies. Surpluses may be sold to the United States and Central America through interconnection points.

Keywords: EnergyPLAN; renewable energy; clean energy; smart energy system; energy planning

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1. Introduction

Climate change is currently approached with deep concern as it is considered a global problem that has multiple consequences, leading in particular to environmental deterioration and altering people's health due to the emission of carbon dioxide (CO_2) emissions into the atmosphere. Among the most relevant aspects that the study focuses on at the present time is the search for alternatives for the production of electrical energy that avoid negative effects on the environment (i.e., leaving aside the use of fossil fuels) [1]. Most countries, aware of the current problems in which we are all immersed and threatened, have considered studying mechanisms that promote sustainability in electrical energy production systems and progressively abandoning the use of petroleum derivatives [2]. Many countries even see an option to leave crude oil on land as a clear and direct manifestation of responsible decision making to protect sensitive ecosystems [3]. Currently there are many renewable technologies that take advantage of the meteorological conditions of the territory itself and properly generate energy in accordance with the concern of supplying energy in an environmentally responsible manner (and above all offering accessibility to most of the populations at low costs) [4]. The renewable energy sources experiencing impressive development lately and that have been well received by multiple countries are wind power and solar photovoltaic sources [5]. There are still others that are about to take off in smaller proportions and are not it loses sight of biomass, tidal power, and green hydrogen, among others, which at any given time can achieve relevance [6].

Just as there are countries that are undergoing a clear energy transition and moving towards a sustainable energy system, there are also countries that have difficulties even accessing energy (as is the case of Haiti) [7]. In some cases, this understandable due to the poor economy of the country in question. However, if at least one country does not start with a policy framework that is geared towards change and begins to design energy models that promote the transformation of their own markets with new technologies, they would be putting future generations at risk and staying with technologies that are obsolete. In the end, they would become recipients of technological scrap and territories with high levels of contamination [8]. In this sense, it is suggested that countries that maintain systems powered by fossil fuels can start their renewal processes and avoid social inequalities. Latin America itself, despite the fact that they pollute the least worldwide, have made efforts in many cases, and despite their weak economies, to proactive with strong actions in favor of life on the planet [9]. The reality is that oil is in decline, as it has resulted in significant social inequalities [10]. It is imperative now to draw up roadmaps for energy use under much more hopeful schemes for such countries [11]. With this, polluting energy systems cannot be ruled out outright since there is a social responsibility to their current workers. They must begin with adequate training so that when these historically polluting systems stop operating, new growth options are provided in cooperation with other more environmentally friendly systems.

The IEA in its recent research has revealed the impact that each outlined scenario can achieve with reference to the years 2030 and 2050. The 'Announced Commitments Scenario' (APS) sees a doubling in clean energy financing over the next decade. However, this acceleration is not enough to overcome the inertia of the currently structured energy system. 2030 is a crucial period, but so far the actions taken so far in this scenario are well below the emission reductions that would be required to achieve Net Zero Emissions by 2050 (NZE). One of the key reasons for this shortfall is that today's climate commitments, as reflected in the APS, reveal stark divergences between countries in the speeds of their energy transitions. In reality, all countries will need to make greater efforts to align their roadmaps to the promised goal and strengthen their targets for 2030. It is necessary to intensify a collaborative global transition in which no one is left behind. Unfortunately, the differences between the results in the APS and the NZE are substantial, which in many cases implies greater investment in their internal transition processes and reaching net zero worldwide by mid-century. This can be seen below in Figure 1.

In Mexico, greater environmental awareness has been achieved overall. However, it is necessary to unify efforts between the legislature and the executive of its government in order to propose solutions that are framed to decarbonize the energy sector with policies and laws that adjust to the specific needs of Mexico [12]. On the other hand, it is important that larger budgets are included for these purposes of improving air quality. Pollution is an evil that has been carried over for many years and is the source of adverse health conditions, in addition to other ills such as traffic congestion and poor working conditions [13]. Most of the electricity that is generated comes from a 'dirty' source [14]. However, the electrical reform proposed by President Andrés Manuel López Obrador and approved in Congress put on the table a reality for better energy production [15]. A report from the Ministry of Energy (Sender) details that during the first ten months of 2020, 75% of the energy available in the country was produced in power plants burning fossil fuels. In 2017, fossil fuels (oil, gas and coal) represented 93% of the total primary energy consumed in Mexico, although the share of renewables has been increasing at an average rate of more than 9% over the last 10 years [16]. Unfortunately, at the level of Mexico and other countries dependent on fossil fuels, it is difficult to reach a consensus on a road map for decarbonization [17]. The barriers to the expansion of renewable energies prevent the development of countries and regions [18]; in this case the modernization of the energy system is difficult. Several innovative planning schemes are notable references, including those carried out in the

European Union [19], Japan [20], South Africa [21], and Australia [22], among others. Under this necessary perspective of offering options to transform the current Mexican energy market, he was motivated to carry out this research and draw up a long-term roadmap [23]. There is an awareness that concrete policies and actions are required to achieve decarbonization and that in some passages of time it requires austerity and putting this priority objective for the country in the foreground. It is well known that the task is arduous, but it is necessary to outline it so that decision makers such as legislators, energy advisors, researchers, and businessmen can discuss it [24]. This is the reason for deep analysis regarding their budgets, growing electricity demands, and social evolutionary processes. In the midst of this, one must not lose sight of the fact that a 100% renewable energy mix is needed by 2050 [25].

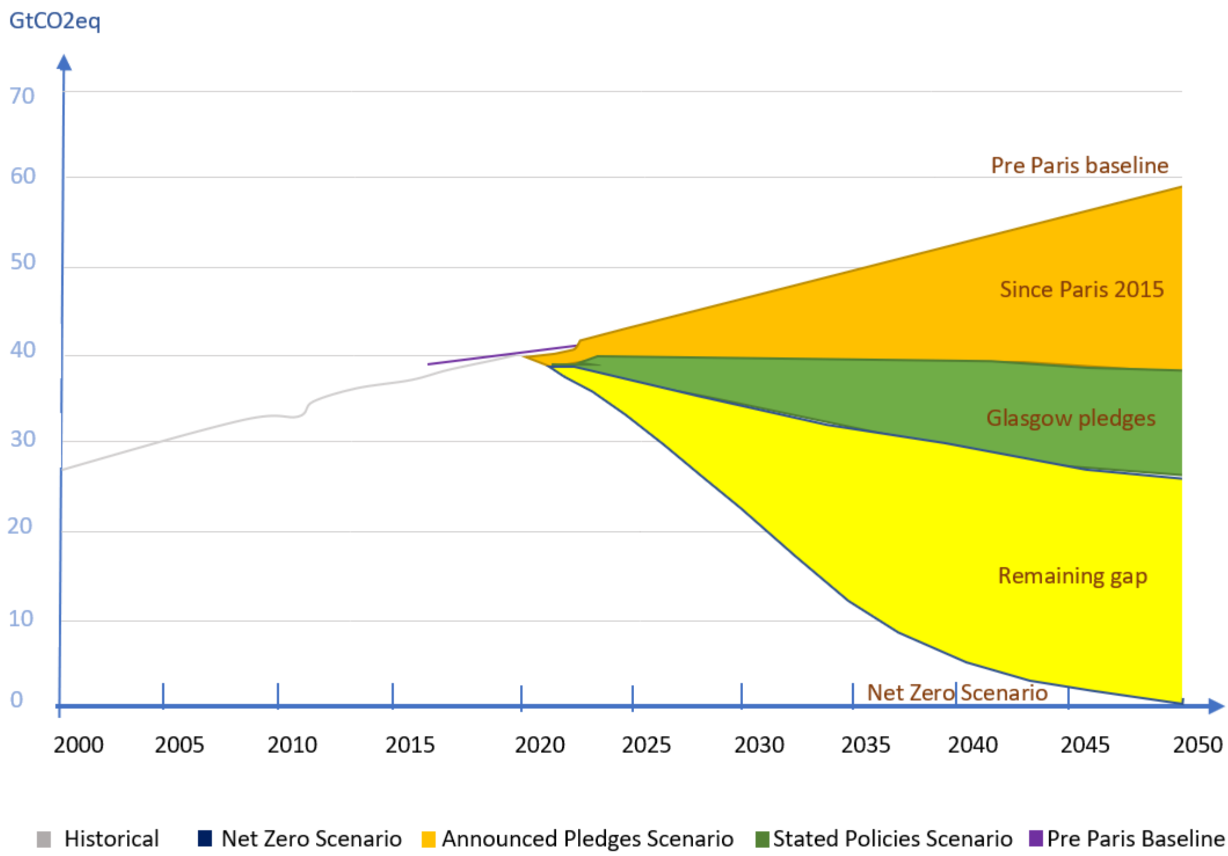

Figure 1. Global emissions by scenario, 2020–2050.

In Mexican territories, energy technologies of renewable origin have a high viability as a result of the fact that the country is rich in natural resources [26]. The different territorial distribution of resources allows for regionalized development (i.e., solar to the north, geothermal to the center, and wind to the south) and are strategically distributed and used in high proportions to achieve an orderly energy transition. According to the National Inventory of Renewable Energy (Iner), the energy sources with the greatest potential are solar and wind [27]. Among the key factors to make a roadmap viable are the political aspect, cost reduction and technological development. The insertion of renewables in the energy matrix has been achieved through the production of electricity [28]. However, today natural gas is gaining relevance due to its low cost and the fact that it is less polluting than other hydrocarbons. In Mexico, its importance has increased: from 2002 to 2022 its participation went from 29 to 55% in the generation of electricity, which contrasts with energy taken from renewable sources [29].

The purpose of this current study is to provide a roadmap to implement the energy transition process with 100% renewable energy by 2050. This analysis evaluates the renewable energy potentials available in Mexico, which mainly include wind, solar photovoltaic and the typical hydraulic, among others of lesser proportion but important to diversify the Mexican energy mix. It must be considered that the Mexican energy sector develops in the midst of changing legislation and a framework of developing policies. In a way, it requires caution when designing energy transition scenarios, and precisely here there are research gaps that need to be considered. Several key questions will be answered to help determine the importance of the energy transition in Mexico.

- To what extent are wind and photovoltaic solar energy used directly?
- How much do renewable technologies contribute to future growing energy demand?
- What is the amount of energy coming from fossil fuels?
- What is the amount of renewable energy that must be incorporated until 2050?
- What other technologies of renewable origin are called to integrate the energy mix?

1.1. Literature Review and State of the Art

Planning at the macro level is carried out from the highest levels of government in cooperation with different sectors involved in each country with the purpose of changing the energy matrix specifically based on renewable energies and leaving aside polluting fossil fuels [30]. However, what is interesting is that when the policies are well established and the technologies meet the needs at the macro level, this feeling is transferred to the micro level (that is, the communities and small sectors of the population also seek to embrace these technologies to meet your needs or simply to replace them with the usual ones) [31]. In reality, achieving this level of trust has not been easy. In fact, there is still a good part of the population that is still waiting to accept or not the new renewable generation technologies. Several countries are including new energy systems such as wind and solar photovoltaic, production costs tend to drop [32]. To identify if these technologies achieve a positive impact regarding climate change, some methodologies have been created to assess the resilience of places and systems and have been widely analyzed, among which the most prominent is a German case study [33]. This study has generated an important socioeconomic impact. Specifically, various business opportunities have been created with renewable energy systems. Germany is a pioneer in RES deployment and has ambitious goals for the future. KH Lee et al. [34] also presented a preliminary approach to determine the optimal size of renewable energy resources in buildings using RETScreen.

C Li et al. [35] conducted a comparative technical and economic study of grid-connected photovoltaic power systems in five climatic zones of China. The results in this study determined that for grid/PV systems, Kunming is the most economical with the lowest NPC ($113,382) and COE ($0.073/kWh). From an economic and environmental perspective, Kunming, with its mild climatic conditions, may be particularly suitable for photovoltaic/grid power generation. Eugene Kozlovski and Umar Bawah [36] evaluated the financial decision support framework for evaluating renewable energy infrastructure in developing economies. In his proposal, he incorporates the financial evaluation of hydroelectric, wind, and solar energy infrastructures. It is formulated and applied to the country of Ghana with an approach for the optimal choice of renewable energy deployment in a specific developing region. Pedro Faria and Zita Vale [37] analyzed the demand response in the supply of electricity with an optimal approach to pricing in real time. For the analysis they used DemSi, which is a demand response simulator that allows for the study of actions and demand response schemes in distribution networks. Finally, they carried out the technical validation of the solution through realistic network simulation based on PSCAD. The burden reduction is obtained using a consumer-focused price elasticity approach supported by real-time pricing.

In the last ten years, scientists and researchers from different parts of the world have focused on energy analysis 100% renewable [38]. Different strategies have been proposed to achieve complete systems that include variable renewable energies. Roadmaps have been drawn up in markets in different parts of the world, including countries such as Spain [39], Japan [20], Sweden [40], United Kingdom [41], Australia [22], Ecuador [3], Brazil [42], Denmark [43] and Portugal [44]. Connolly et al. [19] went further in his analysis and presented a scenario for achieve 100% renewable energy in the European Union by 2050. The energy potential of renewable resources in the territory was analyzed in each of the proposals, the current market was evaluated and served as a base year to draw up the long-term scenarios. Menapace et al. [45] used EnergyPLAN to design the future energy market as a route for the transition of France's energy system to achieve 100% renewable energy. The different studies that involve energy markets completely designed with renewable energies show that it is possible carry out a diversified and 100% renewable energy supply, and this has motivated researchers to carry out different studies in different territories, including islands as presented [46]. Paul Arevalo et al. [47] structured an energy system using EnergyPLAN where the different economic and long-term impact scenarios are analyzed with the diversification of renewable sources for sensitive environments such as the Galapagos Islands. The future decarbonized energy was also analyzed for China for the years 2030 and 2050 and the progress of the scenarios, the participation rate of renewables, and the growing demand for energy were identified [48].

Other investigations have also focused on designing 100% RES energy markets of regional order that involve extensive areas of territory and the energy potential of the entire area is evaluated [49]. For this purpose, cartography has been used where the energy potential by source is identified part by part and discriminates the protected areas that have despite being energetically usable by the order or legislation does not allow it [10]. The feasibility of structuring 100% RES systems destined for much smaller areas where it is not possible to diversify their energy sources such as islands, cities, or remote communities are also the subject of exhaustive analysis [50]. Among their results it has been identified that several energy systems are able to consolidate thanks to the high percentages of wind and solar photovoltaic energy sources [38]. The results of various studies of this nature have been designed with specialized software such as LUT [51], EnergyPLAN [52], LEAP [53], Message [54], MATPLAN [55], among others [56]. All of them have been of immense contribution to outline the scenarios in the medium and long term. Denmark has achieved a great deployment of renewable energy, and is one of countries that serves as an example for promoting the application of sustainable energy [57]. The transition of cities in various social aspects and physical structures are the subject of comprehensive analysis. In addition, 100% RES systems are studied with greater interest today and seek long-term projection in Ref. [58]. There is an interesting methodology proposed by Ilhami Colak [59] for the design of smart cities where next-generation communication systems and artificial intelligence are integrated with energy systems [60]. Other researchers such as M. Mastoi [61] go even further and analyze the fusion of vehicle systems to the great information network and the electrical system and among their results the needs to look for user behavior patterns are specified in order to supply energy from a more organized way in a city that is growing at an accelerated rate.

One of the latest investigations provided by Jacobson et al. [62] in which the development of roadmaps for the transition of 53 towns and cities in United States, Canada and Mexico to 100% renewable energy is discussed is one of the most outstanding examples of interest. The results obtained showed that the fuel costs of the electricity sector may be reduced by $133/person/year. Another important aspect that would be achieved as an impact of renewable energy systems in the long term is the improvement of air quality in the atmosphere. Vidal-Amaro and Sheinbaum-Pardo [63] proposed long-term schemes for the production of electricity based on renewable energy in Mexico. Its methodology is designed where each transition step corresponds to the optimal energy mix for each of the target years. The results indicate that to achieve a 100% RES-based electrical system, the forecast 70 GW of capacity must be replaced by a renewable energy source such as bioenergy, hydroelectric dam, or CSP.

The development of renewable energies is visible and is beginning to have an important deployment throughout the world [64] with few exceptions, and Mexico is in that line of welcoming these clean technologies [65]. Since the early years of this century, wind farms have already been operating in Mexico, especially in the area of the Isthmus of Tehuantepec in the state of Oaxaca, which has extremely high energy potential [66]. The most recently implemented wind farms are being deployed in the Yucatan Peninsula [67]. Although Mexico has access from both the Gulf of Mexico and the Pacific, all of the wind farms in Mexico are inland. This opens an important possibility for study and also falls in line with a global trend to install offshore wind farms and harness energy to speed up energy transition [68]. Getting to develop wind farms in Mexico involves going through adverse circumstances and internal conflicts [69]. For example, in Yucatán, the environmental impact studies carried out for the recent wind energy project have been criticized by the majority of citizens due to their poor socialization [70]. In the Isthmus of Tehuantepec, multiple conflicts with the inhabitants have even led to some companies to abandon their projects [71]. Considering the series of conflicts that have occurred in the past, those promoted by radical environmentalists against onshore wind energy projects, one must have a good understanding of all of the most rigorous forecasts and studies before putting them into practice. On the other hand, the suitability of offshore wind systems in the Yucatan platform [72]. According to experiences in other parts of the world such as France and Spain, offshore areas generally provide more wind energy potential especially for being free of obstacles and other significant advantages of a social order. A very notorious problem in Mexico is land tenure and its legalization, which prevents collective projects from being carried out, a situation that must be legislated and favorable policies created that eliminate certain barriers that prevent the strong deployment of renewable energies (especially wind power) [73]. Although the environmental impacts on the marine area can be an aspect to study strongly and need adequate attention, the impacts of onshore wind farms are considered much more sensitive in Mexico.

Seyedfarzad Sarfarazi [74] developed a strategy for real-time pricing optimization for adding distributed generation and battery storage systems in power communities. This research highlights the use of the storage potential of battery electric vehicles (BEVs) to contribute to vehicle-to-grid (V2G) stability. In this same aspect, C Villante [75] developed a new tool for the evaluation of the expected benefits of the use of V2H charging devices in V2B construction contexts. Thus, the possible coupling of renewable energy generation and electrified mobility. In Mexico it is important to plan an energy system that is more friendly to the environment, the year 2050 is a promising reference point, and it is necessary to make efforts to support new approaches.

1.2. Research Location

Mexico is a country located at the southern tip of North America, (Figure 2). It borders the United States to the north and Guatemala and Belize to the south [76]. It has an eastern coast framed by the Gulf of Mexico, and the Caribbean Sea, which are part of the Atlantic Ocean. To the west, it has a huge coastline framed by the Pacific Ocean. Mexico shares a long northern border with the United States of America and one to the south with Guatemala and Belize. To the east it is bordered by the Gulf of Mexico and to the west by the Pacific Ocean. Approximately 85% of the country is made up of mountain ranges, plateaus and numerous valleys. The Sierra Madre Occidental and the Sierra Madre Oriental run parallel to both coasts. Among them is a vast region of valleys, plateaus and plateaus (average altitude 2000 m.a.s.l.). At the southern end of the plateau are the highest peaks in Mexico: the peak of Orizaba or Citlaltépetl, Popocatépetl and Iztaccíhuatl. The Mexican territory includes numerous islands located in its patrimonial sea, of which Guadalupe Island and the Revillagigedo archipelago stand out. The approximate area of the country is 1,964,375 km^2, which places it in fourteenth place worldwide and fifth in America, after Canada, the United States, Brazil and the Argentine Republic.

Figure 2. Geographical location of Mexico.

2. Methodology

This study presents a roadmap for the energy transition of the Mexican energy market with the purpose of progressively derailing the use of fossil fuels in energy generation processes and on the other hand increasing the percentages of penetration of renewable energies until achieving 100% by 2050. The methodology proposes three strategic phases consisting of data entry of usable energy resources in the territory, adjustment or regulation, and results. Additionally, indirect aspects are included for evaluation, such as the technological modernization of the energy structure and, in what is related to the economic aspect, services at affordable prices are included. These objectives are related to the desire to finally present the technical and economic results that satisfy the future demand for energy by 2050.

In the methodological scientific development, three fully defined phases are contemplated. The first phase consists of entering data from the current energy market and its available energy potentials. The second phase consists of calibration or adjustment, depending on indirect aspects that will surely affect the future, such as the legal structure, environmental and energy policies, among others. All of these aspects that are finally included will have an impact on the results determined in the study and the composition of the future market in Mexico for the increase in renewable systems and macro motivations that can be promoted by the governments in power to accelerate the transition. Finally, in the third phase, the results are presented in terms of installed capacity or long-term energy. The technologies and the socioeconomic results are valued according to the increasing demand for 2050 that is provided by state entities of reliable cut. Additionally, global technological development and international agreements reached at the United Nations Conference on Climate Change are considered.

Long-Term Projection Model

To evaluate the Mexican energy system in the long term, after knowing the energy potentials and determining the base year (that is, the current state in terms of data, especially installed capacity and energy production). It is decided to use the EnergyPLAN design software developed by the Aalborg University of Denmark, considered a reliable tool by different researchers to carry out this type of research regarding long-term energy systems [77]. In this sense, there are step-by-step instructions on how to correctly use the software, there are models developed for different countries on the official website (https://www.energyplan.eu/, accessed on 14 September 2023) on energy transition designs using 100% renewable energy systems under different conditions [78]. This model in its version V16.2 (Figure 3), put online since May 2022 [79] and is detailed in Figure 2. The important thing is to identify the data of the current structure to be entered. The model is easy to use and allows analysis by time jumps until reaching the time horizon (in this case study it is 2050). In the end, the results are obtained in terms of installed capacity and energy balances.

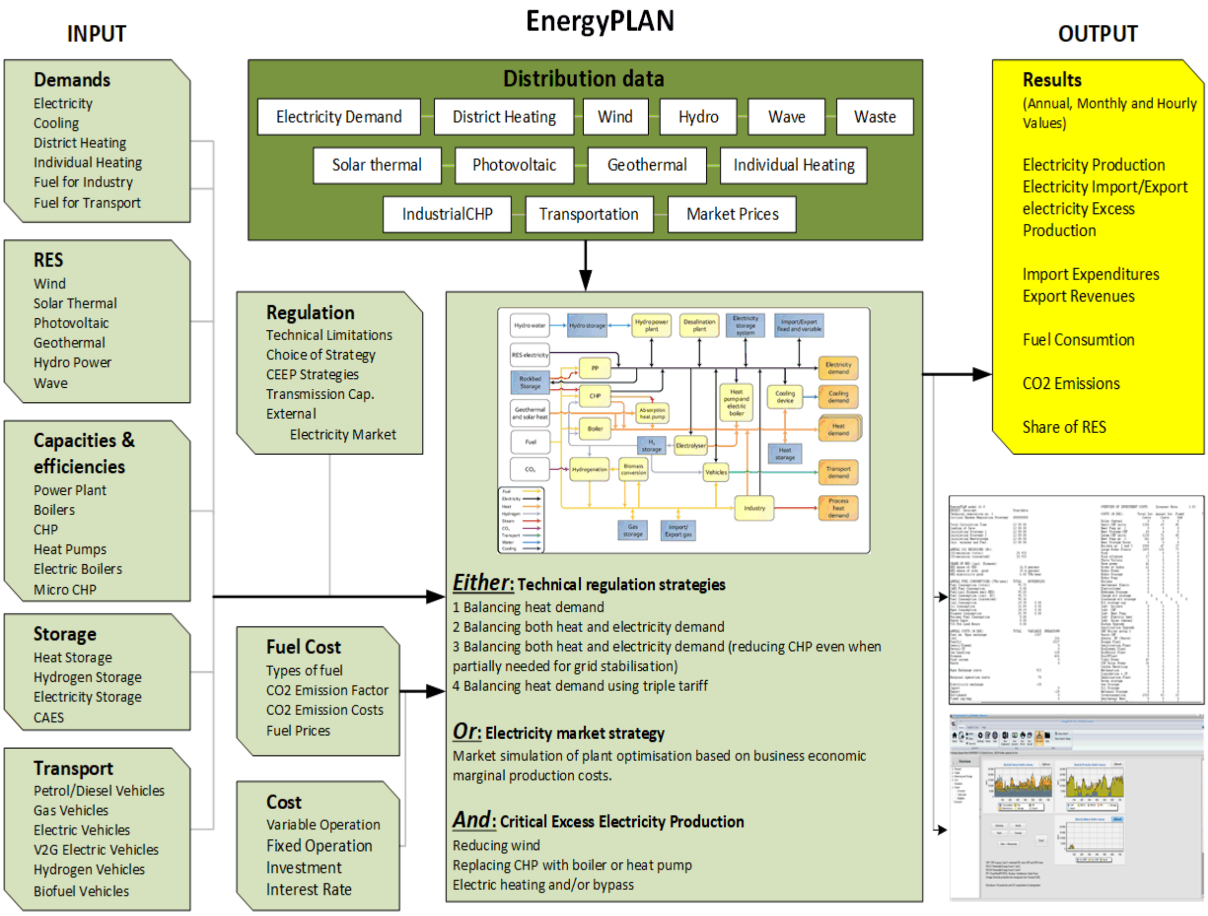

Figure 3. Analysis model for smart energy planning, EnergyPLAN V16.2. Model inspired in [77].

The principle of the energy system of the EnergyPLAN model may seem extensive, in reality it consists of only three phases.

- The input of the energy system consists of energy demands and existing energy production units or resources (wind turbines, power plants, etc.).
- Simulation (defining the simulation and operation of each plant and system including technical limitations such as transmission capacity, etc.).
- Results (Reports in terms of energy production) for the year of analysis, in this case to 2050.

3. Base Year and Its Input Parameters

Figure 4 shows the performance and evolution of the Mexican energy sector during the year 2021 and allows analysis comparisons of its main variables, with what has been observed since 1990 [80]. For the 2021 Preliminary National Energy Balance, the data on qualified supply, portage and losses have been considered for the second time non-technical electrical energy, resulting in the energy independence index, which shows the relationship between the production and national consumption of energy, were equal to 0.71 (dimensionless) presenting a growth of 4.84% compared to the previous year, going from 0.68 in 2021 to 0.71 in 2022 according to the most recent data provided by [81]. In 2022 energy consumption in the industrial sector grew 28.14% in the residential, commercial and public sectors grew by 5.25%, while that the agricultural sector increased by 5.28%.

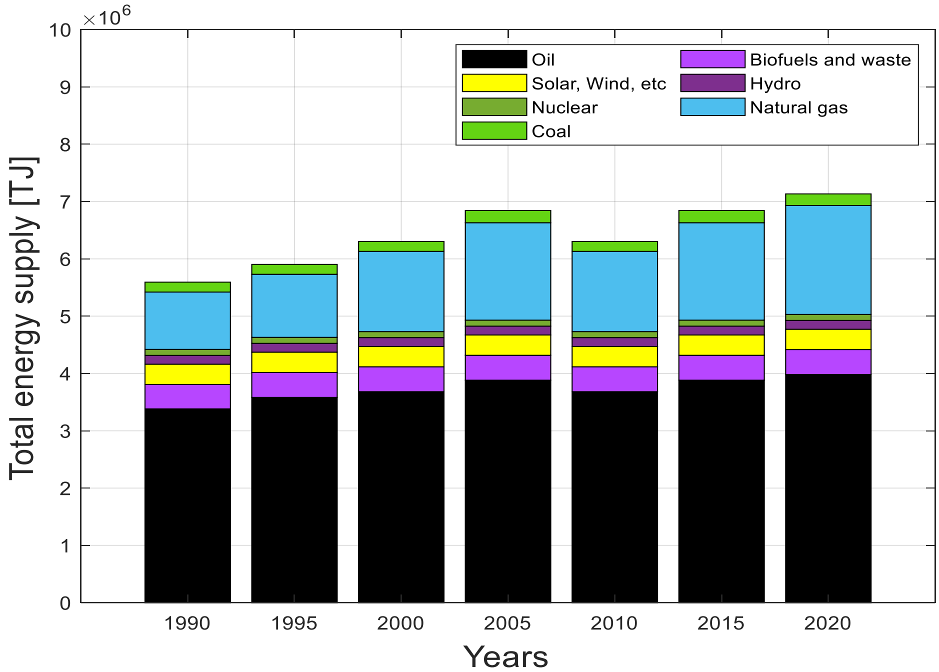

Figure 4. Historical total energy supply (TES) by source in Mexico, inspired from [80].

Mexico maintains a fairly stable economy. It has gone from presenting a high dependence on oil at the beginning of the 1990s to develop as a manufacturing center and today, it is integrated into the value chains world. Social spending and public investment have grown recently. The expansion of the tax base, through the elimination of inefficient and regressive exemptions, it would mean an increase in revenue without raising tax rates. This does not mean that the country is on a clear course towards decarbonization, in reality there is much to be developed to achieve this purpose and rather it is necessary to intensify policies and allocate greater investments in renewable energies with a better structured socialization towards all sectors.

Mexico is a country that historically appears as a net producer of primary energy, as indicated by the self-sufficiency index energy, this is due to the use especially of hydrocarbons; however, since 2004 when the maximum production of crude oil, the exploitation of this energy has declined by 3.88% annually. In 2022, energy production increased 5.47%, which is equivalent to going from 7081.42 PJ in 2021 to 7468.99 PJ in 2022 [82]. Hydrocarbons represented 80.71% of all national production, especially crude oil, which was the energy source with the highest participation in the primary energy matrix (50.98%), so any change in the behavior of hydrocarbon production, It has a great impact on the national energy matrix. In 2022 the production of crude oil decreased by 2.51%, from 3905.63 PJ (1664.71 Mbd) in 2021 to 3807.56 PJ (1622.50 Mbd) in 2022 [81]. Crude oil production is classified by its API degrees, in accordance with the provisions of the "Agreement by which the rules of general character to define the methods of adjustment of the value of the hydrocarbons of the rights on hydrocarbons".

On the other hand, 93.89% of crude oil production was from PEMEX contracts and assignments and 6.11% from exploration and extraction granted to the private initiative. The second energy source with the highest participation was natural gas, which represented 22.20% of the total production of primary energy, with 1657.94 PJ, compared to the natural gas production of the year 2021, it increased 5.17%. The third largest energy sector corresponds to the group of renewable energies, with 15.40% of the total, which grew 10.28%, going from 1042.97 PJ in 2021 to 1150.13 PJ in 2022 [81]. As in the last year, this item presents growth in solar energy, hydroenergy, wind energy, sugarcane bagasse, and geoenergy, with increases of 30.91%, 11.74%, 8.73%, 8.33%, and 6.47%, respectively. In the area of non-renewable clean energy, there is growth in the consumption of uranium at the Nuclear Power Plant of 22.23%, going from 124.99 PJ in 2021 to 152.77 PJ. Condensates were the fuel with the highest growth, since they went from 293.79 PJ in 2021 to 563.00 in 2022, equivalent to an increase of 91.63%. On the other hand, mineral coal had a growth of 0.02% compared to 2021, going from 137.56 PJ to 137.59 PJ in 2022. Below in Figure 5 you can see the levels of electricity consumption by sector in Mexico.

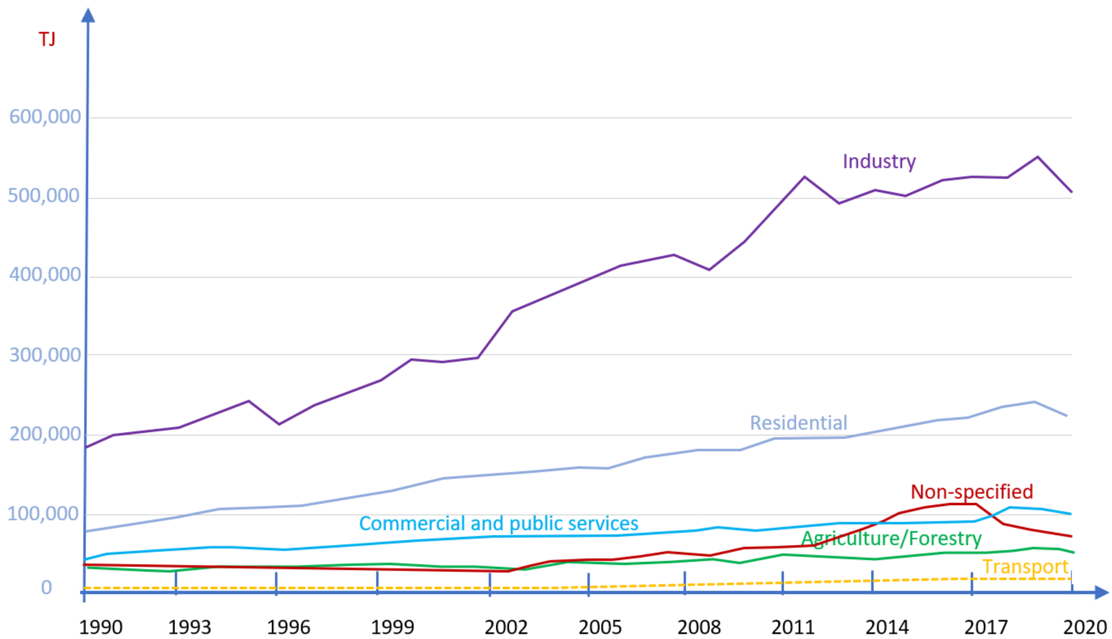

Figure 5. Electricity consumption by sector, Mexico 1990–2020. Inspired by data from [78].

Table 1 shows the historical production and consumption of electricity from 2015 to 2021 in Mexico. Analyzed the values, the generation system supplies enough energy towards the demand for electricity.

Table 1. Historical generation and final consumption of electricity in Mexico provided by ref. [83].

Year	Electricity Supply GWh	Consumption GWh	Consumption Per Capita kWh
2021	336,958	300,957	2375.30
2020	325,506	292,530	2289.10
2019	318,078	278,883	2203.30
2018	332,010	291,182	2323.40
2017	309,143	265,575	2141.00
2016	303,036	263,298	2145.60
2015	297,867	256,557	2114.20

3.1. Renewable Energy Potentials in Mexico

Around the world, billions of people and industries are demanding power 24 h a day, seven days a week. Likewise, it is known that the energy coming from the burning of fossil fuels is extremely polluting for our environment. For these reasons, it is essential to start gravitating towards technologies that do not have negative impacts on our environment.

According to the International Renewable Energy Agency (IRENA), between 2010 and 2019, the world doubled its capacity to produce energy from renewable sources from 1,226,853 MW to 2,536,853 MW [84]. Mexico was not the exception. Within the same time period, it increased its amount of power generated from renewable sources by 90%, from 13,515 MW to 25,648 MW [85]. Currently, Mexico has around 63 photovoltaic parks, 70 wind farms, 4 geothermal energy projects, and 66 hydroelectric plants. Thanks to this, last year it was able to generate 29% of the country's energy from clean sources.

Let's not lose sight of the fact that Mexico has great potential to generate renewable energy. The south of the country has important aquifer resources, of great relevance for the generation of hydroelectric power [86]. On the other hand, in the northern region of the country there are plenty of hours of sunshine, essential for solar energy. Finally, in several areas of Mexico, the presence of the wind is strong, favoring the production of wind energy [87].

However, the National Electric System Development Program (PRODESEN) estimates that the country's electricity demand will grow at an average annual rate of 3.1% in the next 15 years [88]. In order to provide energy to all of Mexico, it is necessary to continue investing in renewable generation plants, since apart from the fact that they do not harm the environment, they turn out to be more efficient and economical.

3.2. Referential Cartography to Identify Existing Energy Potentials in Mexico

In Mexico there is considerable potential for the growth of renewable energies already present in the country such as hydraulic, wind, solar and geothermal sources, with suitable spaces for the establishment of production plants, be it the north of Veracruz or Baja California Sur for the wind energy; the northern part of the country with a desert climate and little cloudiness, ideal for the use of solar energy; or the region of the Transversal Neovolcanic Axis that includes states such as Hidalgo, Guanajuato and Querétaro for geothermal energy. In the case of tidal energy, although it is not yet exploited in Mexico, prospective studies indicate that the northwestern coast of the country has potential for its use [89].

The federal government through the Law of Use of Renewable Energies and the Financing of the Energy Transition (LAERFTE), has the goal that by 2024 the 35% of the capacity installed in Mexico comes from clean sources [90].

3.2.1. Hydropower

According to PRODESEN data [91] (Figure 6), hydroelectric generation represents 17% of installed capacity, with 12,589 MW in 84 hydroelectric plants, that is, 1 out of every 4 MW installed nationwide, the annual generation is clean energy contributes 20.3%, that is, 64,868 GWh, where hydroelectric plants provide the 48% of total generation [92].

3.2.2. Solar Photovoltaic Power

In reference to Latin America, Mexico is one of the countries with the greatest potential to promote the installation of solar panels and generate clean electricity in homes, businesses and industries. According to the Global Solar Atlas (Figure 7), the Mexican Republic is one of the countries with the highest solar radiation, receiving up to 8.06 kilowatts per square meter (kWh/m^2) per day and the possibility of transforming 5.5 kWh/m^2 of electrical energy [93], very similar to those of Chile, Australia, South Africa, and Saudi Arabia.

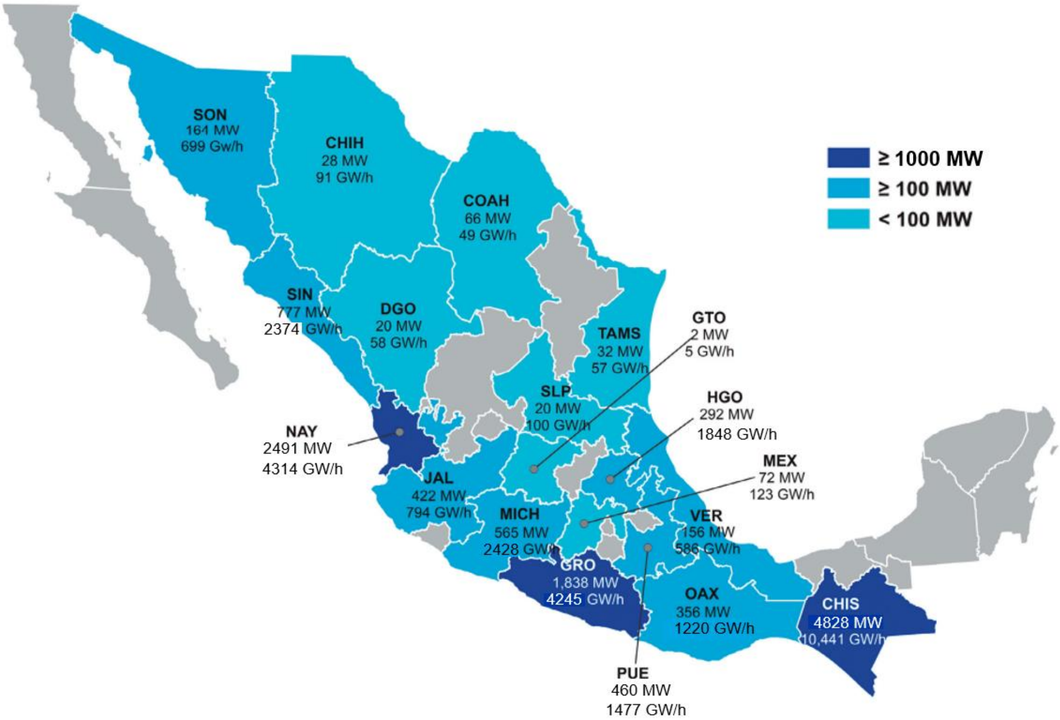

Figure 6. Capacity and generation in hydroelectric plants (MW/GWh). Inspired by data from PRODESEN 2017–2031, SENER [91].

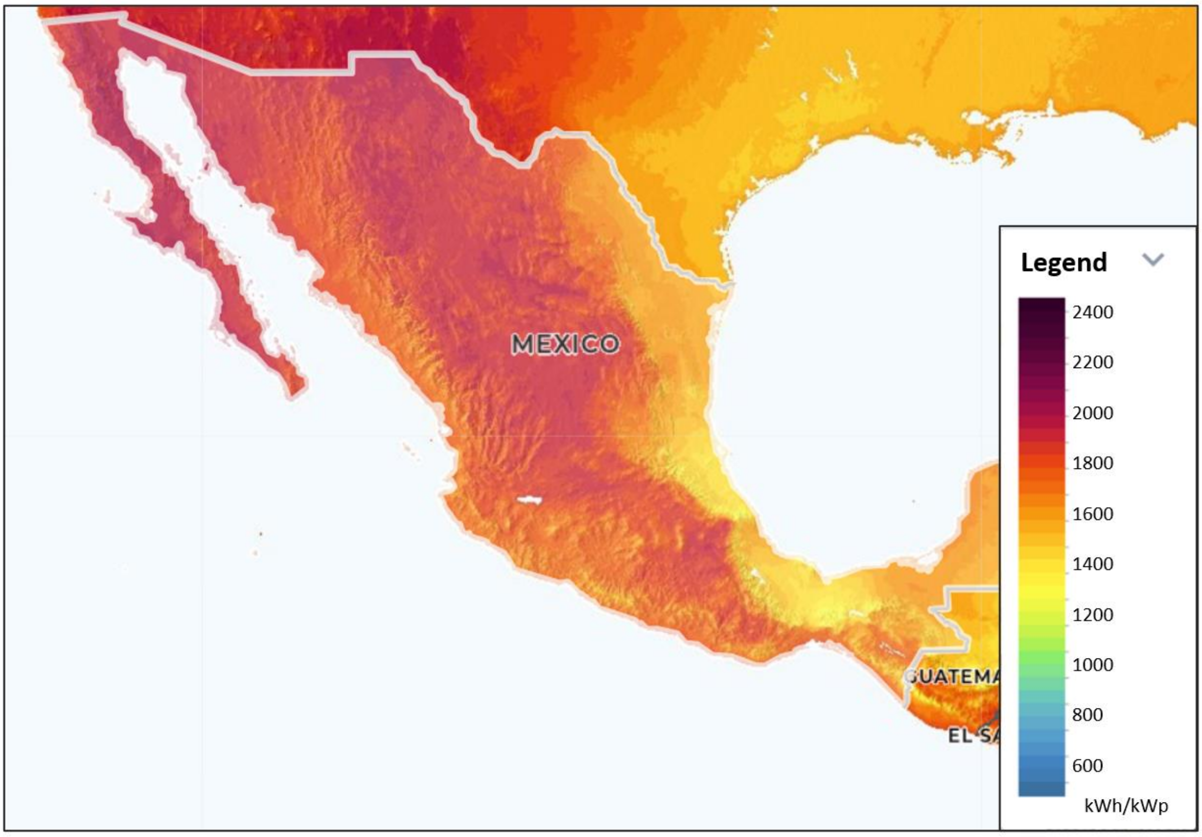

Figure 7. Solar photovoltaic power potential in Mexico, analyzed by the authors in free software Global Solar Atlas [93].

The Mexican Association of Solar Energy (Asolmex) reported that throughout 2019 the first 100,000 interconnection contracts were reached in Mexico, of which 75 percent correspond to homes, 20 percent to businesses, and 5 percent to industries [94]. In addition, by the end of 2019, Mexico added 55 large-scale solar power generation plants. Currently, there are around 50 facilities spread over 15 states of the Republic, with an installed capacity of more than 3700 MW.

The entities where the fields with solar panels are located are San Luis Potosí, Sonora, Aguascalientes, Baja California Norte and Sur, Chihuahua, Coahuila, Durango, State of Mexico, Guanajuato, Hidalgo, Jalisco, Querétaro, Yucatán and Zacatecas.

3.2.3. Wind Power

Mexico has unquestionable wind potential. Although it has only begun exploded in recent years, the sector already shows high dynamism and competitiveness. This is the more than 1900 MW in operation in independent production and self-supply, such as the more than 5000 MW at different levels of development [95].

In independent production, projects such as Oaxaca I-IV and Sureste II show that the wind technology is an effective solution to provide energy to the basic services suppliers through long-term auction processes, at a competitive price.

Analyzing the Mexican wind atlas, the average annual wind speeds exceed 7 m/s at 50 m from land, the usable potential according to the speed ranges correspond to important areas where this renewable resource can be used, especially in the Pacific Ocean and the Gulf of Mexico (see Figure 8).

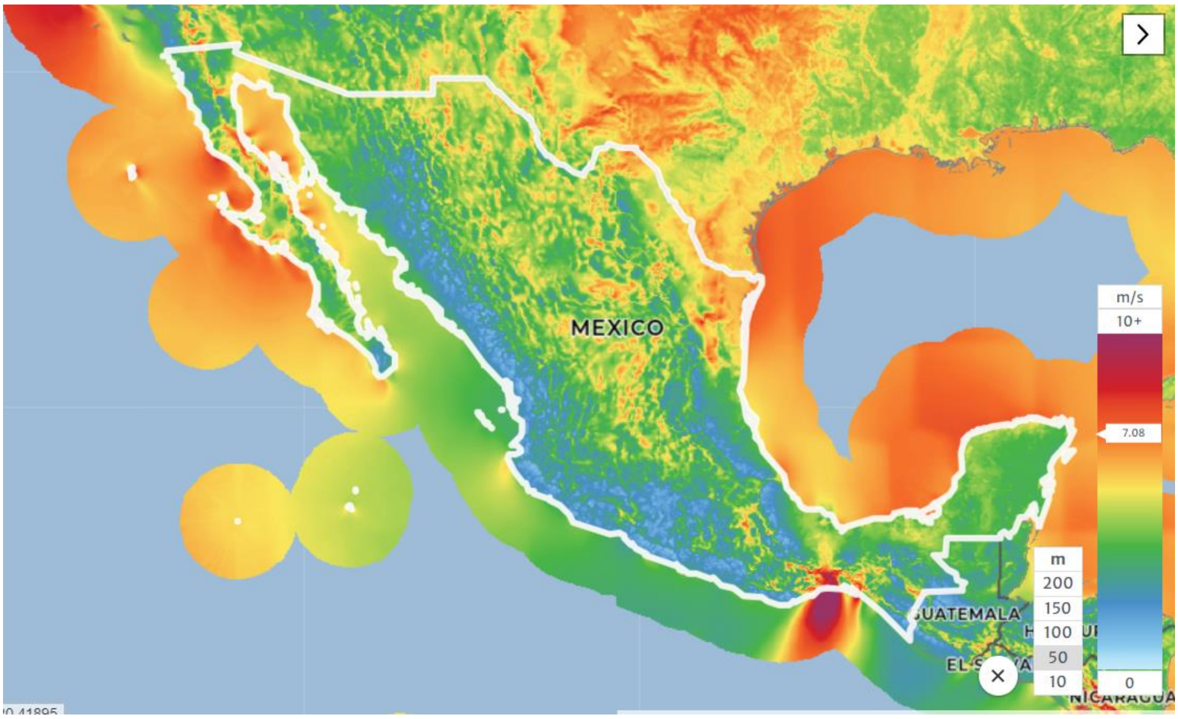

Figure 8. Wind power potential in Mexico, analyzed by the authors in free software Global Wind Atlas [96].

3.2.4. Biomass Power

In Mexico, the installed capacity to generate energy from biomass in 21 states of the republic totaled 646.37 MW and a power generation of 1399.33 GWh [97]. Veracruz is the state that registered the highest installed capacity with 264.06 MW, in addition to Jalisco, Tabasco and San Luis Potosí with 83.32, 41.7 and 40.7 MW, respectively.

Mexico seeks how to take advantage of its potential of 70 million tons of organic, agricultural, livestock and forestry waste per year [98] and fulfill its commitments in the fight against climate change and transition to a low-carbon economy while its economy continues to grow and responds to the needs of its 120 million inhabitants (mostly young people, according to the National Institute of Statistics and Geography) [99].

In La Trinidad, municipality of Guadalupe y Calvo, San Carlos and its annex El Vergel, municipality of Balleza and Yoquivo, Guachochi, there are already plans for electricity generation projects from forest biomass at an approximate cost of 2.7 million pesos, contributed by the National Forestry Commission and the State Government. It is not an isolated episode and, in fact, in facilities such as the Petatalco coal-fired power plant, it would be possible to reduce coal imports. Of the 2500 MW it generates, around 5% could be produced from biomass.

Below, Figure 9 shows the classification of the Mexican territory. The forest segment is very representative and can be very useful for biomass production with 37.72% according to the mapping and report presented by [100].

Figure 9. *Cont.*

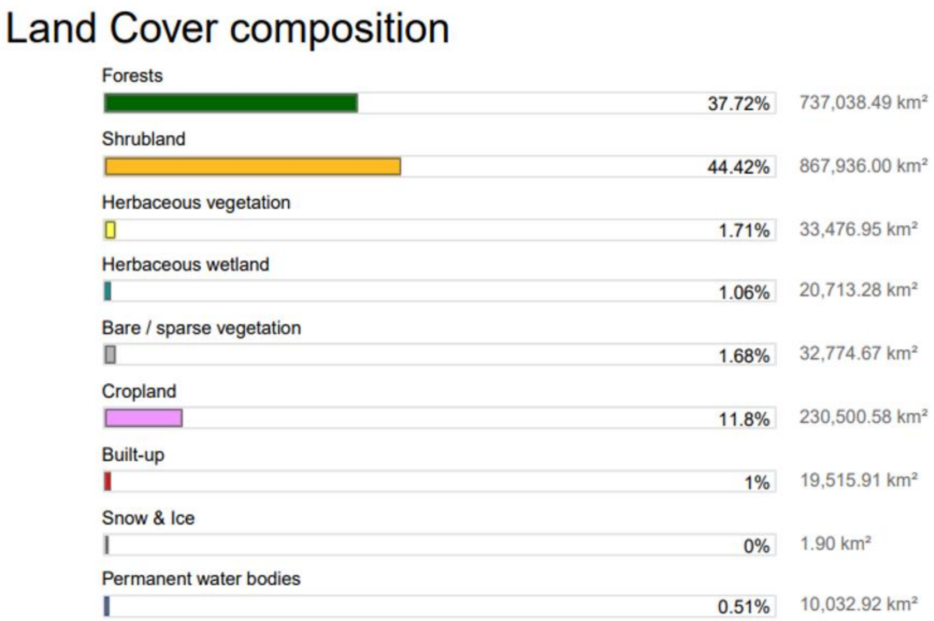

Figure 9. Mapping of Mexican land use for biomass exploitation purposes using the Land Cover Viewer tool [100].

3.3. Expected Energy Demand by 2050

The growth in demand according to the reference [81] among the various sectors also reflects the economic development in Mexico and its long-term growth forecasts, as shown in Figure 10. Today, the industrial sector in Mexico represents 48% of total demand, meanwhile transportation far exceeds industrial demand (28%). The residential and commercial sector currently has the lowest participation in final energy consumption, but by 2050 it will increase according to the scenario proposed by [101].

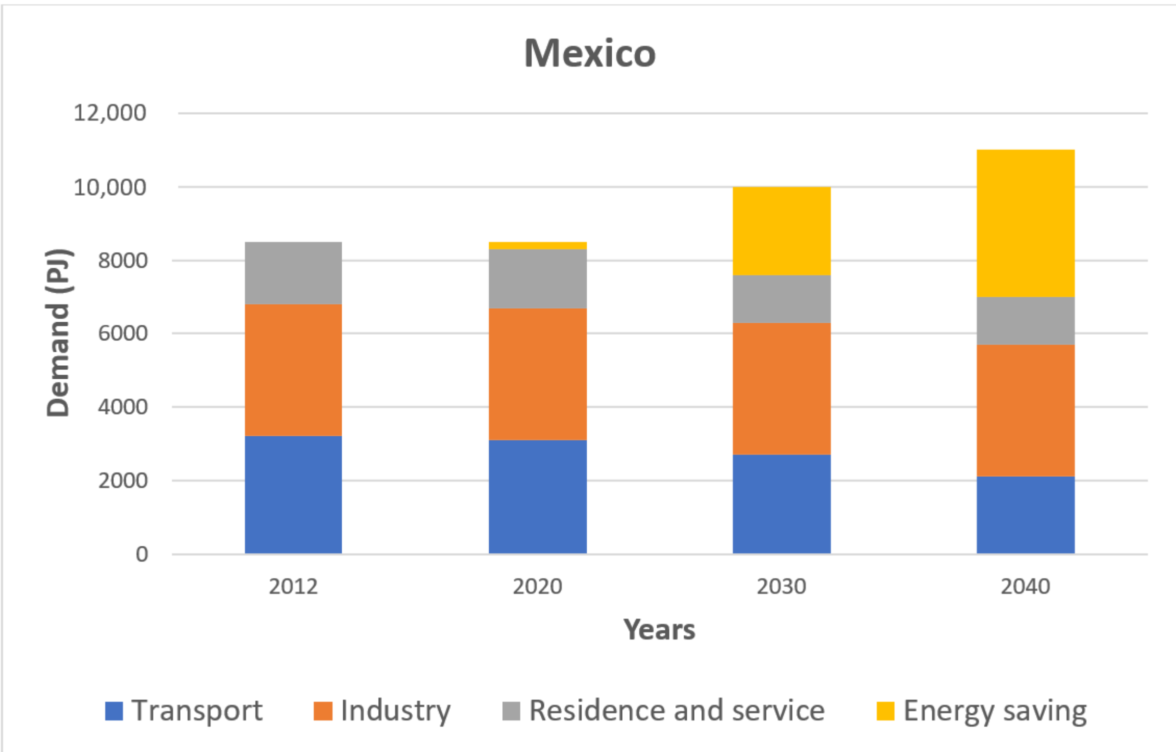

Figure 10. Expected energy demand by sectors in Mexico by 2050.

One reason for the current low share of the residential and commercial sector in total final energy consumption is weather. In Mexico, the climate is more variable, leading to a demand slightly higher than 6 GJ. The gradual increase in the share of demand for housing and services reflects the expected rise in living standards, starting from fairly low levels in much of rural Mexico. Although the input studies on efficiency potentials apply a focus on the effects on final energy consumption. While the evolution scenario for Mexico shows a small reduction in demand in each sector. These potentials still largely depend on social, economic, and political aspects, such as home appliance exchange rates. Limiting future growth in energy consumption, even in newly industrialized countries, without limiting economic development is a precondition for a successful transition to a 100% renewable energy supply system.

4. Results

Table 2 shows the results up to 2050 of the final energy demand for heat and transport. The energy demand must be fully supplied at all times, so the energy mix must guarantee all sectors at all times. The electrification strategy is coherent, taking advantage of the EnergyPLAN tool and effectively proposing the quotas of diversified renewables in each period of time. The result is presented in Figure 11 according to the recommendable feasible approach of the long-term energy system for Mexico. The heat supply increases in a moderate way, meanwhile the power supply sees a very high increase based on growing demand. Particularly due to the energy demand of services, increases in efficiency and electrification of heat and transport.

Table 2. Disaggregated energy demand for transport and heat by 2050 in PJ/a.

(PJ/a)	2020	2030	2040	2050
Transport (incl. electricity)	2269	2194	1839	1710
Heat (incl. electricity)	1538	1538	2131	2618
Power	1331	1331	2565	3367
For the transport	14	14	413	573
For the heat	170	170	243	400

4.1. Power Mix Generate by 2050

The transformation scenario of Mexico applies a strategy of progressive increase of diversified renewable energies, fulfilling phases of increase. The transport sector has a different decarbonization process, based on electrification. By 2050, road transport will be dominated by battery electric vehicles (BEVs) and electric extension cars. Meanwhile, for heavy-duty vehicles, hydrogen fuel cells will play a major role in 2050. As expected according to the energy potential available in the Mexican territory, the energy mix is called to be sustained on solar PV (30%), wind (25%) and hydro (14.5%) instead of fossil fuels that need to be displaced in the medium term above all, see Table 3 and Figure 11. It is clear that the producers of fossil fuels will look for all kinds of legal and political devices to extend their life in the market. This is where governments and legislators must agree and turn around Mexico's energy destination for effective decarbonization and not allow the purpose of decarbonizing the planet to be truncated.

4.2. Expected Development in Transportation

Bus rapid transit systems are already on the way and will be supported by massive investments given the real opportunities that the sector will present, according to reference analysis [102]. With higher economic income for Mexico, electric mobility in private cars is dynamized in a way and the maturity of mobility technologies will allow us to penetrate the national market in addition to achieving affordable prices for different social strata. The transport and electricity sectors tend to merge in a more compact way. This, on the one hand, generates additional burdens for the electricity sector, which needs to provide additional capacity but also provides benefits for the integration of variable renewables (especially in renewable shares above 90%).

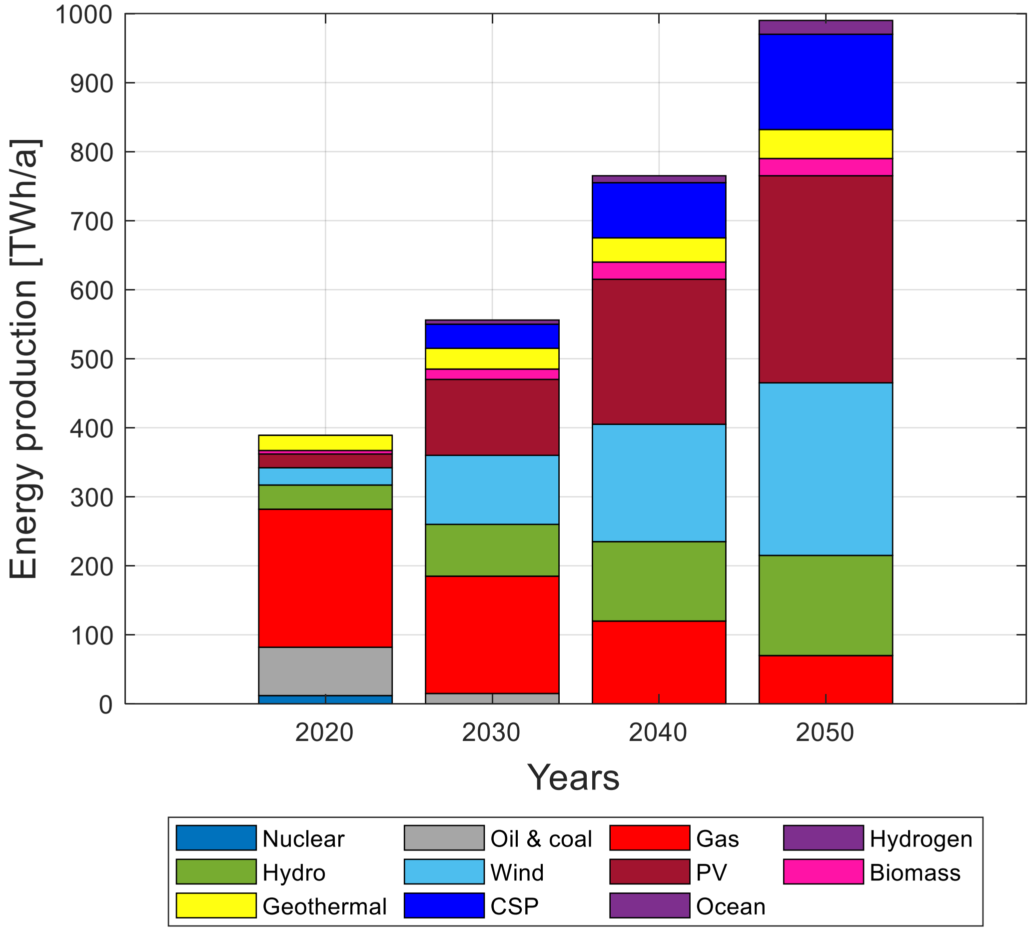

Figure 11. Power production in Mexico for 2050.

Table 3. Power supply by 2050 in TWh/a.

	2020	2030	2040	2050	% in 2050
Nuclear	12	0	0	0	0
Oil & coal	70	15	0	0	0
Gas	200	170	120	70	7
Hydrogen	0	0	0	0	0
Hydro	35	75	115	145	14.5
Wind	25	100	170	250	25
PV	20	110	210	300	30
Biomass	5	15	25	25	2.5
Geothermal	22	30	35	42	4.2
CSP	0	35	80	138	13.8
Ocean	0	6	10	20	2
Total	389	556	765	1000	100%

This transformation of the automotive market also affects the production of hydrogen. In the long term, the direct use of electricity must be supplemented by green hydrogen produced based on renewable sources. With this, a renewable and environmentally friendly transport supply can be achieved. Battery capacities limit the deployment of BEVs for long-range heavy cargo transportation. The biomass alone is constrained and can only provide a reduced 14% share of the transportation sector in Mexico. For this reason, if the consumption of biomass is balanced, it will be a result of the diversification of renewable sources that allocate energy to the different demand sectors [103]. From this point of view, Mexico is called upon to apply a broader diversification of transportation technologies, with which transportation meets the CO_2 reduction targets in 2050. See Table 4 and Figure 12.

Table 4. Power supply by 2050 in TWh/a for transportation.

Source	2020	2030	2040	2050
Oil Products	2150	1700	900	0
Natural gas	50	75	100	150
Biofuels	100	130	150	200
Electricity	0	400	1000	1650
RE Hidrogen	0	75	250	450
Total	2300	2380	2400	2450

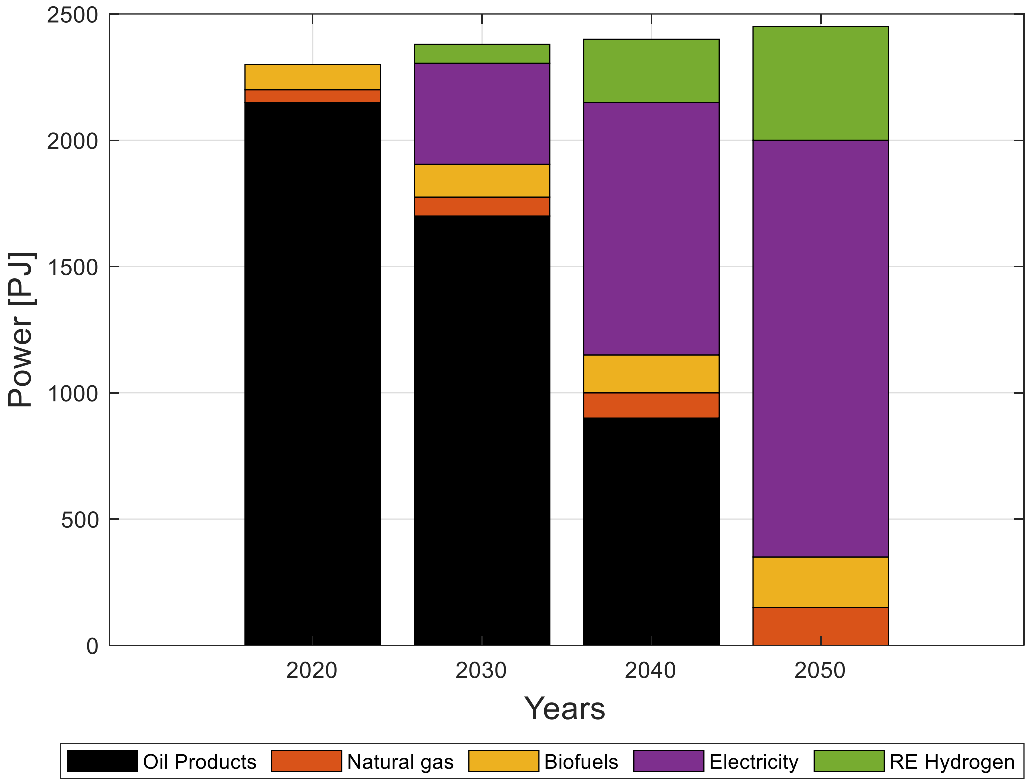

Figure 12. Interaction in the Mexican energy mix. Increased renewable energy and reduced fuel in the long term for transportation.

4.3. Main Policies Currently Developed in Mexico That Will Impact Decarbonization by 2050

The regulatory transformations carried out on the Mexican electricity sector during this century have been oriented towards an accelerated energy transition. Which has been the result of various interests fostered by certain sectors over others (mainly economic rather than social and environmental). This is due to the fact that it is the private actors who have a greater interest in benefiting from the reduction in costs represented by electricity production using alternative means. In this way, it is understood that the energy transition process has two very high barriers to overcome, namely fossil fuels and the private sector trying to make a high profit over citizen interest. Worldwide and particularly in Mexico, the objective is to reduce environmental impact, since concerns about the use of renewable energy sources still do not reflect the initiative from the point of view of energy policy. Unfortunately, there are commitments to generate electricity through sources with a focus more on reducing economic costs instead of prioritizing those with the least environmental impact. The notable efforts made in the search for the development of a regulatory framework for environmental protection in Mexico can be rescued and that the policies are detailed in Table 5 and that have been developed since the 80 s of the last century. However, the lack of normative harmonization in an attempt to protect the environment and in the governmental institutional action in this regard weaken this interest.

Table 5. Lastest main energy policies of Mexico, adapted from.

Policies	Year	Status	Jurisdiction
General Law of Climate Change (Mexico)	2022	In force	National
Heavy-duty Vehicle Emission Standards	2021	In force	National
2022 Package against inflation & famine-Transport fuel and power subsidies	2022	In force	National
Draft standard PROY-NOM-014-ENER-2020, Energy efficiency of alternating current, single-phase, induction electric motors, squirrel cage type, cooled with air, in nominal power from 0.180 kW to 2.238 kW. Limits, testing method and labelling.	2021	In force	National
Nationally Determined Contribution (NDC) to the Paris Agreement (2022 Update)-Mexico	2022	In force	National
NOM-031-ENER-2019: Energy efficiency of LED luminaires for roads and public outdoor areas. Specifications and testing methods	2021	In force	National
Nationally Determined Contribution (NDC) to the Paris Agreement: Mexico	2022	In force	National
Special Program on Climate Change 2021–2024	2021	In force	National
Photovoltaic Power Plant at Central de Abasto (CEFV CEDA)	2021	In force	National
Draft standard PROY-NOM-022-ENER/SE-2020, Energy efficiency and user safety requirements for self-contained commercial refrigeration appliances. Limits, testing methods and labeling.	2021	In force	National
Official Mexican Standard NOM-013-ASEA-2021. Facilities for Storage and Regasification of LNG	2021	Announced	National
NOM-012-ENER-2019: Energy efficiency in condensing and evaporating units for refrigeration. Limits, testing and labelling methods	2020	In force	National
Emissions Trading System	2020	In force	National
Transition Strategy to Promote the Use of Cleaner Technologies and Fuels	2020	In force	National
Increased electricity prices	2020	In force	National
National Programme for the Sustainable Use of Energy 2020–2024	2020	In force	National
"Hoy No Circula" Programme	2019	In force	City/Municipal
Call for Third-party Verifiers for the Guidelines for the prevention and comprehensive control of methane emissions from the hydrocarbons sector.	2019	In force	National

It is observed that the regulation that governs the Mexican energy transition has an interesting short-term perspective, but more aggressive regulations are required to apply it with a long-term vision (especially ones that require greater government investment). For example, in 2008 the Law for the Use of Renewable Energies and the Financing of the Energy Transition was issued, which states that the process of use of the different sources and processes to obtain renewable energy that had objectives will be regulated (other than those of the public service in order to promote and encourage the adoption of this type of technology to obtain electricity). This law was soon amended in the same year in order to ensure the participation of the public and private sectors in the development and benefit of the use of renewable energies.

Analyzed and compared with different methods, it is important to consider several works that are highlighted below. Ning Zhang et al. [104] presented an event-driven distributed hybrid control scheme for the integrated power system. Meanwhile, Lingxiao Yang et al. [105] developed a hybrid reinforcement learning system based on adaptive power management policies for the group of islands with restricted power transmission. In the end, an island energy center (IEH) model is proposed that can carry out the use of energy in cascade. However, Wujing Huang et al. [106] go beyond the two previous proposals and consider the need for optimal planning and configuration of multi-energy systems considering distributed renewable energy. Xuan Wu et al. [107] agree with the previous reference but fail to include optimal energy storage systems and smart switch placement in dynamic microgrids with applications to the integration of marine energy. The article presented here includes a novel component regarding developing policies that are time-varying and subject to change. Therefore, the energy transition will be dependent, it will allow an acceleration or decrease in the development of the proposed processes. This analysis differs from previous studies that are framed in an eminently technical analysis.

5. Discussion

Renewable energy technologies must replace the 86% of energy supplied provided by fossil fuels. This implies greater production of diversified variable energy sources and energy storage to keep the grid stable. By 2050, fluctuating wind (25%) can be very well complemented by photovoltaic energy (30%). This has already been extensively addressed in the literature and very good experiences have been mentioned in other parts of the world. On the other hand, CSP plants (13.8%) with integrated thermal storage provide the required insured capacity for the growing future market. The appropriate thing is to take better advantage of the high potential of solar irradiation in Mexico. As has been stated, wind energy and photovoltaic solar energy would be fully complemented. Old hydroelectric energy sources tend to grow. In fact, there are government projects that are in the pipeline to start up in the future, and in 2050 it could be responsible for 14.5% of energy production. In the scenario approach using EnergyPLAN, hydroelectric energy is considered with a measured growth in order to diversify renewable energy sources, which is the most advisable thing to guarantee energy security in Mexico. The remaining 16.7% of energy production will be made up of other renewable energies that cannot be neglected since they will serve as a basis to avoid large storage volumes and will serve as a cushion for wind, solar photovoltaic, hydropower, and CSP energy to grow.

In Mexico, the power generation capacity tends to increase considerably at least around 2.5 times to supply the long-term demand for electricity. For this reason, a high proportion of renewable energy is necessary and should be increased in investments in the country (but also with less hours of full load production coming from plants that use fossil fuels). Wind and photovoltaic turbines would be dominating the Mexican market and will represent 55% of all total capacity. The permanently secured capacity would be delivered by dispatchable power plants such as CSP, biomass, and geothermal. Batteries can offer additional demand flexibility, demand-side management such as controlled charging of battery electric vehicles applying the V2G concept, and long-range balancing of supply and demand via the power grid.

With nuclear power currently providing less than 3% of power production in Mexico, phasing out this technology does not lead to significant restructuring of power systems. However, for energy security it is appropriate to phase it out. The additional capacity will not only provide higher direct power demand, but also additional demands from electric transportation and electric heating applications. Our analyzes show the technical feasibility of a coupling of this sector, even with much higher percentages of renewable energies, are possible. However, in this study we treat measured data. The scenario developed here for Mexico describes possible future developments of the energy system, which are technically feasible and economically viable.

Reference [12] already stated the importance of developing a roadmap to carry out the energy transition in the Mexican state. In this study we offer this approach within the framework of changes in national policy. Reference [108] considers it essential to carry out a social impact assessment (SIA) in the management of the energy transition. The conclusions of this study highlight the importance of project stakeholders being aware of the changes that are going to be made in the localities of Mexico and the incidence that renewable energy will have. On the other hand, reference [109] provides an analysis from various perspectives on the evolution of clean energy technologies in Mexico and the contributions they can provide in the long term.

Additionally, reference [110] highlights the drivers of GHG emissions from electricity and the role of natural gas in the Mexican energy transition. Finally, accelerating the speed of diffusion of clean energy in Mexico can result in annual net savings of up to USD 11.6 billion in national energy system costs by 2030 and at least USD 70 billion by 2050, taking into account externalities such as health effects and reductions in carbon emissions. The profiles of the main energy parameters are presented as supplemantary material and are highlighted in Figure S1.

6. Conclusions

Currently, the energy transition in Mexico is in a process of change and adaptation. The legal reforms from the energy point of view have sought the diversification of the country's energy matrix and the promotion of the generation of renewable energy, which is abundant in the country and should be taken advantage of. In this sense, wind, solar and hydraulic energy projects have already been carried out in various parts of the nation. However, changes in the government in recent periods have systematically slowed down the development of the energy sector, which should have accelerated and resulted in a change in the orientation of energy policy with a view to effective energy transition.

In the electricity sector alone, there is potential to generate up to 46 percent from renewables each year by 2030, or 280 terawatt-hours, with the largest deployment being wind and solar photovoltaic (PV), followed by small and large hydroelectric, geothermal, and biomass sources.

The recent electricity reform has increased the country's potential to generate more renewable energy. A decade ago, the government eliminated the state utility CFE's monopoly in the Mexican electricity market and expanded it to private sector participation. Mexico is also part of the group of countries that has international commitments to reduce greenhouse gases and a goal of generating renewable energy with low carbon emissions by 2035. By 2050, this research proposes reaching zero emissions, as other countries have already developed a structure to expand the variable renewable energy market.

In the analyses carried out with the support of EnergyPLAN, the combination of wind and photovoltaic solar energy would represent around 55% of Mexico's renewable energy generation by 2050. Hydroelectric will also be influential in the energy mix, as will CSP between the two; in total, 28.3% is accounted for. Among the minor contributions are biomass and geothermal energy as some of the least expensive energy supply options with the most interesting potential. Renewable energy for heating, cooling, and cooking in the home and in various industries offer the greatest potential for growth in relation to current traditional uses and tend to be replaced by modern systems. Total biomass consumption in all end-use sectors for heating or transport fuel will be significant and can reach more than a third of total renewable energy use.

Analyzing the policy framework, it is necessary to take into account the greater land area of Mexico, in which supply and demand are often very separated. Planning must begin to be established with broad criteria that lead to making its execution viable in the short, medium, and long term. It is essential for grid transmission, expansion, and integration to accommodate a full structure of diversified renewables in the face of increasing load interactive demand.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16207121/s1, Figure S1: Profiles used in the Mexican analysis: (a) Supply of photovoltaic solar energy. (b) Wind power supply. (c) Power demand. (d) Charging electric vehicles.

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Abbreviations

ASOLMEX	Mexican Association of Solar Energy (In English)
BEV	Battery electric vehicles
CHP	Combined heat and power
CO_2	Carbon dioxide
COP 27	Conference Of Parties 27
ESS	Energy storage solution
GHG	Greenhouse gas
IRENA	International Renewable Energy Agency
PRODESEN	National Electric System Development Program (In English)
PV	Photovoltaic
RE	Renewable energy
TES	Thermal energy storage
V2B	Vehicle to building
V2G	Vehicle to grid
V2H	Vehicle to home

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