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Consequences of the National Energy Strategy in the Mexican Energy System: Analyzing Strategic Indicators with an Optimization Energy Model

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Abstract: This paper presents an approach to the assessment of the Mexican energy system's evolution under the climate and energy objectives set by the National Climate Change Strategy using an energy optimization model. Some strategic indicators have been chosen to analyze the performance of three integration elements: sustainability, efficiency, and energy security. Two scenarios have been defined in the medium and long-term: the business as usual scenario, with no energy or climate targets, and the National Climate Change Strategy scenario, where clean energy technologies and CO_2 emissions objectives are considered. The aim of this work is the analysis of some of those strategic indicators' evolution using the EUROfusion Times Model. Results show that reaching the strategy targets leads to improvements in the integration elements in the medium and long term. Besides, meeting the CO_2 emission limits is achievable in terms of technologies and resources availability but at a high cost, while clean technologies targets are met with no extra costs even in the business as usual scenario.

Keywords: energy modelling; sustainability indicators; energy policy; mitigation pathway

1. Introduction

In 2013, the Mexican government launched the energy reform with the main objective of building a new energy system aimed at reinforcing the national sovereignty, economic efficiency, and social welfare using the native energy resources in a rational and sustainable way. Main efforts are devoted to increasing the production of energy from clean technologies at a lower cost, to increase the oil incomes, to generate well-paid jobs, and to protect the environment [1].

The reform is accompanied by 21 secondary laws and the national energy strategy (ENE, from the Spanish acronym, Estrategia Nacional de Energía), updated on an annual basis. The ENE 2014–2028 [2] has two major strategic objectives, gross domestic product (GDP) growth and social inclusion; four policy measures, (1) transport, storage, and distribution, (2) refining, processing, and generation, (3) oil production, and (4) energy transition; and three integration elements, sustainability, efficiency, and energy security. To monitor the development of the strategy, a series of 26 indicators were defined.

This work analyses the historical evolution of five indicators representative of the sustainability, efficiency, and security of the energy system:

- Non-fossil fuels participation in the electricity generation
- CO_2 emissions
- Energy intensity
- Energy independence index
- Energy sources diversity

And the future evolution of the objectives under different scenarios using a global optimization energy model.

Those indicators were selected based on the indicators defined in the National Climate Change Strategy [3] to implement mechanisms to measure, report, and verify the strategic axes and lines of action.

On the other hand, regarding climate change policies in Mexico, the government launched in 2012 the General Law of Climate Change [4]. That year, Mexico was the 13th country in the world in greenhouse gas (GHG) emissions, contributing 1.65% of the total. The planning instrument to implement the law is the National Climate Change Strategy (ENCC, from the Spanish acronym, Estrategia Nacional de Cambio Climático) published in 2013 [3]. ENCC sets both climate and energy objectives at the medium and long term. Those targets consist of reducing GHG emissions in 30% by 2020, and 50% by 2050 compared to 2000 levels. In relation to electricity, the objectives for clean technologies' share are 35% by 2024, 40% by 2034, and 50% by 2054. Clean energies include renewables, nuclear, efficient cogeneration, and carbon capture and storage (CCS). Those objectives are in accordance with the ones set by the Law Energy Transition [5]. The main energy and climate laws and targets are described in Table 1.

Table 1. Energy and climate national targets.

Instrument	Targets
Law for the renewable energies exploit and energy transition financing	Maximum generation with fossil fuels 65% by 2024 60% by 2035 50% by 2050
National Climate Change Strategy	I. Climate objectives GHG emissions reduction 30% by 2020 compared to base line 50% by 2050 compared to 2000 II. Electricity objectives Share of clean technologies in electricity generation 35% by 2024 40% by 2034 50% by 2054

According to data from the Mexican Ministry of Energy [6], internal primary energy supply in Mexico from 2005 to 2015 has followed a downward trend with some ups and downs in the intermediate years, as can be seen in Figure 1. In this period, the main energy source is hydrocarbons, whose share in the total went from 83% to 80%, and although crude oil production has decreased, it has been compensated by the increase in gas production. The share of renewables in primary energy is still low, around 10%, and the rest has been produced by coal, which has also risen, and nuclear.

Energy imports have been in continuous growth from 2005 to 2015, mainly for gas, gasoline, and diesel. At the same time, energy exports have reduced dramatically in the same period, crude oil being the main fuel exported. Imports met exports in 2015 [6]. Imports and exports evolution is shown in Figure 2.

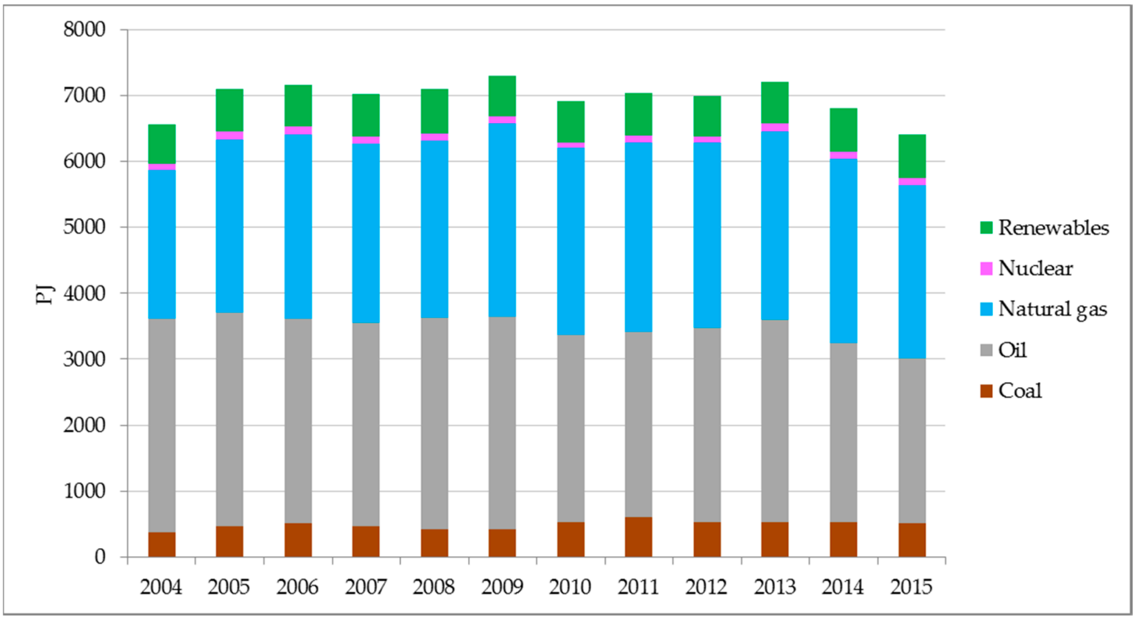


Figure 1. National primary energy (according to data from [6]).

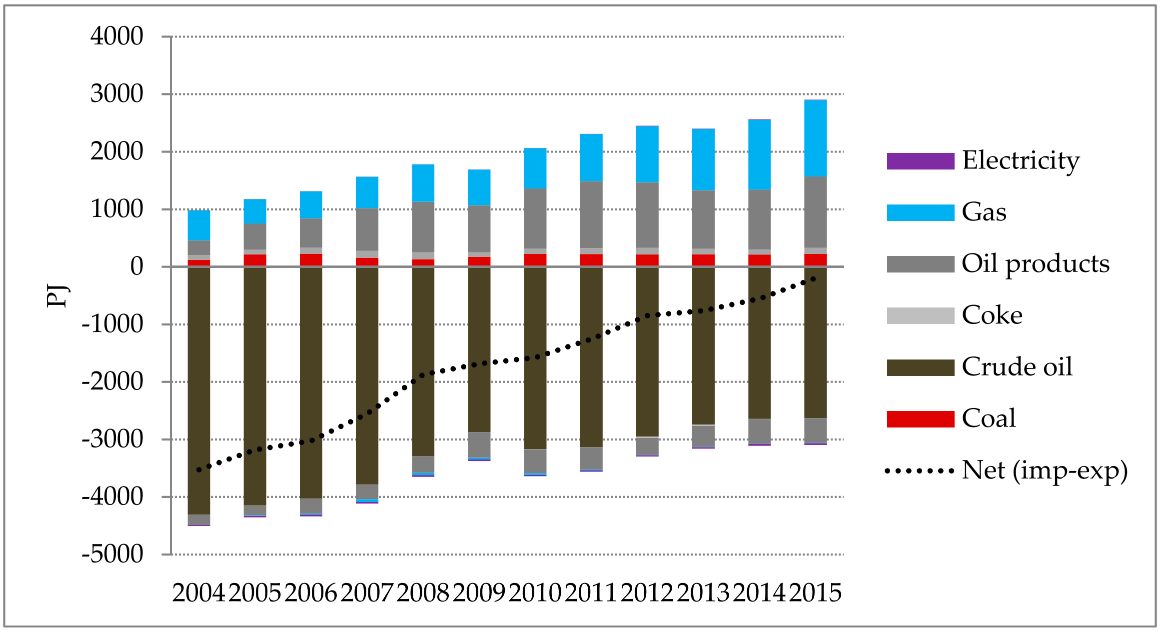


Figure 2. Evolution of energy imports and exports (own elaboration with data from [7]).

Regarding total final consumption (Figure 3), the Mexican Ministry of Energy reports data for the same period [6], which show a growth of 18% in 2015 compared to 2005 with an average annual rate of 2%. The share of the fuels in the final consumption remains almost the same along the period; only electricity and gas grew slightly, while oil products reduced by the same proportion.

Looking at the evolution of the Mexican electricity system from 2002 to 2015 (Figure 4), the main characteristic is the progressive substitution of oil power plants by natural gas combined cycle (NGCC) facilities, whose electricity production has almost trebled, reaching a share of 54% in the public system in 2015. This high increase is the result of a considerable NGCC plants installation, which went from 7 in 2002 to 20 GWe in 2014. In the same period, power generation with oil has reduced by 55%, while generation with coal has remained the same, 13% [7]. In addition, there are two nuclear boiling water reactors (BWR), which contributed 4% to the total electricity production. The installation of new nuclear capacities is planned in the medium term, although it has been included as clean technology in the ENE and ENCC. Regarding the production with renewable sources, it is worth noting that hydropower reached 30,050 GWh in 2015, making up 12% of the total production, and wind power went from 7 GWh to 2386 GWh. In 2015, the total share of renewables reached 15%.

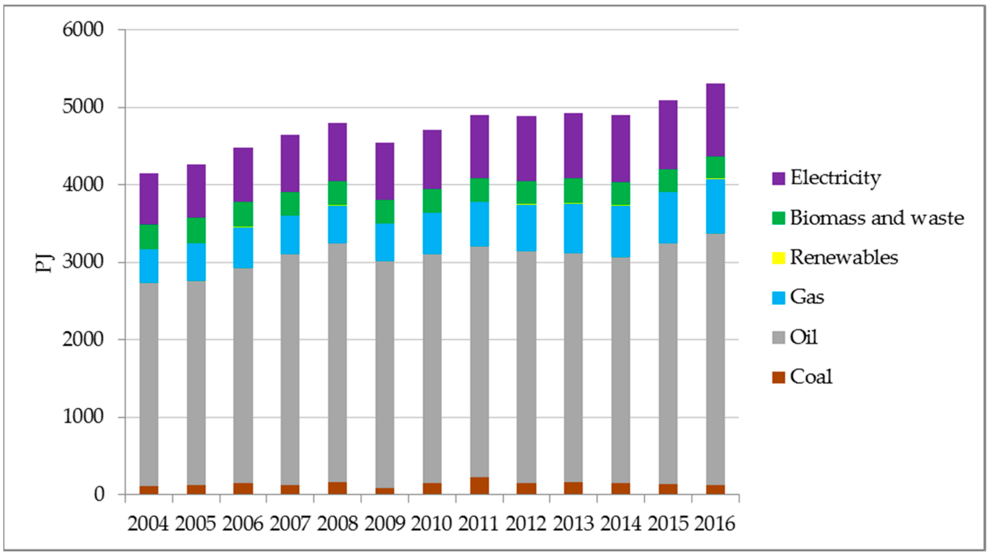


Figure 3. Total final consumption (according to data from [6]).

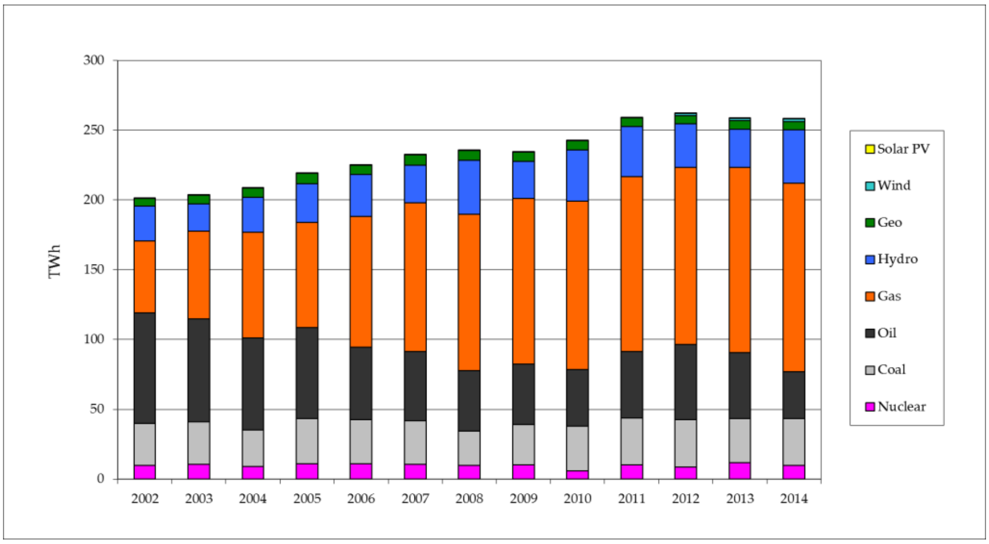


Figure 4. Evolution of the public electricity system in Mexico in 2002–2015 (according to data from [7]).

According to the National Inventory of Renewable Energies, the renewable potential in Mexico is good as may be seen in Table 2.

Table 2. Renewable energies potential in Mexico (PJ/year). Source: [8].

Resources	Geothermal	Small Hydro	Wind	Solar	Biomass
Possible	188	159	315.36	23,400.00	41.35
Probable	163	83	-	-	2
Proven	9	18	72	90	12

Besides, there is good potential for shale gas. According to the U.S. Energy Information Administration [9], Mexico has one of the world's largest shale gas resource bases, estimated in 545 Tcf (trillion cubic feet) technically recoverable [9]. Most of the resources are in the northeast and east-central regions of the country.

The fuel combustion emissions in the energy sector increased 58% from 1990 to 2010, with an average annual growth of 2.4% (Figure 5). The energy sector, comprising electricity and heat production and transport, was the main contributor, with 85% of the total in 2014 [10].

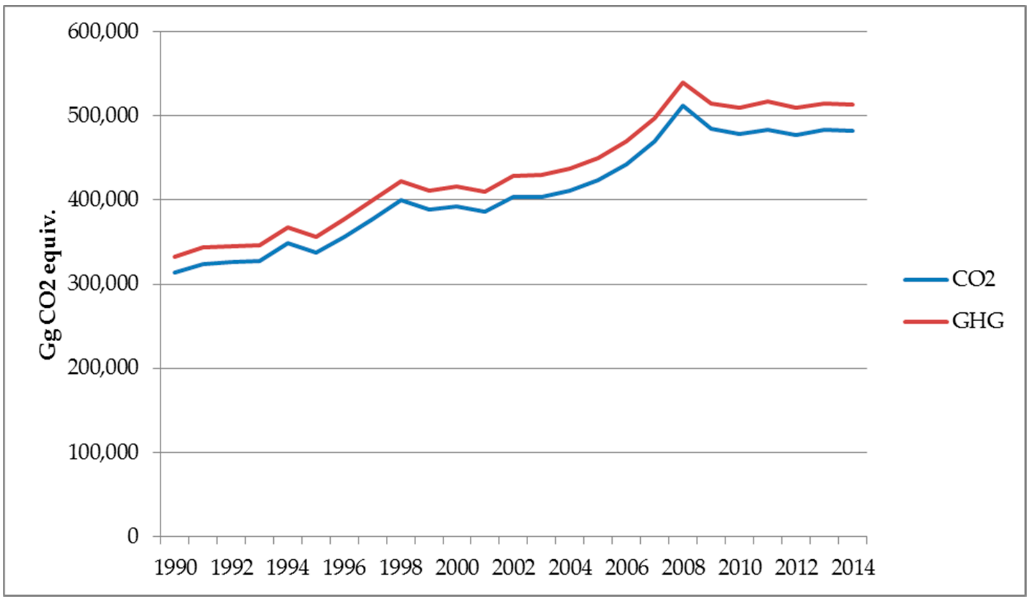


Figure 5. Greenhouse gas (GHG) and CO_2 emissions from the energy sector in Mexico (own elaboration with data from [10]).

Several authors have studied the evolution of the Mexican energy sector. In [11], the authors evaluate three scenarios for the energy sector to 2025. The difference among the three scenarios is the technology mix. Three environmental aspects are reviewed: GHG emissions, acid rain precursors, and energy/environment intensity (GHG/Consumption). The Long-range Energy Alternatives Planning System (LEAP) [12] was chosen for these estimations. The results show that the best performance of the three environmental indicators takes place in scenario E3.

Islas et al. [13,14] estimate the impact of the reduction in GHG emissions in the electricity sector in Mexico from 1996 to 2025. They pose four scenarios of renewable technologies penetration with different annual growth rates. They use a partial equilibrium model developed by the LEAPS platform [12]. The same authors [15] evaluate the CO_2 mitigation costs of the transition scenario based on renewable technologies in comparison with the BaU scenario based on natural gas. As a result, the authors show that, under specific economic and technology circumstances, a transition scenario towards renewable technologies presents favorable economic conditions.

Santoyo-Castelazo et al. [16] present one of the first approaches to the environmental impact evaluation of electricity generation in Mexico. The evaluation is carried out in 2010 using the technology mix for 2006 and applying a life cycle assessment methodology. The main conclusion is that there are great differences in the life cycle unit emissions between the fossil fuel and the renewable technologies.

Sheinbaum-Pardo and Ruiz [17] present a general view of the production and consumption of energy in Latin America and Caribbean (LAC), with special focus on the CO_2 emissions related to the use and production of energy, as well as the lack of energy services for millions of people in the region. Among other data and indicators, the paper shows the energy intensity for LAC. The data for Mexico in 2008 is 0.9 Mboe/USD 2005 PPP (419 MJ/PMx @ 12.48 PMx/USD in 2011). The article presents two other interesting indicators related to the access to energy and, according to the authors' opinion, to the opportunities that energy efficiency and renewable technologies offer to reach a sustainable development in the LAC region.

Sandoval-García and Morales-Acevedo [18] use an optimization model to estimate the combination of electricity generation technologies considering CO_2 and other life cycle emissions. Two demand scenarios to 2050 are proposed. Four restrictive indicators are used: CO_2 emissions, water use, water pollution, and maximum energy performance. The main conclusions are the need for a growth of renewable technologies close to their potentials, the use of nuclear and CCS technologies, and that the best scenario is the one with the lowest demand.

Santoyo-Castelazo et al. [19] evaluate prospective scenarios for the decarbonization of the power system in Mexico by 2050. Different technology combinations are used to get lower levels of emissions. The evaluation is done using life cycle assessment. The main conclusion is that CO_2 emissions reduction is feasible in a relevant amount (up to 80%) if there is a significant penetration of renewable technologies, and nuclear energy growth and carbon capture and storage technologies use are considered. In addition, a reduction in the energy demand until reaching a growth rate below 2.25% is required.

Veysey et al. [20] and Van der Zwaan et al. [21] investigate how Mexico might reverse current trends and reach its mitigation targets using results from energy system and economic models involved in the CLIMACAP-LAMP project. They found that all models agree that decarbonization of electricity is needed, along with changes in the transport sector. However, models find different energy supply pathways, some used renewable energy and others relied on biomass or fossil fuels with carbon capture and storage suggesting that Mexico has some flexibility in designing deep mitigation strategies.

Zenón and Rosellón [22] analyze the use of price incentives to promote the expansion of the transmission grid in Mexico. They use a two-level programming model, with the first level for profit maximization of a transmission company subject to maximum prices regulation, and the second level to deal with the power flow dispatch problem. In addition, they analyze the optimum grid expansion in eight time periods by using a power flow model where one operator maximizes the net welfare. They considered Programa de Desarrollo del Sistema Eléctrico Nacional (PRODESEN) official sector planning for 2016–2030 [23], simplified grid transmission with 54 nodes and 68 main lines, as well as 85 generation plants with average operation costs by technology. As a result, they get the optimum expansion of the transmission grid by 2020. This article shows a good analysis of the transmission grid.

Simon et al. [24] tried to complement the exploratory forecasting scenarios with a normative perspective on what is needed to meet the CO_2 emissions reduction in all the economy sectors in Brazil and Mexico. They used Mesap PlaNet (modular energy system analysis and planning environment—planning network), a bottom-up simulation model with a time horizon of 2050. Energy demand drivers are GDP and population growth. Other input data used are the potential of energy efficiency, renewable energy potential, existing capacity, and investment and fuel costs. The results for Mexico show a contribution of the energy efficiency to the final energy consumption 3 EJ lower in 2050. However, the electricity system needs 362 GW in 2050, from which 11% remains based on fossil fuels. In general, the emissions per capita decrease from 3.3 tCO_2/hab in 2012 to 0.5 tCO_2/hab in 2050.

Vidal-Amaro and Sheinbaum-Pardo [25] aim to design a strategy for the transition from an electricity system based on fossil fuels to one based on renewable energy sources (RES). The target is to reach a 40% share of renewable technologies in 2035, 50% in 2050, and 75% in the following years. The author uses the optimization model EnergyPLAN (advanced energy systems analysis computer model), with one hour resolution. Input data used were the hourly demand growth with an annual growth of 3.5% up to 2050, and the hourly dispatch with RES. Specific ranges of renewable, fossil, and nuclear potentials were set. The result is the estimation of the minimum share of RES technologies capacity in the Mexican power system to meet the objectives.

Barragán-Beaud et al. [26] make a comparative assessment of carbon pricing instruments in the Mexican electricity sector in terms of economic impacts and political feasibility. For that they use model-based scenarios using the optimization model Balmorel-MX and they conclude that an emissions trading scheme (ETS) is the most appropriate instrument.

Finally, Solano-Rodríguez [27] analyze three decarbonization scenarios that have been modelled using a TIMES model soft-linked to a power systems model and conclude that a deep decarbonization of the power system is techno-economically feasible and cost-optimal through renewables (mainly solar and wind).

The objective of the present work and its novelty compared to other the published studies is to analyze 5 strategic indicators of the Mexican energy system in the medium and long-term under energy and environmental policies using an optimization energy model. These indicators are widely used to analyze energy systems and showing the results of their expected evolution under different scenarios can help policy makers to formulate efficient energy policies in Mexico. This paper is structured in five sections. The EUROfusion Times Model (ETM) and scenarios are described in Section 2, results are shown in Section 3, discussed in Section 4, and conclusions and policy recommendations are given in Section 5.

2. Methodology and Scenarios

2.1. EUROfusion Times Model

The EUROfusion Times energy model (ETM) has been used to generate prospective scenarios of the Mexican electricity system. ETM was built in the framework of EUROfusion (former European Fusion Development Agreement), within the Socio-Economic Studies project, SES (former Socio Economic Research of Fusion). The original aim of the model was to analyze the role of fusion in the future global energy system. This is the first time that ETM is used in an analysis out of the framework of EUROfusion.

ETM uses the TIMES model generator developed by ETSAP (energy technology systems analysis programme), a technology collaboration programme (TCP) of the International Energy Agency (IEA). TIMES generates bottom-up optimization models representing the whole energy systems of one or more regions or countries, from resource extraction and production to final consumption. The optimal solution of a TIMES model is the composition of the energy system that meets the demand for energy services maximizing the total surplus, sum of consumers and suppliers surpluses. In TIMES, this is equivalent to minimizing the total cost of the energy system which includes the capital costs for investing and dismantling; the fixed operation and maintenance costs (labor), the variable operation and maintenance costs (fuel, replacements), imports costs and exports revenues, domestic resource production costs, commodities delivery costs, taxes and subsidies, etc. net present value (NPV) of the total costs is calculated by TIMES using the following equation [28]:

$$\mathrm{NPV} = \sum_{r=1}^{R} \sum_{y \in YEARS} \left(1 + d_{r,y}\right)^{REFYR-y} \cdot ANNCOST(r,y) \quad (1)$$

where R is the set of regions in the area of study, $YEARS$ is the set of years for which there are costs, $d_{r,y}$ is the general discount rate, $REFYR$ is the reference year for discounting, and $ANNCOST(r,y)$ is the total annual cost in region r and year y.

A flow chart describing the modelling approach of ETM model is shown in Figure 6.

More information on TIMES can be found in [28,29], and at the ETSAP web site, http://www.iea-etsap.org/.

In general terms, ETM is a multi-regional, global, and long-term energy model of economic equilibrium which uses optimization methods to provide the optimum energy system composition in terms of social wealth and sustainability at the minimum cost. Besides, it is a bottom-up, technology-rich model with thousands of technologies well defined by technical, economic, and environmental parameters.

The energy system in these models is optimized by minimizing total system costs subject to constraints reflecting infrastructure, technology availability, and policy objectives.

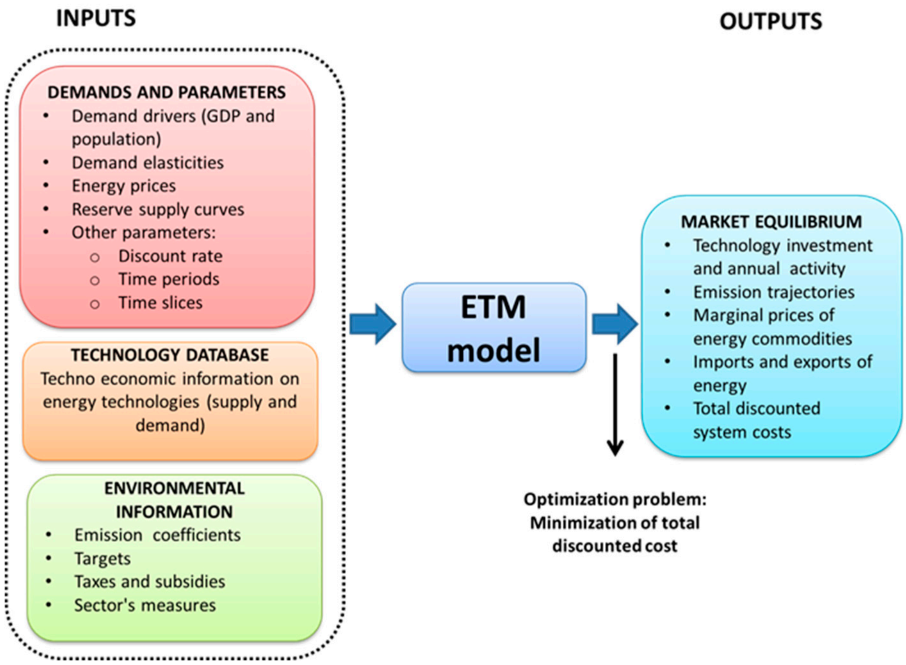


Figure 6. Flow chart of the modelling approach of ETM.

In particular, in ETM, the world is divided into 17 regions with Mexico being one of them, which makes the model suitable for this analysis. Base year is 2005 and calibration to 2010 has been performed by checking the results for this period with real data and using calibration scenarios to approach them. Time horizon is 2100, although in this work, the time horizon used was 2050. There are six time slices for the three seasons (winter, summer and intermediate, being intermediate spring and autumn), and day/night, to cover renewable technology special features which vary with the season and sun light such as the availability factor (AF). There are five demand sectors:

Industry sector: iron and steel, aluminum, copper, zinc, alumina, ammonia, chlorine, olefins, aromatics, methanol, cement, lime, glass, ceramics, paper and pulp, other non-ferrous metals, other chemicals, other non-metallic minerals, and the remaining industries.

Residential sector: Space heating and cooling, water heating, cooking, lighting, refrigeration, cloth washing and drying, dish washing, electric appliances and other energy uses. Regions are divided into four sub-regions for the residential heating and cooling technologies and into two sub-regions for the cooking ones to take into consideration the differences in climate across the region.

Commercial sector: Space heating and cooling, water heating, cooking, refrigeration, lighting, other electric office equipment, other energy uses. As in the residential sector, here regions are also divided into four sub-regions for the commercial heating and cooling technologies.

Transport sector: cars, buses, trucks, two- and three-wheels vehicles, international and domestic aviation, freight and passengers trains, internal navigation, and international water shipping.

Agriculture sector: with only one energy service demand met by two technologies, agriculture appliance and machineries, consuming a mix of fuels.

Regarding the supply, the model considers the upstream and the heat and power generation. The former includes the mining, production and processing of primary energy sources (uranium, fossil fuels, and biomass). The second includes all the electricity and heat production technologies with their corresponding technology, economic and environmental parameters: pulverized coal (PC), integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), coal and gas carbon capture and storage (CCS) available from 2020 and 2030 respectively, oil, fuel cells, biomass, nuclear fission and fusion available from 2050, hydro and small hydro, centralized and decentralized wind onshore and centralized offshore farms, centralized and decentralized solar PV, parabolic troughs and solar tower CSP with and without storage, geothermal, wave and tide, biomass combustion and gasification, and auto-production combined heat and power (CHP). Although hydrogen can play an important role as energy storage medium needed for high renewable energy share in the electricity system, the use of power to hydrogen technologies has not been considered commercially available for Mexico in the time frame analyzed in this study.

Renewable suitable areas, potentials, and availability factors have been estimated using a geographical information system (GIS), and some new technologies have been recently introduced, such as concentrated solar power (CSP) with storage or advanced nuclear with fuel reprocessing.

One of the main data inputs is the end-use energy services demand. The projections of the demands are the result of the general equilibrium models GEM-E3 [30] and Gtap [31]. Input data for these models are GDP and population. The projections for those parameters for Mexico are represented in Figure 7.

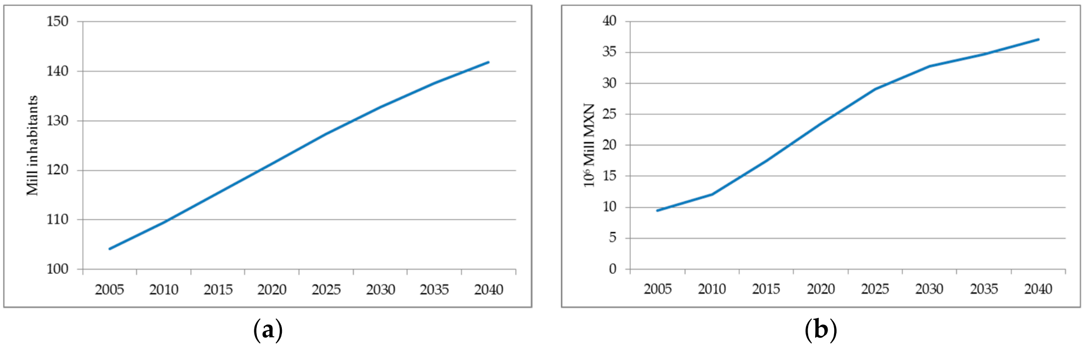


Figure 7. Population (**a**) and GDP (**b**) projections in the model.

Other inputs are the existing stock of energy-related equipment in all the sectors and the remaining time of operation, the potential future technologies with their corresponding parameters gathered through literature searches, the present and future sources of primary energy supply including different forms of biomass, such as energy crops and industrial and municipal waste amongst others, and current environmental and energy policies. Energy trade is described as an inter-regional exchange process, a trade of commodities such as gas, coal, etc. among the different regions.

ETM also contains CO_2 emission data derived from fuel combustion, as well as some extra emission factors for processes without combustion.

Energy balance data have been taken from the International Energy Agency [32], and, in the case of Mexico, national data have also been considered, mainly from the Mexican Ministry of Energy [7] and the National Institute of Electricity and Clean Energies (INEEL) (personal communication).

Using a global model to analyze the Mexican energy system is not the ideal approach unless a significant effort to characterize Mexico's energy system in the global model is performed. In order to overcome this shortcoming in the ETM model, Mexico's energy system has been characterized in detail and validated by national experts.

An additional possible limitation of using global energy system optimization models is that they optimize the global energy system, leading to potentially suboptimal results at the national level. However, an important advantage is that they can include the effects of international trade and regional policy constraints that otherwise would be not properly considered. This approach is also used in [20], where the framework of the CLIMACAP-LAMP project, two global general equilibrium models (EPPA, Phoenix), two global energy models (GCAM, IMAGE), one energy market equilibrium model (POLES), and one global bottom-up linear optimization energy model were applied to investigate how Mexico might reverse current trends and reach its mitigation targets.

2.2. Long Term Scenarios

Scenarios are suitable tools to explore the future. In this work, two scenarios have been built to analyze the evolution of the Mexican energy system under different policies. The first one is the business as usual scenario (BaU), which represents the evolution of the energy system without any environmental or energy target. In BaU, the evolution of the energy demand is estimated using the GDP and population growth in order to prospect a possible development of Mexican energy system without any efforts to limit GHG emissions. The second is the National Strategy of Climate Change (ENCC) scenario, which considers compliance with the strategy [13]. The ENCC sets several objectives for the next 10, 20, and 40 years. The environmental objectives are translated into a limit of GHG emissions to 442,859 ktCO_2 by 2020 (−30% regarding a baseline scenario with no mitigation measures) and 210,880 ktCO_2 by 2050 (−50% compared to 2000 levels). Regarding the energy targets, the ENCC sets a share of clean energies in electricity production of 35% by 2024, 40% by 2034, and 50% by 2054. The ENCC scenario has been built to introduce the CO_2 emission limits, taking into account that, in Mexico, CO_2 is responsible of 65.9% of GHG [3], and the clean energy targets. Table 3 shows a summary of the assumptions in the BaU and ENCC scenarios.

Table 3. Scenario matrix.

Scenario	Assumptions
BaU	No energy or climate policies 4.2 GW max new nuclear capacity by 2030
ENCC	I. Climate objectives 442 Mt CO2 total by 2020 (−30% compared to 2000 levels) 210 Mt CO2 total by 2050 (−50% compared to 2000 levels) II. Electricity objectives 35% share clean energies in electricity generation by 2024 40% share clean energies in electricity generation by 2034 50% share clean energies in electricity generation by 2054 III Other 5.6 GW max, new nuclear capacity by 2030

In both scenarios, the renewable potentials considered are those shown in Table 2.

Regarding nuclear power capacity, a maximum cumulative capacity of 5.6 GW by 2030 has been assumed as described in the PRODESEN scenario [33]. In the BaU scenario, the assumption is to not install more than two new power plants.

3. Results

Due to the dynamic pace of energy issues' evolution and the multifaceted nature of the topic, the model's outcomes from the BaU and ENCC scenarios have to be seen not as a forecast but as possible evolutions of the Mexican energy system. They can be useful as an input to frame the strategic definition of the energy policies in Mexico. With this limitation in mind, this section presents the results obtained from the modeling exercise.

First results demonstrate that the clean energy targets are met, even in BaU scenario by 2040, as can be seen in Figure 8. In this scenario, the electricity generation with clean technologies goes from 20% in 2010 to 33% in 2030 and 48% in 2040, the main technologies being solar, wind, and nuclear (see Figure 9). Electricity generation with fossil fuels comes from gas followed by coal technologies. However, in the ENCC scenario, clean technologies generate almost 100% of the electricity from 2030. In this scenario, there is an important contribution of natural gas with CCS technologies, which even substitutes the generation with coal with CCS technologies abandoned in 2040. Among the renewables, solar, wind, and geothermal present the highest shares.

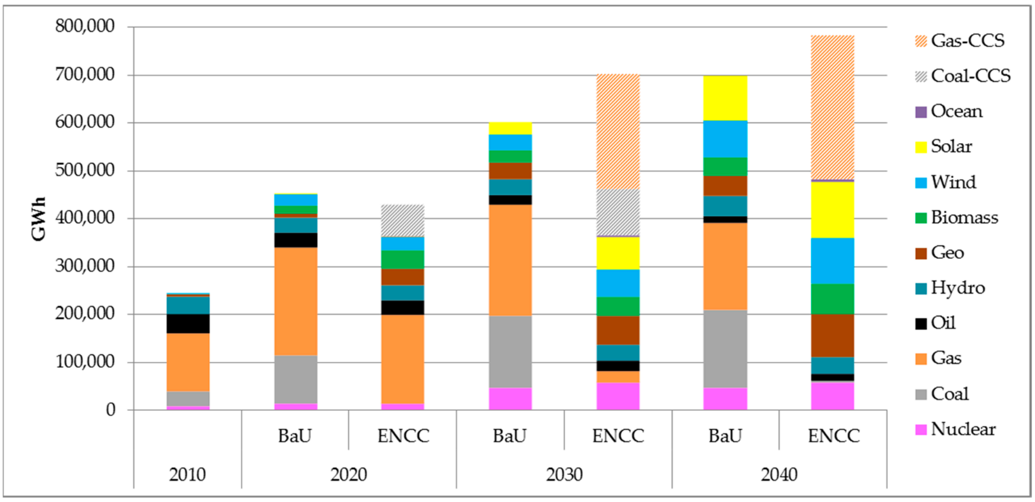


Figure 8. Electricity generation in the BaU and ENCC scenarios.

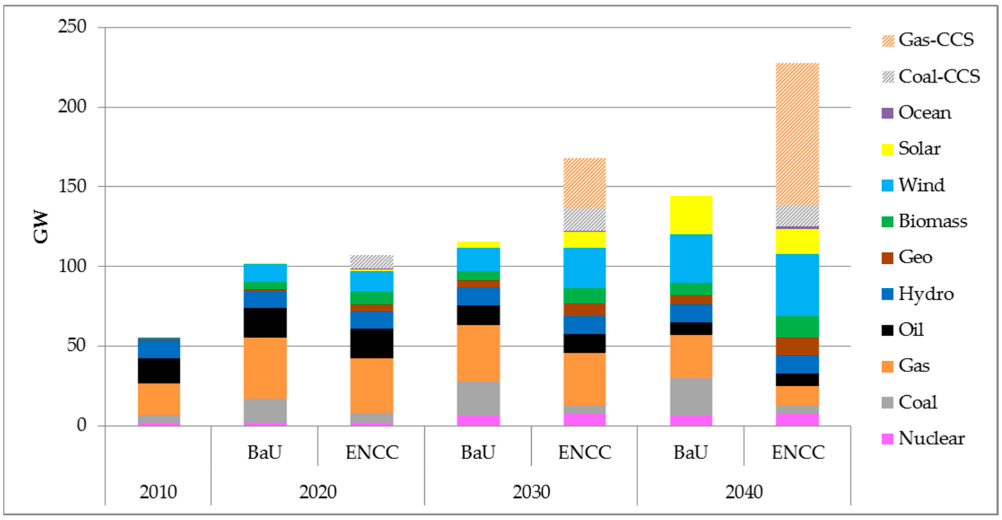


Figure 9. Installed generating capacity in the BaU and ENCC scenarios.

In the BaU scenario, in 2040, half of the electricity is still generated by fossil fuels (51%), with the rest being nuclear and renewable. Generation with natural gas still occupies the first place (39% in 2030, 26% in 2040) at the same time that the production in the oil facilities reduces in two-thirds. Coal power plants, however, still play a relevant role, contributing 23% to the total generation in 2040. Among the renewable technologies, the most relevant at the end of the time horizon are wind onshore (11%), solar PV (10%), and geothermal flashed steam and binary cycle (6%). CSP technologies contribute 3% of the total production. In this scenario, clean energy objectives are almost met in 2034 (39%). However, in 2040, the interpolated target to 2040 (43%) is easily reached (49%). Similar results are obtained by [26], who found that gas power plants dominate electricity generation and clean energy targets were attained even in the Base scenario. As pointed out by these authors, this might indicate that the current market conditions are sufficient to attain the clean energy targets in the electricity sector.

In the ENCC scenario, the distribution of electricity technologies is very different with a considerable participation of CCS technologies (38% in 2040), in fact, by this year, fossil fuels are only consumed in CCS plants. This results in 99% of clean technologies being, in 2040, the main contributors CSP with 15%, wind with 12% (2% offshore), and geothermal 11%. Electricity generated with biomass comes from CHP technologies in the industry sector. Nuclear technologies produce

7% of the electricity. Such a difference between both scenarios is due to the commitment of the CO_2 emissions reductions which, as shown in Table 1, are very ambitious.

Regarding the CO_2 emission limits, the objectives are also achievable in terms of technologies and resources availability but at 26% higher cost than in BaU. Results are shown in the next section.

Finally, the results of the historic evolution of the strategic indicators have been calculated from data gathered from literature and databases on the Mexican energy system. Then, the projections of those indicators have been estimated for the two scenarios described in Table 3 using the ETM energy model.

3.1. Environmental Sustainability

Two indicators have been defined to measure the environmental impact evolution of the energy system: GHG and CO_2 emissions from the energy sector and the share of non-fossil sources in electricity generation. The energy sector includes all the sectors and activities described in Section 2.1.

Past evolution of GHG and CO_2 in Mexico is shown in Figure 10. Emissions in 2014 are around 500 $MtCO_2eq$ for GHG and 480 Mt for CO_2. From then, in the BaU scenario, emissions continue growing until doubling the emissions of 2014 in 2040. Table 1 shows how ambitious the objectives of the ENCC are.

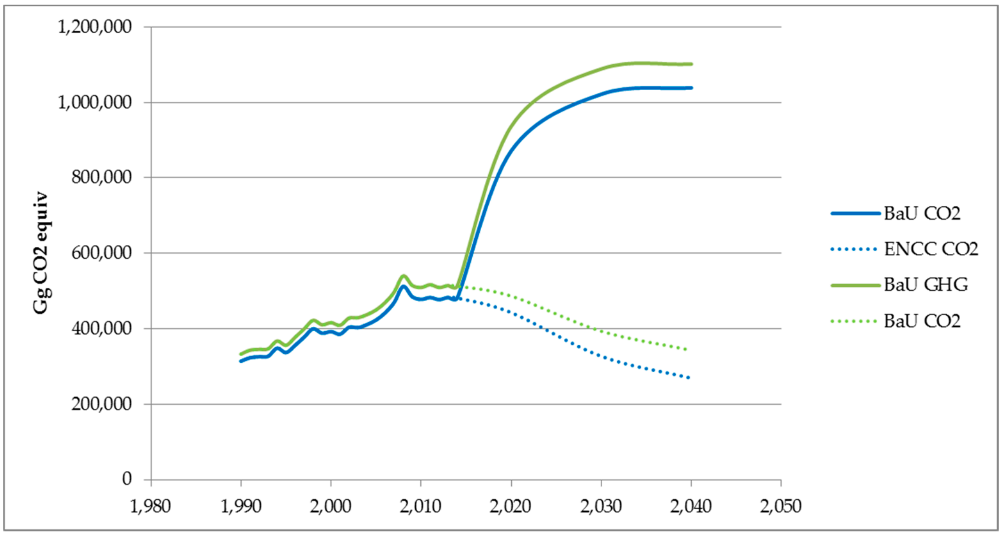


Figure 10. GHG and CO_2 emissions in the medium and long term for BaU and ENCC scenarios.

Meeting these objectives involves making some changes towards a sustainable energy system. All the sectors move to the use of technologies and fuels that are more efficient and less polluting. Figure 11 shows the evolution of final energy consumption by fuel and sector in both scenarios. In the case of the electricity generation sector, non-fossil technologies gain importance as described below.

The historic evolution of the share of clean energy sources in the electricity generation has been calculated from data from the Mexican Ministry of Energy [33]. This share has gone from 20% in 2002 to 22% in 2014. The evolution in the medium and long term calculated with the ETM model in both scenarios is quite different. While in the BaU scenario the growth of non-fossil sources share is constant with an average growth rate of 50%, in the ENCC the increase is much higher, reaching 94% in 2030 and 98% in 2040. The results of the past and future evolution are shown in Figure 12. Similar results regarding clean energies penetration in electricity production transport can be found in [20] when using the IMAGE and ECN-TIAM models.

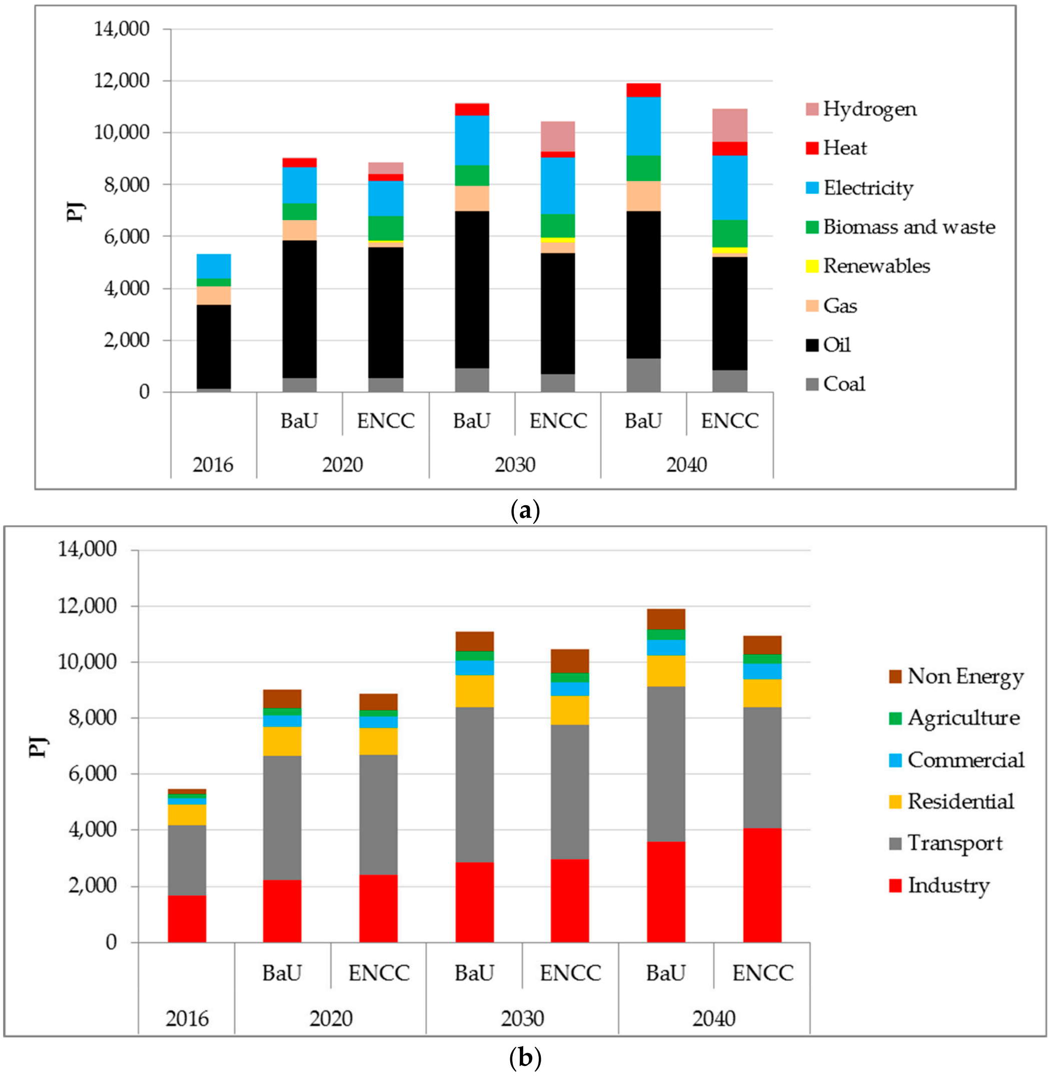


Figure 11. Final energy consumption by fuel and sector for BaU (**a**) and ENCC (**b**) scenarios.

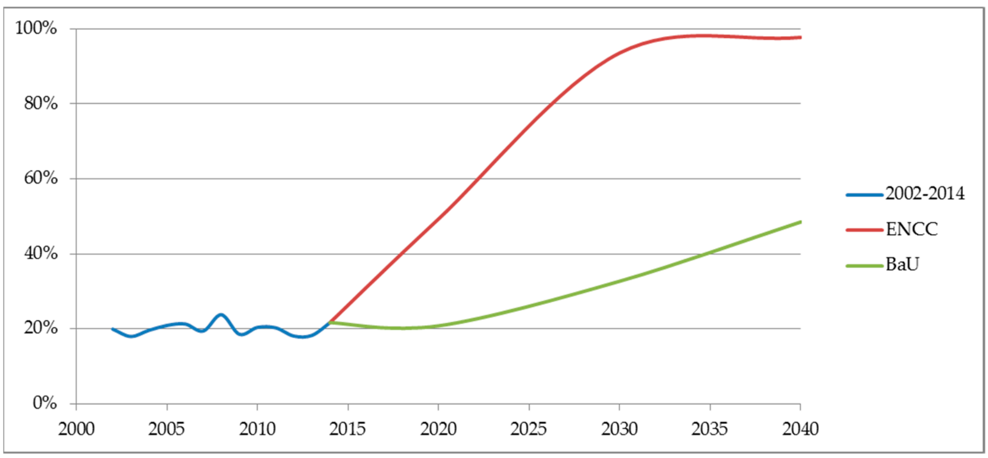
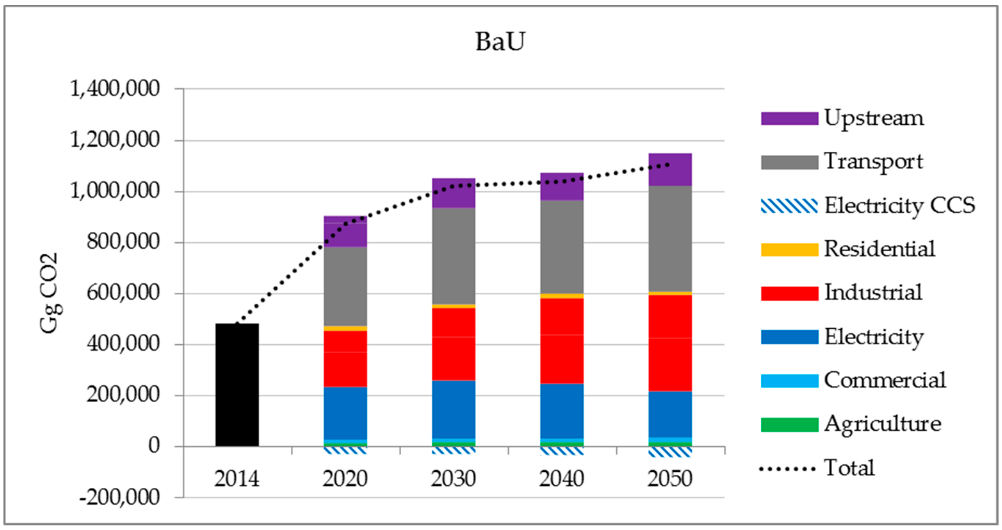


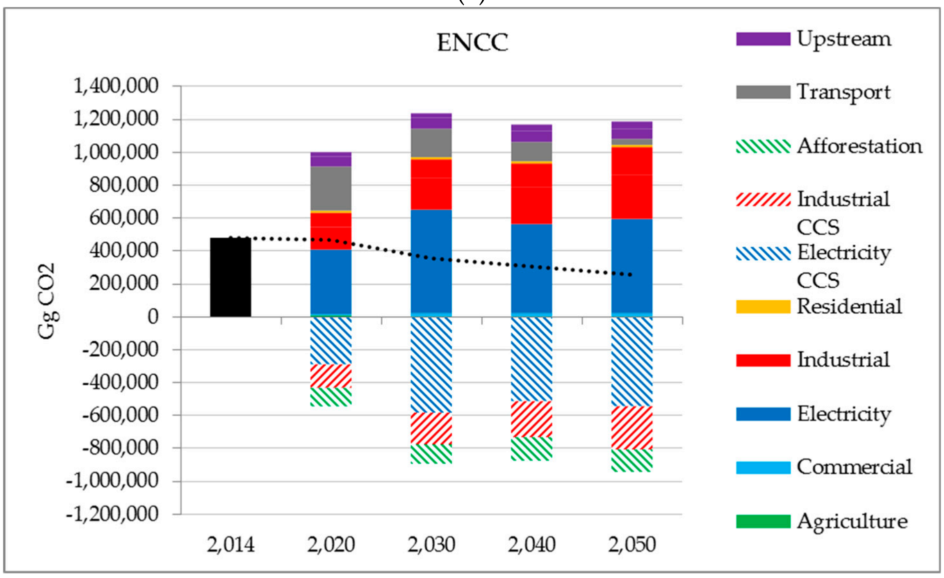
Figure 12. Past and future evolution of the share of clean sources of electricity generation.

Regarding GHG emissions by sector, Figure 13 shows the results obtained with the model in both scenarios.

Finally, the difference in total system costs in both scenarios has been estimated, showing that meeting the climate objectives leads to 26% increase in the energy system cost while the clean technologies targets are achieved without additional charges.



(**a**)



(**b**)

Figure 13. CO_2 emissions by sector in the BaU (**a**) and ENCC (**b**) scenarios.

3.2. Energy Security

Energy independence index and the diversity of sources in primary energy are the strategic indicators defined by the ENE to meausre the performance of the energy sector in terms of energy security.

Energy independence for the period 2004–2014 has been calculated as the ratio between the national energy production and the national energy consumption using data from [6]. The lower the ratio, the higher the dependence is. Future evolution of the indicator is the result of ETM for the two scenarios and is shown in Figure 14.

To estimate the diversity of sources in primary energy, the Shannon Index (H) [34] has been calculated using data on primary energy production by fuel from the Ministry of Energy [6] and from the modelling results from 2020 to 2050. The equation used for the calculations is as follows:

$$\mathrm{H} = -\sum_i (p_i) \ln p_i \quad (2)$$

where p_i is the share of fuel i in the total primary energy supply.

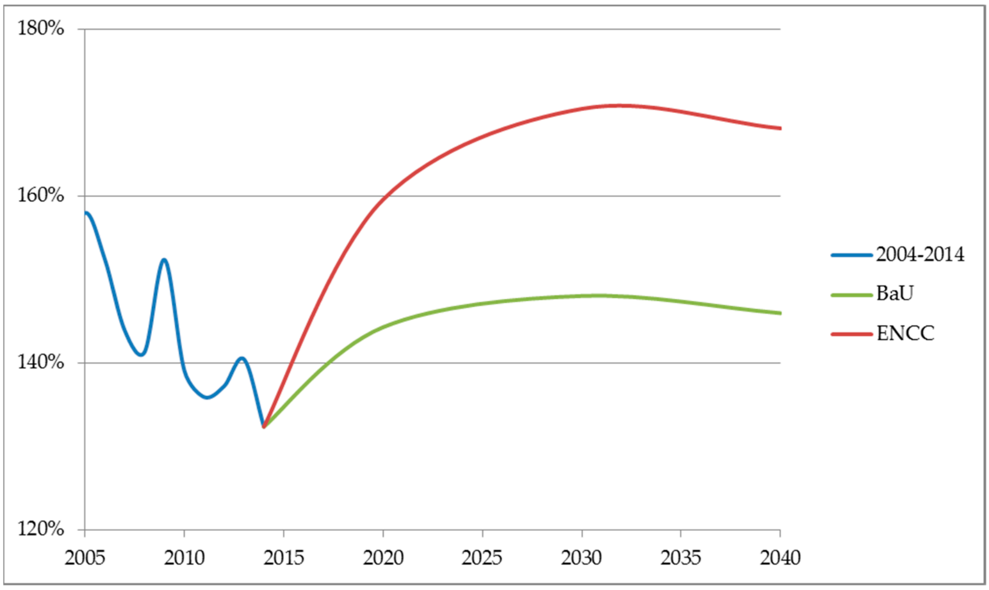


Figure 14. Past and future evolution of the energy independency in Mexico.

The higher the value of the index, the more diverse the system is. In this case, the index has increased 15%, from 0.98 to 1.12, in the period 2004–2014. This is the result of the introduction and growth of renewable sources: geothermal, solar, wind, and biogas (Figure 15).

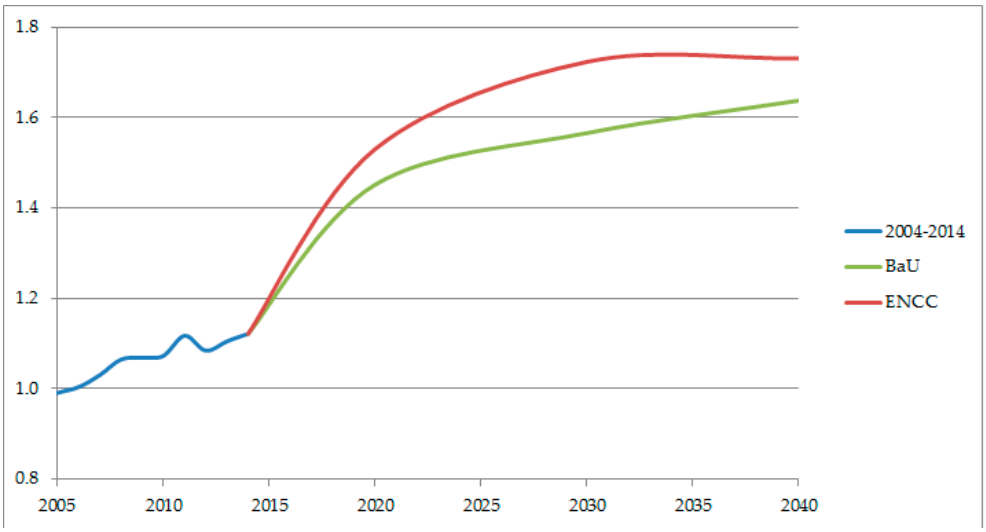


Figure 15. Past and future evolution of the diversity of energy sources in Mexico.

The trend of the index in the medium and long term is to continue growing in both scenarios until 2040, then in both cases remains constant with a slight decrease at the end. This is due to the penetration of renewable sources in the primary energy supply which, in ENCC, at the end of the period present similar shares as the fossil fuels in the previous periods. That is, diversity does not change, only some sources substitute others but in the same proportion.

3.3. Efficiency

The energy efficiency indicator chosen in this analysis is final energy intensity, defined as total final energy consumption divided by gross domestic product (GDP) at current prices. The lower the energy intensity the higher the efficiency is. To calculate the energy intensity evolution in the past, data from SENER for the final energy consumption [6] and data from INEGI [35] have been used. Results are shown in Figure 16. From 2004, the energy intensity has grown in a continuous way, except for 2009 when GDP and final energy were 1% and 5% lower than in 2008, respectively, as a consequence of the financial crisis. That means that energy efficiency in final consumption in Mexico has decreased in the period of 2004–2014.

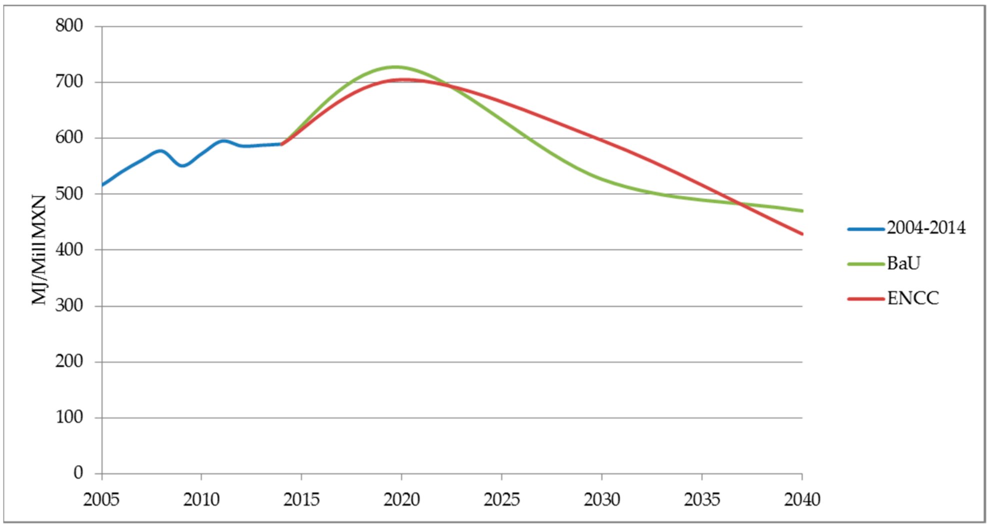


Figure 16. Evolution of the final energy intensity.

Final energy consumption in the medium and long term has been analyzed with the ETM model for both scenarios by sector and by fuel. Results have been shown in Figure 16 above. GDP projection comes from the general equilibrium model GEM-E3 under high demand assumptions.

4. Discussion

The results of the composition of the electricity sector under the ENCC scenario show how solar thermal technologies with storage and gas with CCS are ahead of solar PV and wind in the power sector. This could be considered unlikely due to the recent cost evolution of solar PV technologies. These results are at odds with some other from the recent literature, such as [26,27]. However, it should be kept in mind that costs are not the only factor affecting the penetration of electricity technologies in the model results. Aspects such as intermittency of some renewables, such as solar PV and wind, play an important role in a system with very high penetration of renewables. As recognized by [26] in their results, solar PV generation could reach an upper limit unless the system incorporates storage.

Comparing final energy in BaU and ENCC, there is, on average, a 6% reduction in the ENCC scenario as a consequence of the introduction of more efficient technologies, mainly in the transport sector where consumption decreases 28% in 2040 compared to BaU. The introduction of those technologies leads to higher efficiency that can be seen in Figure 16 from 2020 when energy intensity starts declining. The analysis of final energy consumption has shown that gas and oil consumption in ENCC scenario is considerably lower than in the BaU scenario, while renewables (especially biomass) and electricity and heat are higher. There is an early penetration of hydrogen in the ENCC scenario in the transport sector, which is the sector making the biggest effort in reducing energy consumption.

Concerning GHG emissions, the electricity and transport sectors are the ones making the biggest reduction effort either by capturing CO_2 in CCS power plants or by switching to low carbon fuels in the transport sector. Similar results are also obtained in the literature [20], where all the models agreed that decarbonization of electricity is needed along with changes in the transport sector, or in [14], that showed the relevant contribution that the electricity sector had to the national emissions reduction.

Regarding energy independence, the trend from 2004 to 2014 is to decrease. As has been seen in Figures 1 and 3, while national primary energy remains constant in the period, final consumption continuously grows, so energy dependence is higher from one year to the other. When the results of the optimization exercise in the medium and long term are analyzed, the evolution of the energy independence in both scenarios is quite different. While in the BaU scenario the trend is to start increasing again, in the ENCC one, it grows at the beginning but then reduces, always being above 140%. Although both primary and final energy in ENCC increase from 2020 to 2050, at the end of the period, the growth rate in the final energy consumption is higher than in the primary energy production, mainly because at the end fossil fuel's national production experiences reductions around 10%.

Finally, one study [36] establishes an additional methodology that allows considering a technical indicator in the selection of scenarios for the transition of electrical systems to a greater participation of renewable energy sources. The methodology allows one to optimize the combination of technologies of renewable energy sources (wind, photovoltaic, and bio) when there are future production limits for fossil sources. The optimization is obtained with the combination of technologies that requires the lower additional capacity of a natural gas combined cycle. The EnergyPLAN model is used to evaluate systems with high participation of renewable energies and with hourly information that allows one to consider the fluctuation of demand and production. The results show that in general, the greater penetration of bioenergy is desirable. In this article, the authors used a methodology similar to the one we are using for the evaluation of scenarios; the use of optimization models serves to validate the methodology we are using, however the main difference lies in the configuration of the scenarios.

5. Conclusions

The present study aims to analyze the impact of the National Energy Strategy in Mexico on the energy system in the medium and long term. Strategic indicators evolution has been investigated using an optimization energy model under two different scenarios, BaU and ENCC.

Five strategic indicators have been chosen: energy independence index, diversity of sources in the national energy system, energy sector CO_2 emissions, share of non-fossil sources in the electricity system, and energy intensity. Results show that the evolution of all those indicators when the ENCC targets are reached is positive, meaning that all the integration elements analyzed improve in the medium and long term.

In addition, analyzing the solutions of the optimization problem, that is the total costs of the energy system in all the periods, results demonstrate that meeting the CO_2 emission limits is achievable in terms of technologies and resources availability but at a high cost. However, the clean energy targets could be met even in a BaU scenario.

When CO_2 targets are set, solar thermal technologies seem to be a good option for the Mexican electricity system as well as gas with CCS technologies. Mexico must increase the proportion of renewable energy and clean technologies in its electricity generation mix by 2050 in order to achieve its goals for CO_2 emissions. However, in the current Mexican energy environment, the costs of increasing renewables or clean technologies could place an additional burden on electricity generation cost. This burden could be alleviated, at least in part, by the government supporting diffusion and innovation in renewable and clean technologies to create an industrial-urban-transport ecosystem. Such policies would help Mexico meet its sustainable development targets in the future as has happened in other regions, such as the European Union, where the effects of the policies can already been observed.

Possible policy implications of this work can be the convenience to promote investment in solar thermal and gas CCS technologies as these technologies seem to be good options for decarbonizing the Mexican electricity sector. Government support schemes addressed to these technologies and research and innovation programs are therefore recommended.

After the electricity sector, transport is the sector making the biggest GHG reduction effort by switching to low carbon fuels. Policies addressing research and promotion of low carbon fuels in Mexico are therefore recommended.

Author Contributions: All the authors conceived the work. D.C. and M.P.F. undertook literature reviews. A.R.-M and R.J.R. provided data-base, politics analysis and validation. Y.L. and H.C. worked and provided the results with the energy model. All the authors analyzed the data, prepared the writing-original draft, participated in the writing-review and editing, and worked on the discussion.

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