Power Generation Capacity Planning Under Ecological, Security and Economic Criteria: The Mexican Case[1]

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Abstract
There are increasing environmental concerns in México, as in many other countries, regarding the CO_2 emissions tendency, due mainly, to the intensive use of fossil fuel based electric generation. Recently, several laws and amendments have been passed in Mexico with the objective of promoting non-fossil generation technologies, aiming to increase their relative participation in the energy portfolio mix. Although several mid and long term objectives in this regard have been established in Mexico, these would be hard to achieve if the investment capabilities should continue to be directed mainly to fossil fuel thermal technologies, like natural gas on combined cycle plants, and proportionally less, to investment in non-fossil technologies. This article presents and evaluates three scenarios based on a System Dynamics model, to assess the non-fossil generation capacity investment and timing requirements, in order to achieve both ecological and safety strategic objectives, and at the same time satisfying the electric energy Mexican demand expectations.

Key words: Electricity policy. Non-fossil generation capacity expansion. Scenario analysis. Mexico.

Introduction

The demand for electric energy in Mexico is growing at an accelerated pace, and financial resources, both public and private, are insufficient to cover all investment needs in this field

Electric energy generation in Mexico is heavily based on fossil fuels. Mexico has abundant oil and natural gas reserves, but a significant oil production rate decline is expected to take place in the next decade.

CFE (Comisión Federal de Electricidad or Federal Electricity Commission), the Mexican state-owned electricity monopoly lacks sufficient investment resources, this situation has been a main driver to open the electricity generation industry to private investment. Since 1992, almost all new fossil fuel (mainly natural gas) power stations have been built and financed by the private sector thought some form of PPP (Private-Public Partnership) structure where the location, technology and fuel type is defined by the CFE.

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Several mid and long term ecological and system efficiency objectives have been established in Mexico. However, these will be difficult to achieve if investment in new capacity continues to be directed mainly to fossil fuels technologies, like natural gas combined cycle plants, and proportionally less to investment in non-fossil technologies.

The Mexican Power System

The first electric generation plant, coal fired, appeared in Mexico in 1879. Since then, the Mexican power system has been developing trough several technological stages; using hydro-electric non-fossil technologies; and, coal and fuel-oil technologies. In this period some crucial events have taken place, like the foundation of the CFE in 1937, the nationalization of the electric sector in 1960, the LSPEE law (See the glossary) allowing private investment in 1992 and the LAERFTE law in 2008, designed to foster the non-fossil generation technologies (Figure 1).

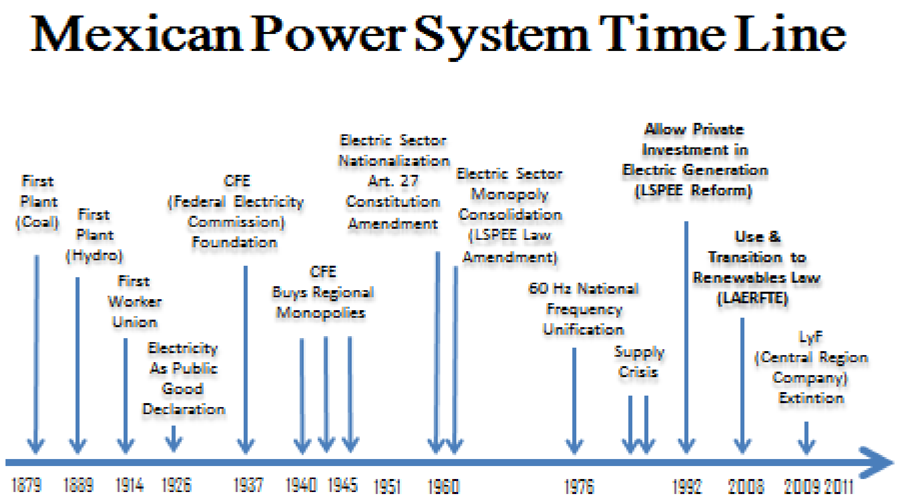


Figure 1. Main events in the Mexican power system.

Elizalde (2010) distinguishes three periods in the electric power generation sector in Mexico, each of them dominated by three different types of energy sources: the hydro era from 1965 to 1975, the fuel-oil era from 1975 to 2000 and the natural gas era from 2000 to the present. It is expected that in the next years this trend will continue with natural gas and combined cycle technology increasing their share (Figure 2).

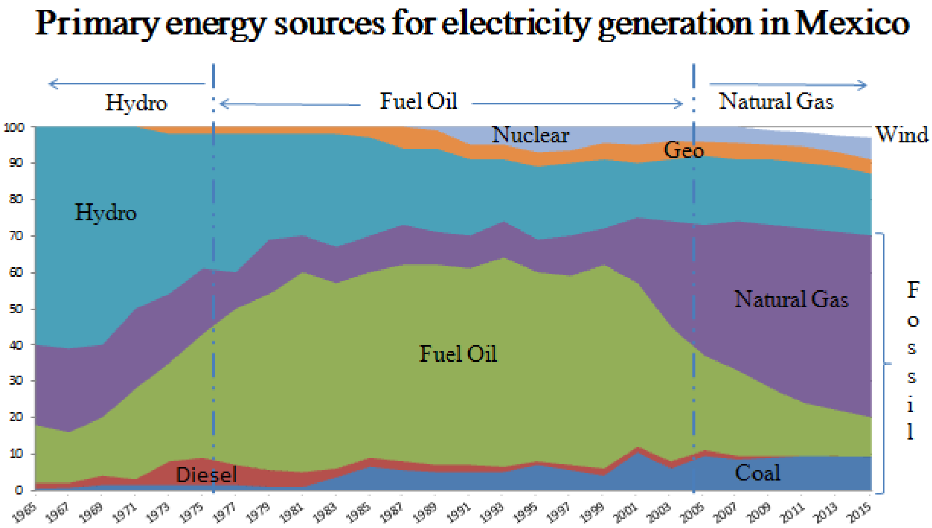


Figure 2. Increasing tendency of natural gas participation.
Source: Based on Elizalde, et al. 2010; SENER, 2009b.

The Mexican power system (Table 1) ranks 14th in electric generation capacity in the world. CFE has a Constitutional monopoly on electricity generation, transmission and distribution. Exceptionally, as a result of the LSPEE the private sector is allowed to participate in generation where it has proportionately little participation. Mexico's transmission and distribution grid presently has a total of 803,712 km.

The Mexican Power System

Installed Capacity (2010)	52.4 GW
Total Generation	236 TWh
Reserve Margin	49.1%
% Non-Fossil Participation	28.1 %
Total CO_2 Emmisions	132 Million metric ton CO_2
CO_2 emissions per capita	1.2 metric ton CO_2 / capita
Emissions from electricity generation	455 gm CO_2 / kWh
Losses	13.6 %
Transmission & Distribution	State Monopoly (CFE)
% Private Generation	31 %
Per cápita electricity use	1,810 kWh per year
Electricity Coverage	97.61 %

Table 1. Mexican Power System global data
Source: CFE, 2009; SENER, 2009a & 2009b.

There is a great potential in non-fossil resources in Mexico (Table 2) that may be efficiently exploited with an effective energy policy and capacity planning design.

Great Potential in Renewable Energies

	Actual Installed Capacity and Annual Generation	Estimated Potential
Oil	2.9 million barrels / day	Exhausted in 9.2 years 14,717 million of barrels
Natural gas	Mainly Imports	Exhausted in 9.7 years
Hydraulic	11.4 GW 19 TWh	80 TWh (3.25 GW Mini-Hydro)
Biomass	459 MW	803 MW 4.507 MWh per yer
Geothermic	965 MW 7.4 MWh	1.3-12 GW
Wind	492 MW	10-40 GW
Solar	25.1 MW	14 GWh 5 kWh/m2 per day

Table 2. Potential of the non-fossil technologies in México.
Source: SENER, 2009a & 2009b; Domenge, 2011; Romero-Hernández, et al., 2010

Current Mexican Energy Policy

Since 1993, when the LSPEE law was passed, the Mexican electricity sector has been experienced a process of opening allowing the participation in generation of private capital. Independent Power Producers (IPP) or private generators were allowed but must, save for a few self consumption concerns, sell all their capacity and production to CFE. The main technology used by the IPP is the combined cycle thermal plants.

In 2008, the Law for Using Renewable Energy Sources (LAERFTE, 2008) was introduced, designing a renewable energy program with the specific strategic objective among others, of: increasing, promoting and regulating the renewable energy portfolio mix (Figure 3).

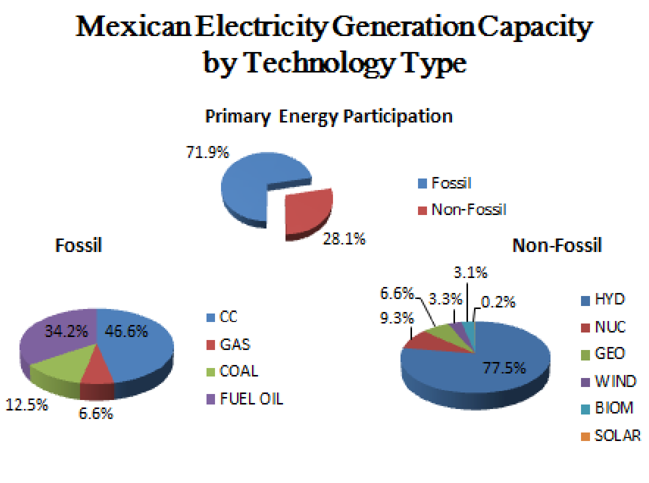


Figure 3. Mexican energy portfolio mix.
Source: CFE, 2009; SENER, 2009a & 2009b.

The IPP participation in electric energy generation has been growing as well as the use of natural gas generation technology (Figure 4) and there are several concerns about the tendency of using this kind of fossil technology in the future and proportionally less in non-fossil capacity. IPP current generation represents 22.1% of Mexico's installed capacity.

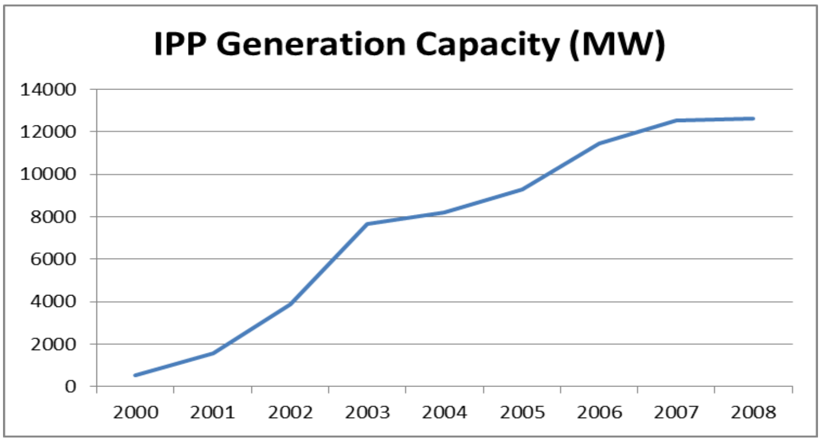


Figure 4. Independent Power Producers capacity.
Source: SENER, 2009b.

The energy policy and its practical implications, especially the use of primary energy sources in Mexico, is a function of its relative price and the available technology in each time period.

The Mexican Government's Energy Secretariat (SENER) is the public department responsible for directing the Mexican energy policy, regulating and promoting, among other duties, the use of non-fossil technologies and reducing fossil fuel dependence. There are three strategic lines that guide the Mexican electricity energy policy (SENER, 2009a & 2009b):

- Full Coverage with quality.
- Increase non-fossil usage in the energy portfolio mix:
  - Reduce dependency on fossil fuels (Reduce impacts of oil and natural gas price volatility, more diversification therefore more energy supply security and stability).
  - More Ecological and less CO_2 emissions.
- Improve the efficiency of the power system:
  - Reduce waste of energy consumption.
  - Reduce the system losses (transmission, distribution & theft)
  - Reduce long term costs.

Research Question

What are the generation capacity and timing requirements necessary to satisfy electric energy demand and ecological electricity generation mix strategic objectives in the 2012-2050 planning period?

The model

The analysis is based on a system dynamic model that generates and evaluates three scenarios. The objective of the model is the identification of the non-fossil and fossil generation capacity expansion, and time pacing requirements in order to achieve both ecological and reliable strategic objectives while supplying electric energy demand.

Model Structure

The conceptualization, structure and construction of the model is based on several sub-systems or molecules (Hines, 2005; Sterman, 2000; Lyneis, 1980; Albin, 1998); the stock management module describing the new power plants capacity construction dynamics, considering the fossil and non-fossil delayed times and capacity expansion levels (Ford, 2001, 1999; Albin, 1998; Sterman, 2000, Sánchez, et al., 2007, 2005); the electricity demand module based on a function considering population growth as exogenous variable and system and consumption efficiency per person as policy parameters (Davidsen, et al., 1990; Whelan and Msefer, 2003); the CO_2 emissions (Qudrat-Ullah, 2005; Flynn and Ford, 2005) and the cost modules (Ford, 1999) as technology functions and the fossil and non-fossil capacity construction investment (Olsina, 2005; Bunn, et al., 1997; Jalal and Bodger, 2010; Vogstad, K. 2004) decision as a goal seeking dynamics module.

Figure 5 shows the black box model structure. The model has three decision variables derived from policy changes, five outputs or performance measures and a series of parameters. Exhibit 1 shows the system dynamics model structure.

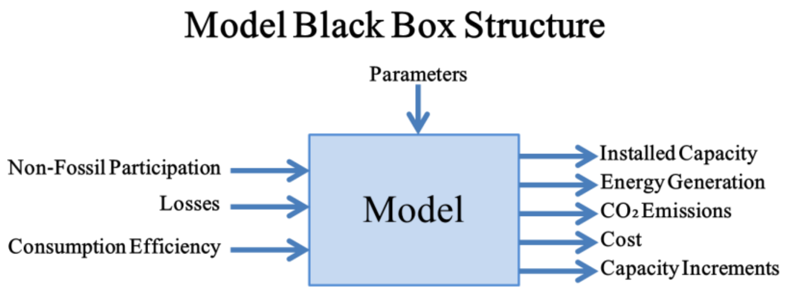


Figure 5. Model black box structure.

The model considers two electricity generation technology types: fossil and non-fossil. The fossil category includes gas, coal and oil as primary energy inputs. The non-fossil category includes water, nuclear, geothermal, wind, biomass and solar technologies.

Based on an electricity demand forecast, the model assigns the type of installed capacity requirements -fossil or non-fossil-, considering a given technology mix objective strategic, and an energy loss, a consumption efficiency and a reserve margin. It is also takes into consideration capacity expansion levels and a capacity construction periods for each technology.

Decision variables

- Non-Fossil participation: is the relation of the non-fossil installed capacity divided by the total installed capacity. It is part of the Mexican energy policy.
- Consumption efficiency factor: energy demand is a function of the population growth, the increase in per capita consumption and the consumption efficiency factor. A change is expected in consumption efficiency derived from the Mexican energy policy: the energy savings program (SENER-PRONASE, 2009), created to foster actions and programs necessary to achieve energy savings.
- Losses: there are several energy losses (technical and power theft) in the transmission and distribution activities. It is expected a loss reduction from 13.6% in 2012 to 8% in 2025 (CFE, 2010) following the CFE energy saving program.

Parameters

- Annual population growth rate: A 0.2% geometric average annual population increase is considered, based on Cancino (2010) data.
- Electricity use: It is expected that the demand per capita would increase faster than the population. Its actual value is 1,810 kWh per year but it is estimated to reach a value of 7,510 kWh in 2050 (based on Cancino, et al., 2010). It is also expected that the greatest growth will be in the tourist sector.
- Capacity expansion level: is the incremental amount per year for each type of technology (fossil and non-fossil). It is considered that there can be several investment projects at the same time for a given technology. Capacity increment has a delay or time lag between the investment decision and the real installed capacity. Capacity decisions have a "wave effect" causing periods of high and low reserve margins (Ford, 1999 & 2001), non-fossil participation, emissions and costs.
- Capacity useful life: for the relative short period of time considered (2012-2050), compared to the useful life of the electricity generation plants, the assumption in the model is that a minimal real decrease occurs in the installed capacity, both for fossil and non-fossil plants. For some different generation technologies, the useful life is: gas 25 years, coal 40 years, nuclear 40 years, photo voltaic solar panels 15 to 30 years and hydro 50-100 years (ONYSC, 2008; Alonso, et al. 2006; Jalal and Bodger, 2010).
- Costs: The values that are used in the model were the levelled or levelized costs of electricity (LCOE) lifetime cost approach. The LCOE is the unitary cost of generating electricity for a particular technology system over its economic life. It includes all the estimated costs and the amount of electricity generated over its lifetime: capital expenditure or initial investment required to engineer and construct the plant, cost of fuel consumed to generate electricity, fixed operation and maintenance costs (salaries, insurance and others that remain constant irrespective of the electricity generated), variable operation and maintenance cost (materials used or consumed as a function of the electricity generated), carbon emissions cost, decommissioning cost and the cost of capital, based on the discounted cash flow method (Khatib, 2010; AEO 2011; Alonso, et al., 2006; OECD, 2010). In the model, the parameters used are the weighted values using the technology participation for fossil and non-fossil primary energy source.
- Emission factor: is the amount of CO_2 emitted per TWh generated, based on Vijay (2004), for each type of technology (Lightbucket. 2008).
- Generation factor: is the weighted average of the electricity generation divided by the installed capacity for each type of primary energy source. The parameters used

in the model are based on data from CFE (2010). It is considered that all new fossil fuel capacity is a combined cycle technology.

- Reserve margin: is the difference between the effective installed capacity and the maximum demand of an electric system (CFE, 2009b), expressed as a percentage on the maximum demand. It is considered a value of 20% in the model.

Parameter	Value	Units
Annual population growth rate	0.2	% per year
Electricity use (2012) Electricity use (2050)	1,810 7,510	kWh per capita per year
Reference Reserve Margin	20	%
Fossil Emission Factor(1) Non-Fossil Emission Factor(1)	609 16	CO2 Mtons / GWh
Fossil Generation Factor(1) Non-Fossil Generation Factor(1)	6.48 3.21	Generation / Capacity
Fossil Cost(2) Non-Fossil Cost(2)	0.09 0.11	US Dll/ kWh
Fossil Capacity Expansion Level(3) Non-Fossil Capacity Expansion Level(4)	25 15	GW
Fossil Construction Capacity Period Non-Fossil Construction Capacity Period	5 2	Years

Table 3. Model parameters.
Notes: (1) Weighted (2) Levelized Weighted (3) CC (4) Renewables

Outputs or performance measures.

- Installed capacity: including the fossil and non-fossil new capacity expected expansion decision in the planning horizon, measured in Giga-Watts.
- Generation: total Tera-Watts-hour generated by the fossil and non-fossil generation capacity.
- CO_2 Emissions: total metric tons of CO_2 emission considering the fossil and non-fossil technologies.
- Cost: total cost of electricity generation considering both technology types.
- Capacity Increment: total number of times that the fossil and non-fossil capacities are expanded in the planning horizon.

Model Validation

Model outcomes credibility is based on model validation so several procedures were applied in order to do it, considering the assessment of the non-fossil generation capacity investment and timing requirements objective: boundary adequacy, structure verification, dimensional consistency, parameter verification, behavioral sensitivity and extreme conditions (Quadrat-Ullah and Baek Seo, 2010; Forrester and Senge, 1980; Quadrat-Ullah, 2008; Oliva, 2003). The boundary adequacy and structure and parameter verification are appropriate in terms of the inclusion of the important concepts, scenario parameters and the model structure for the policy decisions considerations. The behavioral sensitivity test is evaluated assessing the outputs and the model behavior for alternative parameter values. The extreme conditions assessment was made by changing the parameters values (Table 3) considering their possible real system value ranges. The dimensional consistency test was made by using the units consistency and syntax test tool provided in the Vensim software. Both units and syntax tests shows positive results, which means that the model does not include any dimension consistency errors. The results of the model validation tests were reasonable and expected.

Scenarios and Policy Changes

It is considered a model simulation time period from 2012 to 2050. The analysis is based on three scenarios with different goals for 2050. Planning assumptions and objectives are based on the conceptualization of each of these three scenarios (Table 4).

- Base Scenario: the goal of this scenario is to have a trend reference of the outputs or the performance measures, understanding system behaviour and giving insight into the elements, parameters, causal relations and drivers of the electrical generation system. This scenario takes the actual values of all the parameters of the system in the time horizon considered.
- Efficient Scenario: the assumptions on this scenario are a decrement in the system losses in transmission and distribution (CFE, 2010: Electric Sector Investment Program), and a final user savings (SENER-PRONASE, 2009: Mexican Government Saving Program).
- Green Scenario: the assumption in this scenario is a combination of an increment in the participation of the non-fossil electricity generation technologies (SENER, 2009a), a reduction of the system losses and a final user savings.

	Base Scenario	Efficient Scenario	Green Scenario
Non-Fossil Participation (NonFossil / Total)	28.1%	28.1%	40%
Losses	13.6%	7%	7%
Consumption Efficiency Factor	0%	1%	1%

Table 4. Scenario assumptions & 2050 objectives.

Results.

The scenario simulations show that there are no significant cost differences between the Green and the Efficient scenarios (Table 5 and Exhibits 3 and 4), although the installed capacity is higher in the latter. In the Green scenario, the emissions are lower than in the other scenarios, as expected, and also the number of new non-fossil expansions is higher in this scenario compared to the Efficient one. The Base scenario has the higher outputs due to the lack of ecological and efficiency policy decision application (Table 5 and Exhibits 2a to 2d).

	BASE	EFFICIENT	GREEN
Electricity Demand (TWh)	783	486	486
Total Installed Capacity (GW)	183	129	144
Total Generation (TWh)	946	692	740
Total CO_2 Emissions Index	74	62	57
Total Costs Index	81	66	67
Fossil Capacity Increments	3	2	2
Non-Fossil Capacity Increments	4	2	3

Table 5. Performance measures outputs.

Conclusions and Further Applications.

Electric generation capacity expansion decisions must face tradeoffs in choosing among several power generation technologies, primary fuels, environmental impacts, political situation and regulatory schemes. If the strategic objective is to be achieved (energy demand under ecological, security and economic criteria) the non-fossil/fossil generation mix capacity expansion decisions and time pacing assessment are crucial.

The Green scenario simulation shows that there are no significant cost differences between this scenario and the Efficient one, but it has a significant difference in CO_2 emissions. The cost difference between these two scenarios and the Base one is due mainly to the system losses and consumption efficiency policies (demand difference) and not to the technology used.

The model could be used as a tool to raise awareness about challenges in electricity generation capacity expansion investment requirements, energy system and final user efficiency policies, and business opportunities in the non-fossil fueled generation technologies in the next decades in Mexico.

The expected dynamics of each type of consumer demand could be considered in the model : (Residential: 26.7%, Industry: 56.5%, Commercial: 7.4%, Services: 4.3%, Agricultural: 5.1%). Model applications could be expanded and parameter adjusted for each type of generation technology, fossil and non-fossil.

Exhibit 1. The model.

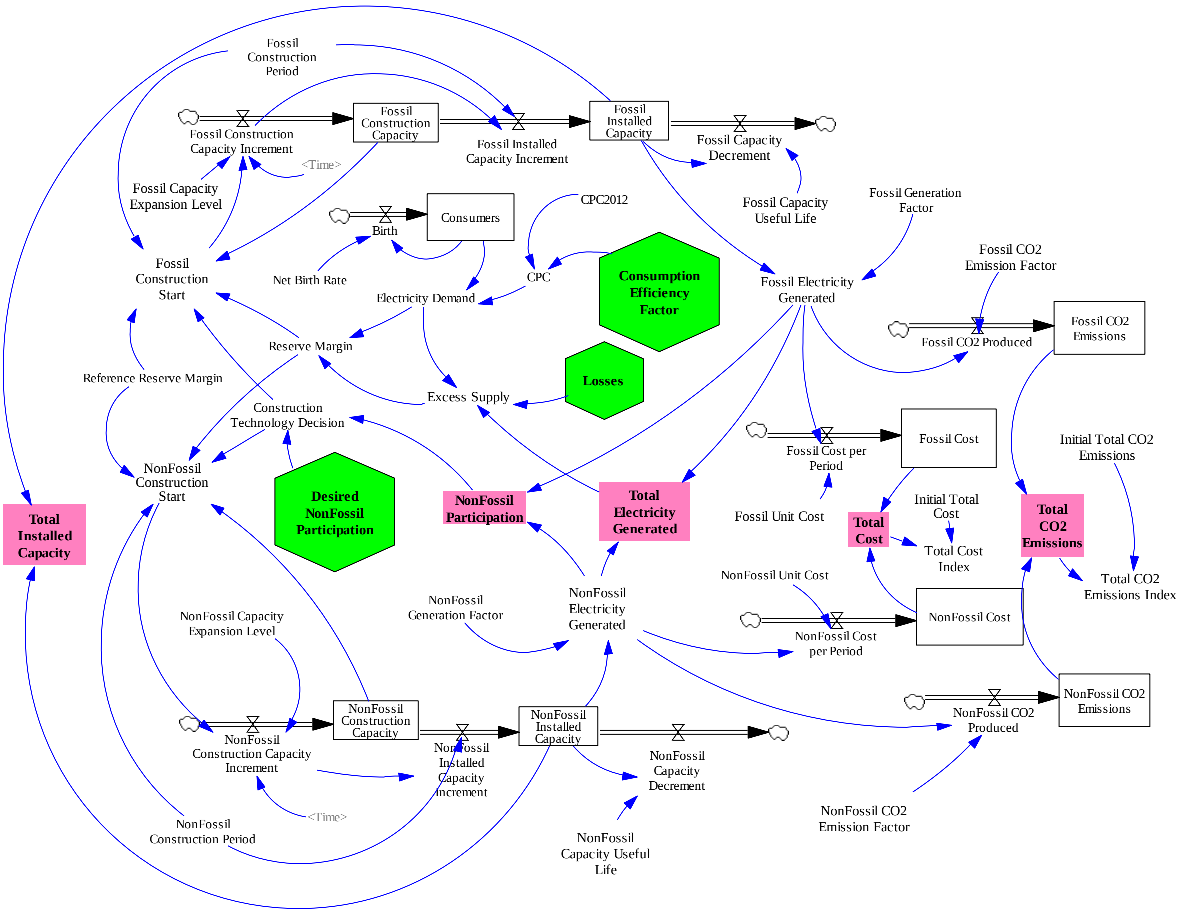


Exhibit 2a. Installed Capacity Increments: Total

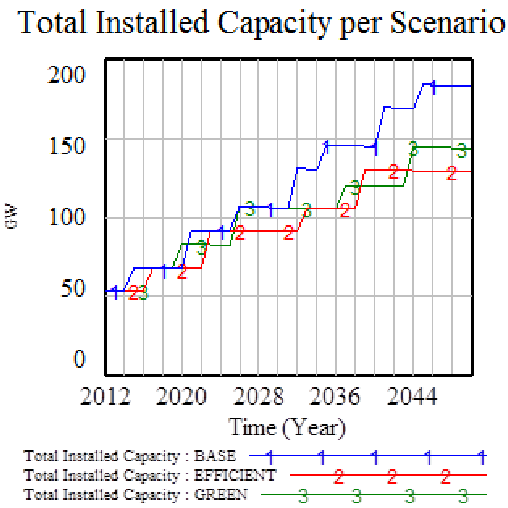


Exhibit 2b. Installed Capacity Increments: BASE Scenario.

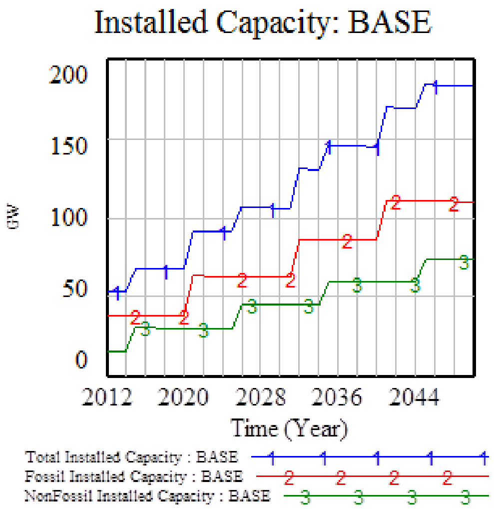


Exhibit 2c. Installed Capacity Increments: EFFICIENT Scenario.

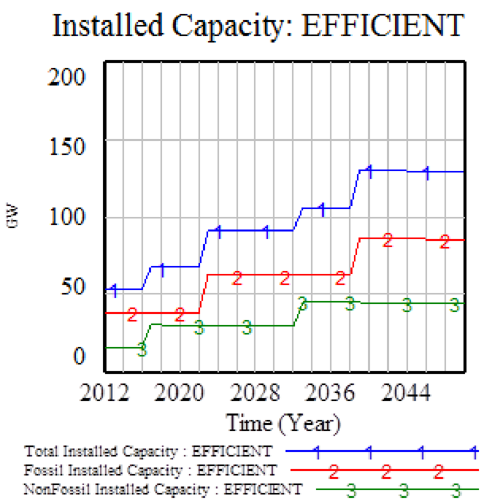


Exhibit 2d. Installed Capacity Increments: GREEN Scenario.

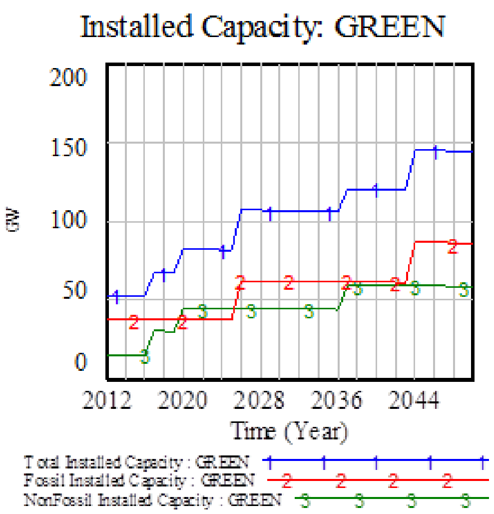


Exhibit 3. CO_2 Emissions.

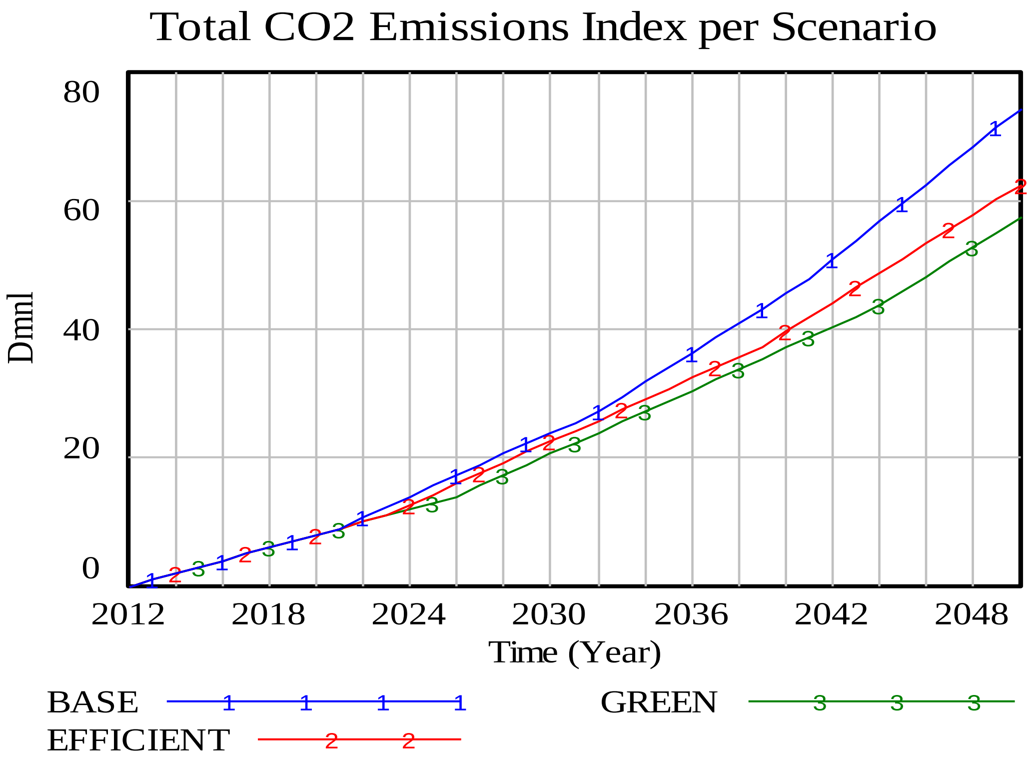
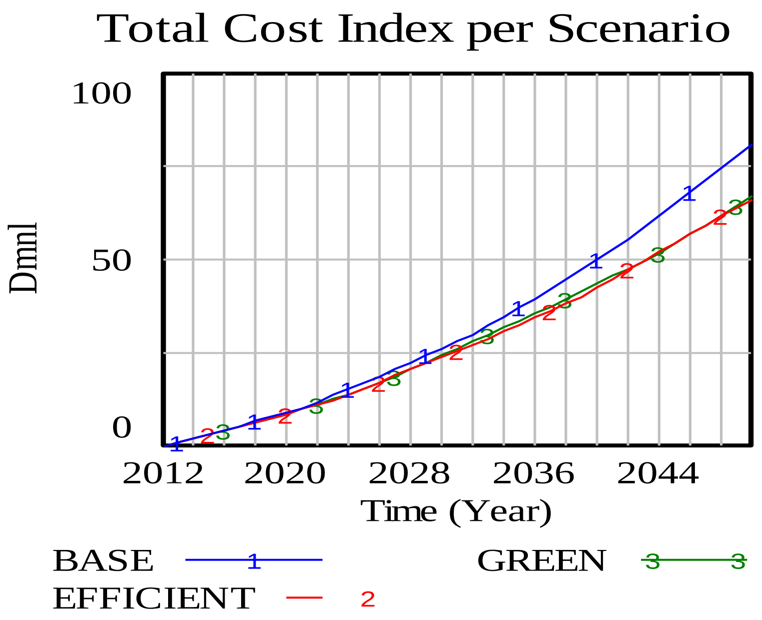


Exhibit 4. Total Costs per Scenario.



Glossary

CC:	Combined Cycle gas based electricity generating plant.
CFE:	Comisión Federal de Electricidad. Federal Electricity Commission, the Mexican state-owned electricity monopoly.
IPP:	Independent Power Producer. Private owner electricity producer.
LAERFTE:	Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética. Law for Using Renewable Energy Sources
LCOE:	Levelized or levelled costs of electricity.
LSPEE:	Ley del Servicio Público de Energía Eléctrica. Electrical Public Sector Law.
LyF:	Luz y Fuerza del Centro. The Mexican state-owned electricity company that operated in the central Mexican states. It was closed in 2009.
PPP:	Private-Public Partnership.
PRONASE:	Programa Nacional para el Aprovechamiento Sustentable de la Energía. Energy savings program.
SENER:	Secretaria de Energía. Mexican Government's Energy Secretariat.
W:	Watt: Electric power generation capacity (stock) unit. kW = 1000 W; MW = 1000 kW; GW = 1000 kW; TW = 1000 GW
Wh:	Watt hour: Electric energy unit. Amount of energy consumed or generated (flow) per hour. kWh = 1000 Wh; MWh = 1000 kWh; GWh = 1000 kWh; TWh = 1000 GWh

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