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Trade-offs in Electricity Planning in Mexico

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Trade-offs in Electricity Planning in Mexico

by

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Dedication

A mi padre

Porque su amor a la vida e inquebrantable integridad

Me han marcado un camino a seguir

A mi madre

Porque su ejemplo me enseño

A hacer fáciles las decisiones difíciles, a escoger lo bueno sobre lo malo,

A que ser un buen hijo me hace ser un buen hombre

A mis hermanos

Por su incondicional cariño e interminable alegría

A Paloma, Rodrigo, Isa, Toño

Para que sepan que siempre estamos a su lado

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Abstract

Trade-offs in Electricity Planning in Mexico

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Electricity generation is a vital element of economic growth, and it is necessary to encourage a growth model that does not endanger the capacity of a country to generate electricity.

Generating electricity entails costs. This cost is not only economical but can also be, for example, environmental. This implies that there are different trade-offs associated with choices about how to generate electricity, such as technologies, fuels, impact on the environment, construction costs, budget constraints and so on.

The Federal Government owns Mexico's electricity sector. As such not only does it write the rules of the electricity sector but it also executes these rules. The government has stated a series of guiding principles regulating the electricity sector. These guiding principles reflect the priorities that should be taken into account when designing electricity portfolios.

My thesis uses financial tools to offer a new approach to the problem of developing electricity portfolios. I assume that the electricity generation mix can be seen as a portfolio of assets. Using portfolio management techniques, I demonstrate scenarios for efficient portfolios given key assumptions about generation choices and prevailing costs. I also illustrate the implications of prioritizing one guiding principle over the other in terms of portfolio cost.

Finally, my use of a portfolio modeling approach highlights the complexities inherent in public policy making given the technical and cost-driven nature of the electric power businesses and value chains. My work provides a possible method for more productive evaluation of various approaches in light of mixed priorities and the broad diversity of stakeholders in Mexico.

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Introduction

As a developing country Mexico faces many challenges. One of the most important is sustainable growth. Mexico must grow at a rate close to 5% for at least 15 years to achieve the status of what is considered today a developed nation.[1] Economic growth requires, and implies, a rise in the consumption of energy. The provision of energy entails both costs and benefits. With current technology these costs and benefits could be considered economic, environmental or related to supply. While some sources of energy offer a high benefit/cost ratio, others offer a low impact to the environment but also a low benefit/cost ratio. The incentives involved in the decision over which facility to build change from country to country. In general, countries and societies strive to achieve net benefits from energy provision and use, balancing economic and ecological concerns. This undertaking is fraught with difficulty given the challenges in measuring life cycle, energy balance costs and benefits (lack of data and information and lack of transparency in many policy arenas). Most countries prioritize economic considerations over environmental. One notable exception is Germany, which prioritizes environmental and national security concerns (Federal Ministry of Economics and Technology, 2010). But even in this case, economic considerations are highly considered: it is unreasonable to invest in non-economic solutions.

Ideally speaking, energy sources would not deplete, have zero impact on the environment and be nearly free. Ideally, also, people would use energy in the most efficient possible way. The truth is that generation and transmission of energy is costly. It can have net negative impacts on the environment and most known generation fuels

[1] Considering a criteria of reaching a GDP per capita of USD $25,000. This figure does not take inflation factors into account.

deplete. The truth also is that energy is a consumer good and consumers freely choose how to use it. The impacts of the generation of electricity depend on the type of fuel that is used. This means that every fuel has different economic, environmental, and supply issues to consider. This implies that there are trade-offs between each fuel. The *trick* is to correctly assess these trade-offs so it is possible to take a correct decision, one that considers all relevant variables.

Trade-offs in the generation of energy are not clearly defined in the public mind. There is an awareness of the impact that an indiscriminate use of some resources can have on the present and future availability of other resources. This has made environmental issues part of the public agenda. This awareness also forces democratic governments to promote environmentally safe programs and processes. On the other hand, this awareness has not led to an increase in public knowledge. In general, people are cognizant that generation of energy can have an ecological impact, and that it is desirable to reduce this impact. However, ideology crashes with reality. While it is desirable to reduce the environmental impact of generation of energy, it comes with a cost. What is this cost? What are the trade-offs?

This thesis will attempt to provide guidance of what these trade-offs are. It will focus in generating electricity in the Mexican context. What are Mexico's priorities in the energy sector? What is the cost of choosing each priority? The scope of my thesis will be to analyze the government priorities and compare it to an efficient and feasible design of electricity generation portfolios. I do not intend to be exhaustive but to offer a guide that could be applied if contextualized properly. I will begin by describing and explaining the concept of cost-benefit analysis and the financial tool that will help my analysis. After this is done I will describe the current technologies that provide electricity to the world, as well as their net benefits, as they are understood though the description of the electricity sector. Next, I will describe the current Mexican energy sector and then discuss and evaluate the government's policies. To round up, the thesis will offer a new approach to the development of new electricity portfolios in terms of financial theory. This will help develop a series of efficient and feasible electricity portfolios. Finally a cost-benefit analysis will put together all the work done throughout my thesis.

Chapter 1: Theoretical Framework

This thesis will use a cost benefit approach to suggesting solutions to the design of the electricity portfolio in Mexico. In order to do so I will use portfolio theory to develop feasible portfolios. This chapter describes the basics of these theories and justifies its use within this work.

COST BENEFIT ANALYSIS

The cost benefit analysis is a decision tool that establishes a criterion that assigns cost and benefits to a certain project. In order for the project to be accepted, benefits should exceed costs. A traditional cost benefit analysis consists of six stages (Pearce, 1998):

Stage 1: Definition of project

Stage 2: Identification of Project Impacts

Stage 3: Which Impacts are Economically Relevant?

Stage 4: Quantification of Relevant Impacts

Stage 5: Applying Net Present Value (NPV)

Stage 6: Sensitivity Analysis

In order to correctly assess the cost and benefits for this thesis, I will describe the electric industry and the situation of the electricity sector in Mexico. Defining correct costs and benefits could be hard when analyzing intangible issues. My thesis will use a cost-risk approach to defining portfolios. This will help understand the associated costs of designing electricity portfolios. Chapter five will present a set of guidelines that define national priorities in the design of portfolios. Government priorities cannot simply be defined in terms of numerical costs and benefits, as it is not a private company. Nonetheless it must still define its choices in terms of a defined set of costs and benefits.

If the priority is to connect two towns then the decision should be made in that sense. The fact that no economic benefits are considered is no justification to, for example, build a high-speed train rail if it is not needed and not part of the benefits and needs. Chapter seven will retrace the eight stages of a cost-benefit analysis in order to apply them to the decision problem that Mexico's Energy Ministry, Secretaría de Energía (SENER) will face.

PORTFOLIO THEORY

This paper will propose a model of sustainable development based on basic financial theory. Financial theory is useful for understanding the concepts of risk and return and how they can be used to create a portfolio, or collection of assets, efficiently. This paper will use this theory to develop a model that could be a guideline for an energy portfolio mix for Mexico.

To create a portfolio built upon physical assets is different than creating one based upon financial assets. Modern portfolio theory assumes that it is possible to sell in short[2] and that you can divide any asset as needed. It is evident that achieving theoretical ideals is not always possible when building a portfolio standard and some of these considerations must be taken into account (Awerbuch and Berger 2003).

Risk and Return

The notion of risk and return is one that is innate in all of us: the more there is at risk the higher the reward you could expect[3]. Traditionally, risk is measured as the standard deviation of expected returns. The standard deviation measures the average

[2] This means to buy an asset through debt to sell it in order to finance the acquisition of another asset.
[3] A higher standard deviation (risk) does not in fact imply a higher return. It implies that there is a possibility of a higher *expected* return.

dispersion the values from the media. The idea is that the greater the dispersion is the greater the uncertainty about the future returns.

The expected return of a portfolio is simply the weighted average of the expected returns of all individual investments. It can be defined as follows:

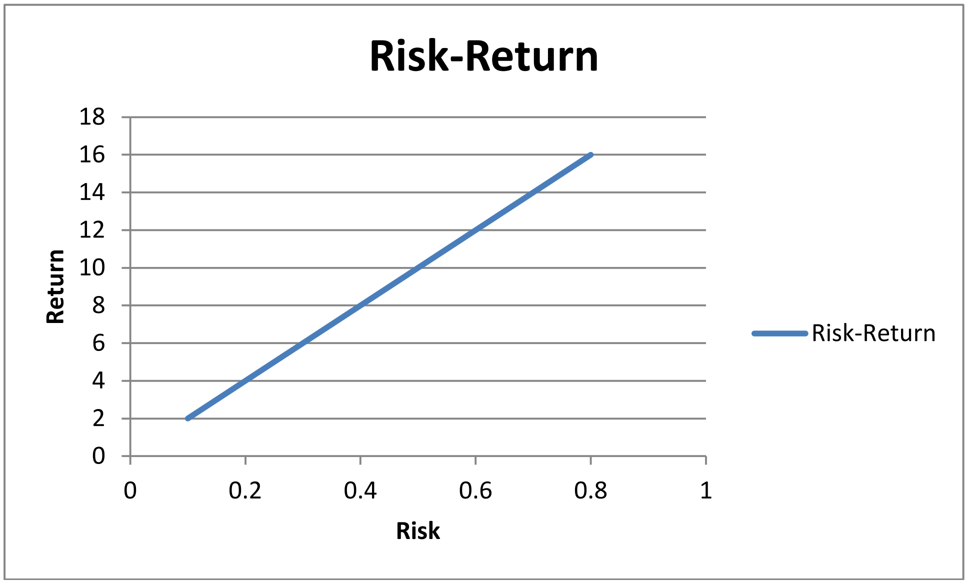
$$E(R) = \sum_{i=1}^{n} W_i E(R_i)$$

The standard deviation of a portfolio includes one new concept: covariance. Covariance is as a measure that indicates how much two variables move in respect to their individual means. This indicates the direction and degree in which these two variables move. It is a key concept in designing investment portfolios because it is the variable that permits us to reduce risk through diversification. In order to better interpret the covariance it is important to standardize the result. This standardization yields the correlation ρ, which is a number between -1 and 1. This number is very easy to interpret, the sign indicates if both variables move in the same direction, and the result the degree of correlation, where 1 indicates perfect correlation and 0 indicates no correlation at all. The standard deviation of a portfolio is[4]:

$$\sigma_{portfolio} = \sqrt{\sum_{i=1}^{n} w_i^2 \sigma_i^2 + \sum_{i=1}^{n}\sum_{i=1}^{n} w_1 w_j Cov_{ij}}$$

[4] $Cov_{ij}= \rho_{ij}\sigma_i\sigma_j$

Figure 1: Relationship between risk and return



There is an evident tradeoff between risk and return. Risk-averse investors will prefer to choose those portfolios that offer the least risk even though they will also offer the least expected return[5]. Not all individuals are risk averse and some will prefer to obtain a higher return. In any case the efficient frontier shows the ideal portfolio for any preference (Reilly and Brown 2003).

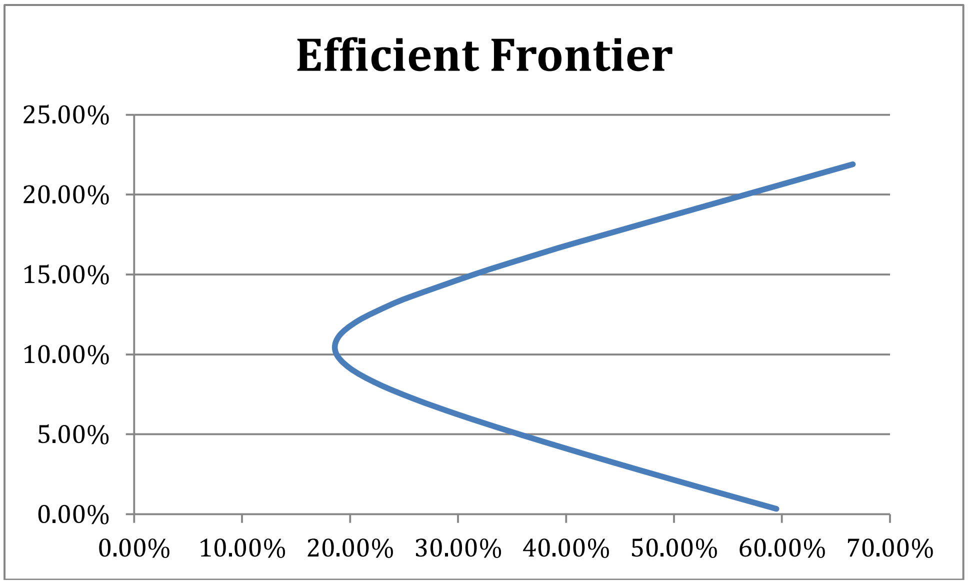
Efficient Frontier

Imagine a portfolio with two assets: A and B. Asset A has an expected return E(r) of 17% and a standard deviation, σ, of 41%. Asset B, on the other hand, has an E(r) of 7.2% and a standard deviation, σ, of 26%. These two assets show a correlation, ρ, of 0.8. Intuitively we would expect, if we want a portfolio with the lowest possible risk, to select one made up entirely of asset B. This proves to be inefficient. Because of the effects of

[5] We should remember that even in this scenario the investor is better off than by investing the asset with the lowest standard deviation.

correlation, there are combinations of assets that, for less risk show a greater return. The following figure shows the efficient frontier of this portfolio.

Figure 2: Efficient Frontier of a Portfolio



This figure clearly shows the advantages of diversification. For the same amount of risk, for example 30%, there are two possible Expected Returns: 7% and 15%. Rational investors will always choose the latter. It is possible to choose portfolios with lower risk and higher return than asset B. This is possible if a portfolio M is chosen. Portfolio M consists of 30% asset A and 70% of asset B. If an investor finds the level of risk of asset B acceptable, he could choose portfolio N, consisting of 66% asset A and 34% asset B. If on the other hand the investor is looking for a level of return similar to that of asset A (15%) he could choose portfolio O, consisting of 80% A and 20% B. This analysis could be done for any desired risk-return combination over the efficient frontier. This same concept will be very useful later on when this same concept is applied to the design of efficient energy generation portfolios.

Chapter 2: The Electric Industry

The electric industry describes the process that converts raw material into end use electricity. This chapter will begin by describing the energy value chain and by describing the most common technologies that generate energy.

The electric industry could be considered the sum of three processes. These three processes are the ones that generate value to the industry. The energy value chain can be described as follows (Moore and Wustenhagen 2003):

Figure 3: Energy Value Chain

Not unlike other industries, the electric industry has certain characteristics that are critical for understanding the value chain. In order to understand the difficulty of planning electricity systems it is important to note that the value chain is restricted by some unique attributes.

The first attribute has to do with physical laws, specifically thermodynamics. The first law of thermodynamics states energy of a system remains constant. This means that by definition an electrical system can only "break even." A second restriction arises from the second law, which describes entropy. Systems tend to lose energy. These laws basically mean that all electric systems are, by definition, inefficient. This causes several evident problems when planning and operating an electric system. Different technologies offer different efficiencies and this has a direct impact on the cost of generation.

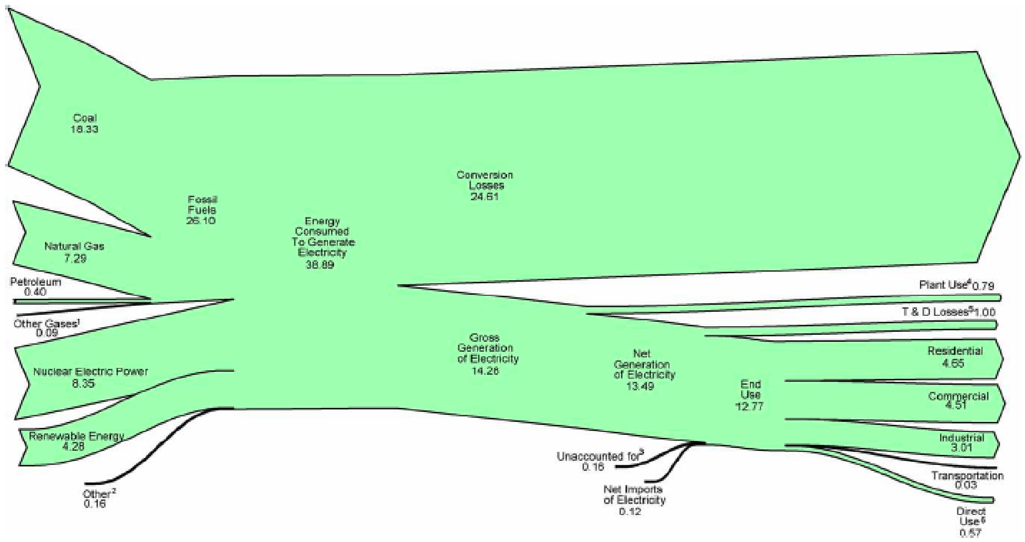
A second attribute is that electricity cannot be stored. Current technology makes the storage of energy absolutely unviable. Electricity has to be generated as it is consumed. The consumption of electricity is not constant throughout the day or even across seasons, resulting in different load profiles. Electric power systems must be planned for base, intermediate, and peak loads. Different generation technologies are more or less suitable for each type of load. This means that electric systems have to be planned according to accurate forecasts and appropriate demand management is needed because the system must be built so it can meet the highest peak load at any time. Market forces can provide that demand side management (rationing electricity usage in response to price). Alternatively, policy makers and regulators can impose demand side management regimes, but these are almost always less effective with many unintended consequences.

A third attribute is that electricity has to be constantly transformed. In order to more efficiently, and therefore more economically, transport electricity, it is converted to a higher voltage through a transformer. Electricity then moves to a substation. The system of transmission lines is known as the grid. The grid usually operates in Alternating Current (AC). However, when transporting bulk electricity through very long distances, High Voltage Direct Current is used for its lower costs. Electric power systems suffer fewer losses when high voltage is used, but that high voltage is not suitable for end use consumers; hence, the current must be again transformed to a lower voltage for distribution.

All of these particular attributes of the electric industry lead to an overall natural inefficiency inherent in the system. This inefficiency also creates a "media" problem, as the general public is not aware of these issues. Public support for renewable technologies obviates these facts.

The following data is useful to understand how inefficient the system really is. According to data from the U.S. Energy Information Administration (EIA) only 13 quads from the 40 quadrillion Btu consumed for power generation in the United States are actually used as electricity. The following figure describes the flow of electricity in the United States. It shows how it is fueled and the final uses. The most notable thing is that almost 25 quads are lost in the process.

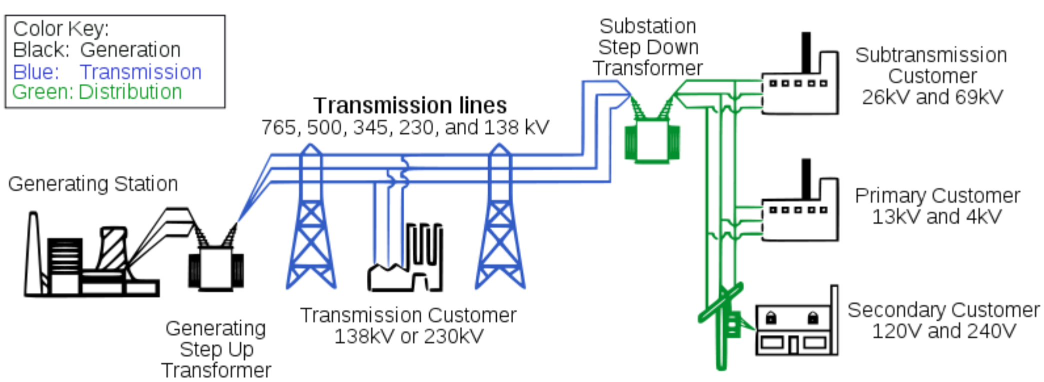
Illustration 1: Electricity Diagram in the United States



Source: EIA, 2009

As mentioned before, three processes form the electricity value chain: generation, transmission, and distribution. The following illustration graphically describes these processes, as described briefly above and in more detail below.

Illustration 2: Graphic Diagram of Electricity Value Chain



Source: Wikipedia (Public Domain)

GENERATION

Generation is the most important process of the electric value chain. It is through this process that a raw material is converted into electricity. While there are several ways to generate electricity, most of the electricity generated in the world comes from the conversion of mechanical energy, created using thermal processes, to electrical energy.

A generator in a power plant produces electricity. The power plant process is divided into two basic steps, motion and electricity generation. Traditionally the process consists of creating motion so that it turns the blades of an electromechanical generator. This movement results in the generation of electricity. At the end of this process electricity goes through a transformer that will increase the voltage of the electricity so it can be transported more efficiently.

There are different types of generators, which depend on the way they are fueled. Electricity is a secondary form of energy. The primary form of energy is the fuel feedstock. This is especially important because it is easier to administer demand. Since electricity cannot be stored, it is useful to have a "safety net" in the form of fuel; the fuel source acts as the store of energy. Fuels come from different sources; traditional and renewable sources.

Conventional Sources of Electricity

The term that refers to traditional energies is not well defined. It is normally used as a synonym for fossil fueled energies, but that leaves out nuclear energy. In any case a practical way to describe traditional energies is to define them as those whose input diminishes with use. The energy sources that can be classified under this label are:

- Fossil Fueled
    - Coal: It is mainly used for electric generation. Power plants have high capacity factors. Coal emits the highest amount of emissions of all fossil fuels.

- Natural Gas: It used for different purposes: residential, electric, and as liquid fuel. Combined cycle gas turbine (CCGT) technology has made natural gas a very popular choice. These plants have the shortest construction period. Along with relatively low unit costs and high unit efficiencies, that the ease of building and introducing CCGT has led to an increase of natural gas in the electricity mix. Another advantage of natural gas is that it is the cleanest fossil fuel in terms of emissions.
- Petroleum: It is mainly used as a liquid fuel. The contribution of petroleum as an electric fuel source and heat is significant (not as a percentage of the final use, though, but as volume).

- Nuclear: It is used for electric generation. The level of technologic development necessary to deploy nuclear is still very high. Few countries have the capacity to develop nuclear energy. Aside from this there is strict international vigilance over any attempt to develop nuclear energy by countries with no nuclear capability (nuclear proliferation concerns). Nuclear plants show very high efficiencies and have no emissions.

The technological development of all these conventional energies is very mature. There are, however, continued developments in order to increase efficiency and reduce environmental impacts. New generation power plants are considerably more efficient and cleaner than previous power plants.

One very clear advantage of conventional sources is that they can store energy in the fuel source, as noted earlier. This is very important for an electric system. Fuel storage provides reliability and above all certainty; as long as there is enough fuel, there will be sufficient generation of electricity.

Renewable Sources of Electricity:

Renewable energies are those whose input does not diminish with use, excluding deterioration and depreciation of the mechanical conversion equipment. To be more explicit, we could say that renewable energy is the energy where rate at which the input replenishes is greater or equal to that at which the input diminishes with use.

The following table is a list of current available renewable energies. These technologies are all in different stages of development. This list is very useful to understand the origin and state of development of the different technologies available (Frenk 2009).

Table 1: Renewable energies by source, level of technological development, and final use

Renewable Energy	**Energy Source**			**Technological Development**			**Energy Use**		
	Sun	Earth	Moon	Traditional	New	Development	Electricity	Heat	Liquid Fuels
Wind	■				■	■	■		
Solar	■				■	■	■	■	
Hydro	■			■			■		
Biomass	■			■	■	■	■	■	■
Geothermal		■		■		■	■	■	
Waves	■					■	■		
Tides			■			■	■		
Ocean Currents	■					■	■		

The most important renewable sources of electricity in terms of penetration are hydroelectric and geothermal, respectively. Wind shows the highest rate growth but its contribution to the total generation is low. Generation from other sources, including solar, is still insignificant.

Non-traditional renewable energies (all but hydro and geothermal) have a pervasive problem: intermittency. This means that there has to be sufficient back up technology to support these technologies, as they are not reliable enough to stand on their own. The consequence is that even if there was absolute determination to "go 100% green" it would be impossible with current technology: the system would be unreliable.

As mentioned before, electricity cannot be stored. As such, generation must be made at the time of consumption. Because of this, generation system capacity must be large enough to meet minimum demand. This is known as base load. Demand, however, is dynamic. Demand is monitored in varying time increments in order to correctly assess current needs. When demand reaches its highest daily point this is known as peak lead. Power plants operate at economies of scale, so different technologies are more or less suitable for each kind of load.

The most suitable plants for base load are those with low marginal costs (largely driven by fuel cost), take a long time to heat up enough to generate electricity, and are constant (show little intermittency). For this reason nuclear and coal fueled plants are the most suitable for base load from the traditional fuels. Natural gas base load can be used, but given that natural gas turbines typically have lower heat rates, they are more commonly used for peak load service. Hydroelectric and geothermal technologies are the most suitable renewable technologies to be set as base load power plants.

All other renewable energies are not suitable for base load. This is mainly because of their intermittency. Current technological developments and economic viability make it impossible for renewable energies to become base load power plants. A great deal of thought is being given to how best to balance renewable technologies against each other, for instance balancing diurnal, night time wind with day time solar. Even this kind of strategy bears many consequences for back up reliability, transmission voltage management, and other constraints. Another issue that makes other renewable energies unsuitable for base load is the discrepancy between the time electricity is generated and the time that it is needed.

TRANSMISSION

The transmission of electricity is known as the process that moves electricity from generating plants to distribution centers. In order to do this, the electricity that is generated in the power plant must first be *transformed* to a higher voltage. This is done because higher voltages provide fewer losses than lower voltages. As electricity travels through a transmission line, part of the energy is lost in the form of heat.

There are two technologies used to distribute electric power, AC and DC. Most systems are connected through AC. More specifically, a three-phase AC current is used. This is done to reduce cost in materials. AC offers a greater advantage for interconnecting synchronized systems.

DC is less frequently used. This is because of higher capital costs and less maneuverability. However, DC lines are useful to connect unsynchronized systems. They are also economically attractive when connecting long distances. For a 1,000 km line a typical DC tie will lose about 5% of energy, while an equivalent AC line for that same distance could lose up to 20% (ICF Consulting, 2002). It is for this reason that they are used to transport energy over very long distances and for underground and submarine transmission lines.

In any case the costs of transmission lines are very high. According to the World Bank, a 230 kV line could range between $108,205 and $151,956 per kilometer for an AC transmission line (The World Bank Group, 2006); a DC line could be six times higher, mainly because of the higher cost of the converter stations (ICF Consulting, 2002).

Transmission lines are often redundant. This is because electricity travels across the path of least resistance. Redundancy also provides system back up transmission; if a line fails, the system does not necessarily break down.

There are different voltage capacities installed within a system. High-tension lines usually range from 150 kV to over 765 kV. Higher voltage tension lines are more efficient when transmitting electricity, but are also more expensive.

DISTRIBUTION

Distribution is known as the process where electricity is transformed to a lower voltage and delivered to the final user. In order for electricity to be transmitted across long distances it is transformed to a higher voltage. Most consumer products and lighting use electricity in low voltages. As a comparison, transmission lines have voltages higher than 150,000 volts, while most appliances use 110 volts.

The distribution system is composed of step down transformers and substations. These substations transform the electricity to the voltage needed by the end user. The distribution system does this by using low voltage transmission lines. These lines are less than 60kV and as low as 220 V.

There are different types of end users: residential, commercial, and industrial. Each of these sectors uses different voltages. Residential users use the lowest voltage of all. In North America residential users use 110 V appliances. Electricity is distributed through 220 V and 240 V lines and a mini transformer lowers the voltage to be suitable for residential use. Residential users are the most expensive to serve. This is because they are dispersed and have inconsistent consumption (Center For Energy Economics, 2006).[6] Residential users are socially the most important consumers. Because of this, they are subsided in many countries.

Industrial users are the heaviest users of electricity in the world. They consume about 30% of the world's total energy (World Energy Council, 2004). They have higher voltages than other users. They are also less dispersed and have more constant usage, so they are less expensive to serve (Center For Energy Economics, 2006). This is reflected in lower electric prices in free markets. Depending on their consumption levels and

[6] The Center for Energy Economics is based in the Bureau of Economic Geology at UT's Jackson School of Geosciences.

voltage needs they are sometimes served directly from the transmission process bypassing distribution.

Commercial users are similar to industrial users because they also have more predictable consumption loads (Center For Energy Economics, 2006). Unlike industrial users they are served directly from the distribution network at lower voltages just like residential users.

The distribution sector is where final metering and billing occurs. It is at this end that the consumer has the most interaction with the electric process. If in the future the electric industry widely adapts smart metering, distribution will become a major player in the electric value chain.

Electricity and the Environment

Power plants have impacts on air, land and water. Every type of technology has impacts in some way. There is always a trade-off over the kind of impact the generation of electricity will have on the environment. In the public mind, air impact (emissions) is the most important impact. This has to do with the formation of ozone (from nitrogen oxides or NOx; potential effects from sulfur dioxides or SOx; the impact of particulates; the public health effects of pollutants, and concerns of the potential impact of global warming. It is important to remember that there are no "free rides" when generating electricity. It is a matter of choosing which kind of disruption we want to cause, and how strong these disruptions are.

Impacts on land and water are mainly regional. Land impacts have to do with usage and contamination. Water impacts have to do with pollution and the use of water by power plants. Power plants can be heavy users of water, but differences vary widely across generation technologies. Water is used to cool down and to turn the turbines that actually generate the electricity. Most technologies depend on water, converted to steam, to generate electricity. Another concern is potential impacts on ground water. The extraction of fuels can pollute groundwater streams. Because these streams directly run to urban centers it is very important to promote clean developments in mining.

Land impact varies among technologies. Not surprisingly renewable energies have the most impact on land. Hydroelectric generation is the most disruptive land impact. This is sometimes offset by the fact that the land is converted into a recreation area, or from benefits associated with agricultural or industrial activity. All other renewable technologies are disruptive with respect to land use: because of their low efficiencies, large areas of land are needed to generate enough electricity for the renewable technology application to become feasible. In the case of fossil fuels there is more damage done during the lifetime of the plant, although life cycle effects of renewable technologies are not known and have not yet been studied[7]. Extracting these fuels can be disruptive to land and water resources, especially with respect to coal. Land and water impacts are widely mitigated through the use of rehabilitation that, in best practice cases, returns land and water resources to pre-impact quality and even beyond. Since renewable energies do not deplete, the impact on the environment is permanent. It could be considered that the visual impact of a renewable plant not be considered pollution[8] although "view shed impacts" along with noise and reflection are becoming increasingly significant issues for wind and solar projects.

Air emissions are the most disruptive of all impacts. As mentioned earlier, air emissions can be disruptive in three ways: greenhouse gas emissions and related, acid rain and smog. The effects of air impacts can be of global reach (for example, new research indicating deposits of ash from Chinese coal generation on the Arctic ice sheet and potential effects on melting) and can have a direct impact on human health. Emissions are composed of several gases as well as solid particles. NO_x, and SO_x can be very dangerous for public health if appropriate prevention and mitigation are not deployed. Fossil fuels have different emission factors. The most carbon, nitrogen and sulfur intensive fuel is coal, while natural gas is the cleanest fossil fuel (in terms of

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[7] This has emerged just lately as a big issue. The National Academies of Science will very likely attempt the first study of life cycle impacts and we expect them to be substantially larger than expected (relatively more material components per unit of electricity produced in additional to energy consumed in making components, especially batteries if battery storage is assumed).

[8] It can be argued that windmills are a sigh of progress and "look good."

emissions). The following table details the Green House Emission Factors for several fuels according to the EIA:

Table 2: Emission Factors for each Fossil Technology

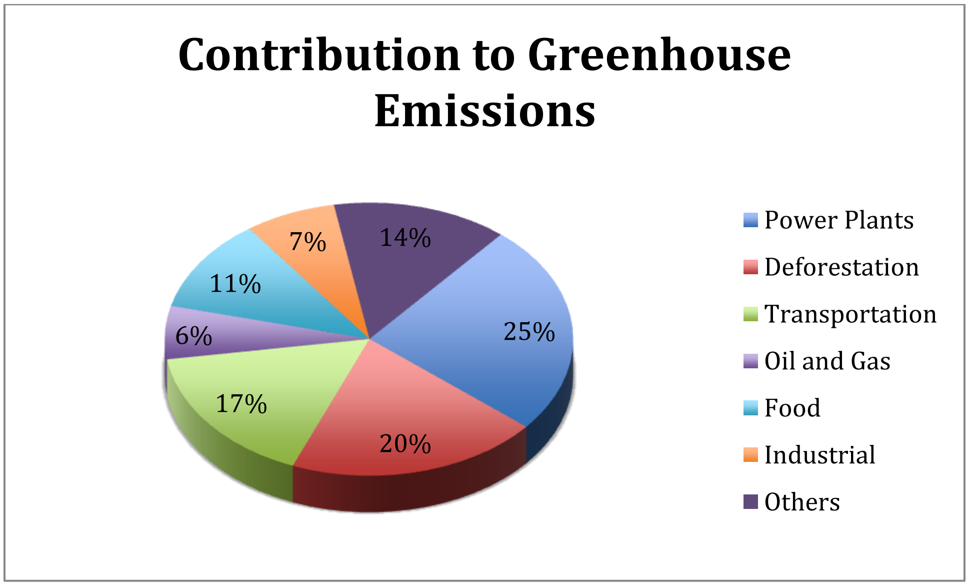
Fuel	Carbon E.F.	Methane E.F.	Nitrous Oxide E.F.
Coal	94.7 kg CO2/MMBtu	1 g/MMBtu	1.5 g/MMBtu
Natural Gas	53.06 kg CO2/MMBtu	3 g/MMBtu	0.6 g/MMBtu
Crude Oil	74.43 kg CO2/MMBtu	1 g/MMBtu	0.1 g/MMBtu

One of the widely debated concerns associated with electric power generation and systems is global warming. Global warming is caused by gasses not only emitted during the burnt of fossil fuels but also through agricultural and industrial activities. Among all these, the most relevant is the emission of gasses emitted by fossil fuel burning. Out of these CO_2 is the most heavily emphasized although water vapor is the most prevalent and potent component of atmospheric gases. CO_2 and other greenhouse gasses are believed to trap solar heat from leaving the earth, causing a "greenhouse effect". The effects of this problem could be catastrophic although climate modeling is extremely complex and poorly understood, with very large deviations in model results and new controversies related to fundamental assumptions and reliability in climate modeling data streams. Anthropogenic (human accelerated) global warming is believed to lead to rise of water levels in the coasts, massive displacement of people, food shortages, negative effects on the wildlife, expansion of desert-like climates, among other potential problems (Webber, Energy and the Environment 2009). Anthropogenic emissions are not the only source of greenhouse gasses. Indeed, human emissions are only about 4% of total global emissions (based on UN Intergovernmental Panel on Climate Change, IPCC, reports). Greenhouse gasses come from a natural process and they heat the Earth enough to sustain life as we know it. There have always been variations in the levels of greenhouse gasses and CO_2. Since the industrial revolution the levels of industrial CO_2 have risen very sharply and steadily, although monthly and annual rates of change in atmospheric accumulations are highly variable, uncorrelated with economic cycles, and largely random (apart from well-defined events such as El Niño and La Niña and major volcanic eruptions). Current CO_2 levels in the atmosphere are close to 400 parts per million. The highest recorded data is close to 300 ppm. In geologic history, CO2 levels have far exceeded these concentrations. Correlations between CO2 and climate events in the geologic record are mixed; higher water vapor concentrations generally are associated with warmer, wetter periods in Earth's history. It is not clear where all emissions go. Even though it is estimated that about 45% of CO_2 emissions end up in the atmosphere, it is not well understood what the other 55% does. This means that the final impact of human activity is not yet measurable (Borenstein, 2010). The degree of uncertainty about future projections makes climate change a complicated and polarizing issue dimension in energy policy. Sharp differences of opinion exist about whether cost-benefit analysis supports broad climate policy. Many cost-benefit analyses typically use low discount rates in order to achieve positive net present value (NPV) outcomes, with the justification being concern about future generations. However, many economists and analysts argue that these approaches create bias and also underweight the importance of continued future technology gains, which might make GHG reductions cheaper in the future than they are today[9].

The generation of electricity is responsible for nearly 25% of anthropogenic greenhouse emissions (Allianz, 2009). This means that even if all fossil fuels were to be removed from the electricity mix, there would still be a high number of emissions. In any case it is important to reduce emissions from any source possible. The following figure details the breakdown of each sector to the emissions of anthropogenic greenhouse emissions:

[9] Based on a broad review of climate science and economics literature provided by Center for Energy Economics at UT (unpublished working paper). Examples of the debate are Nordhaus, 2007 and Borenstein, 2010.

Figure 3: Contribution to Greenhouse Emissions by Sector



Looking at the previous figures one might be tempted to forget the importance of trade-offs. While nuclear and renewable energies are not carbon intensive they have their drawbacks. Nuclear has strong impact in terms of high level radioactive waste (if reprocessing is not used). The handling of nuclear high level waste is complicated although many nations, notably France and Germany, have demonstrated successful long term remediation strategies. An increase in the development of nuclear energy will lead to a problem of handling waste. The renewable sources have several impacts that were discussed before and potentially many more that are unknown. These facts remind us of the problem stated at the beginning of this section: "there are no free rides when generating electricity." It is not possible to live in a world without pollution. As humans interact with the environment our affects can be both positive and negative. These positive effects can't be attributed to the Kuznets curve effect alone. The Kuznets curve theorizes that as a country's output grows eventually its propensity to pollute will begin to decrease, turning polluting into a decreasingly marginal activity after output reaches a certain point (Aaron Kearsley, 2010). It seems to be that with appropriate political, social, and scientific developments it is possible to "recover" and actually improve the conditions of the planet (Garte, 2008). It is important to accept this fact and try to have the least possible negative impact so as to not jeopardize the availability of resources for future generations.

Chapter 3: The Mexican Electricity Sector

Mexico is a large and complex nation. Part of this complexity is the nation's abundance of contrasts. These contrasts, while innate and natural to Mexicans, can be quite confusing to the outside viewer. Absolute contrasts can, and will be found in every aspect. The energy sector is definitely not the exception. Ever since the Constitution of 1917 the energy sector has been considered strategic. As such, the government was the only authorized entity to operate in the industry. This law was not really enforced until the 1938 expropriation of the oil industry. And ever since the energy sector has been considered a matter of national pride and sovereignty. Energy as a whole is considered a full responsibility of the state; nonetheless some distinctions have been made regarding this "ownership". The oil industry is the flagship of Mexican sovereignty and as such is, at the moment, closed to public investment[10,11]. On the other hand the electricity sector is relatively open to private investment. Private investment is allowed through different legal frameworks that will be detailed later.

CURRENT SITUATION

The electricity sector depends on the Secretary of Energy (SENER). It is currently divided into two regimes, public service and private service. Public service consists of government owned CFE (Comisión Federal de Electricidad) and Independent Energy Producers and it is responsible for 86% of the installed capacity. CFE and LFC (Luz y Fuerza del Centro) were, until 1992, the only two companies allowed to generate

[10] In Mexico public investment means investment from the Public Sector (i.e. the Government) while private investment comes from the Private Sector. This distinction is not made here, where the traditional English definition is used.

[11] The oil industry allows for certain participation in some areas, mainly complimentary. In any case, under constitutional law, no company is allowed ownership of the resources. Petroleos Mexicanos (PEMEX is authorized by law to extract value from Mexico's subsoil resources for the benefit of the citizens (patrimony).

and distribute electricity in Mexico. LFC used to distribute energy in Greater Mexico City and had little generating capacity (2% of total installed capacity while it was responsible for 16.6% of total sales and controlled nearly 9.7% of transmission lines). During 2009 LFC was dissolved by a Presidential decree and CFE took over all of its operations[12].

The Mexican electrical system is subdivided into nine regions for generation and distribution. These regions are: North East, North, North West, Western, Central, Eastern, Peninsular, Baja California, and Baja California Sur. They are all integrated into one interconnected grid except for the two Baja California regions[13].

In 1992 the electricity sector was opened, under certain conditions, to the private sector. Even though the Constitution was not modified, supplementary laws allowed the existence of several legal figures that allowed for private investment:

- Independent Energy producers (IEP): Production of electricity with a power plant with capacity of over 30 MW. All its production must be either sold to CFE or exported. They are considered part of the public service.
- Cogeneration: Cogeneration that can only be used by the generator of the electricity ("inside the fence"). It also specifies that it must be with vapor engines (i.e., cogenerated with natural gas).
- Self-supply
- Small producers: Generation of electricity destined to:
    - Be sold to the CFE (the capacity of the project must be lower than 30 MW)

[12] As of June 2010 the conflict is not yet resolved. LFC had a very powerful union and it is still in court debating the legality of the Presidential decree. Most of LFC employees have accepted the generous compensation package offered by the federal government.
[13] The Baja California system will be interconnected in 2014.

- The supply of electricity to rural areas (the capacity of the project must be lower than 1MW)
- Export
- Import

The private service was, during 2007, responsible for 7,980 MW of installed capacity. This was equivalent to 13.5% of total installed capacity in the country.

Generation

The electric sector has an installed capacity of nearly 60,000 MW and has an effective generation of nearly 40,000 MW[14]. Total consumption for 2007 in Mexico was of 203,688 GWh. This number had been growing an average of 3.9% annually for the past ten years. Gross generation of energy for the period 1999-2009 grew at an average of 2.6%. While this number might seem lower it is still larger than the average annual growth of the economy (if measured as GDP) for the same period of time: 1.74%.

This implies two things. For one, as the country fights to abolish poverty and raise standards of life (especially in rural areas) the electric sector will grow to make up for past under-achievements. The second implication is that as Mexico industrializes and shifts production from *maquila* assembly plants to more complex products, the industry's electricity requirements will grow[15]. If the country's economy grew at a faster rate than generation of energy such an outcome could be due to an increase in efficiency. Following implementation of the North American Free Trade Agreement (NAFTA), increased competition led Mexico's major steel manufacturer's to install modern furnace

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[14] SENER
[15] Later in this chapter it will be shown how this situation will become in fact an incentive to generate renewable energy.

equipment and make other improvements that ultimately resulted in a gain of about 30% energy efficiency for that industry (based on information from CEE-UT).

Figure 4: Comparative annual growth between generation of electricity and GDP for 1999-2009 in Mexico.

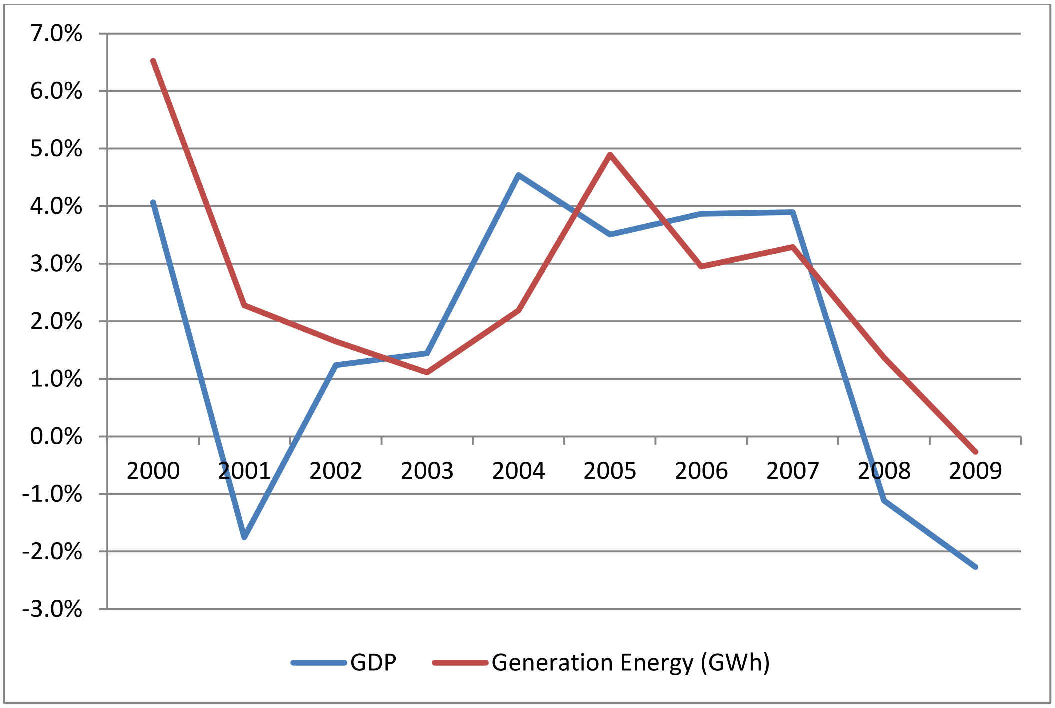
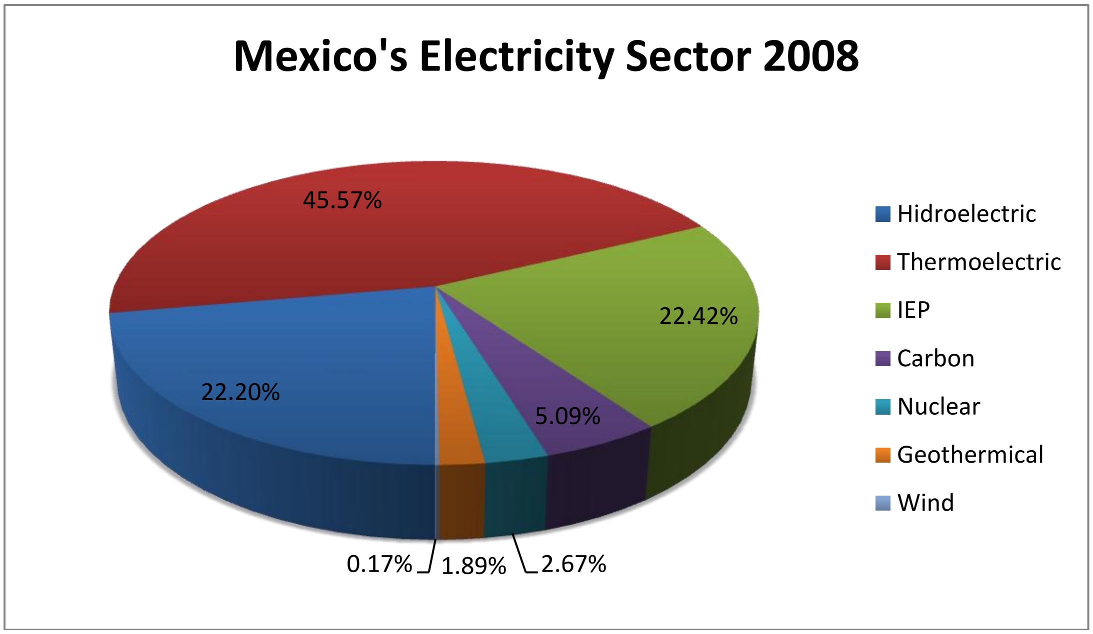


Figure 5 details the breakdown of each technology's contribution to the total. Mexico relies heavily on the contribution of fossil fuels for the generation of energy (SENER 2010). This is mainly due to the fact that the government has a constitutional mandate to generate energy based using the least cost alternative. The consequence of this is that because of its low cost of installation, thermoelectric is the most common technology in the country. It should be noted that contrary to the United States, thermal coal plants make a very small contribution to the generation of energy in Mexico. Most thermal production of electricity in Mexico is generated using natural gas. Hydroelectric power is a major contributor to the production of electric energy.

Figure 5: A breakdown of Mexico's Electricity Sector in 2008.



Transmission and Distribution

Even though the electric sector has opened up to private investment in the generation process, a comparable opening has not been achieved for transmission and distribution of electricity.

The transmission system in Mexico is divided into three categories: transmission, sub-transmission, and low tension and distribution. Transmission lines are the ones with the highest voltage capacity. In the case of Mexico these are those of 400 kV and 230 kV. They run from the generation centers to the distribution points (and some industrial users). Sub transmission are also consider high tension but at a lower voltage than transmission lines (from 69kV to 161kV). They are built on a regional basis. Low tension and distribution are the lowest voltage lines. Distribution lines are built with a capacity from 2.4 kV to 34.5 kV. These lines cover small geographical regions. Low-tension lines have a capacity of 220 and 240 volts (SENER, 2010).

The following figure shows the increase in transmission lines from the year 1998 to 2008.

Table 3: Transmission Lines in Mexico (in kilometers)

Type of Line	**1998**	**2008**	**Growth**
Transmission	32,541	48,456	48.91%
Subs transmission	38,681	47,790	23.55%
Distribution	307,422	387,077	25.91%
Low Tension	216,071	266,207	23.20%

All types of lines have shown a similar growth rate except for transmission lines (the ones with the highest voltage), which nearly doubles the growth rate shown by the other transmission lines. This makes sense as Mexico is trying to modernize the electric system and make it more efficient.

One important aspect of Mexico's transmission system is non-technical losses. All transmission systems experience losses, as it is part of the process of moving electrons across conducting materials. These losses are considered technical losses. Non-technical losses are those derived from illicit connections and default payments. SENER estimates total losses of 2008 at 17.6% and does not differentiate between technical and non-technical losses. However, data from the US suggests that non-technical losses are extremely high for Mexico (during the mid-1990s, SENER estimated non-technical losses to be as high as 50% in Mexico City[16]. For the year 2008 the United States suffered technical losses of 5.8% (Energy Information Administration, 2010), typical of industrialized, fully developed countries. The difference between the two

[16] Information from CEE-UT based on interviews with SENER executives at the time. Moreover, SENER indicated that non-technical losses were covered through PEMEX's oil export earnings, resulting in a further drain on Mexico's fiscal balances (Energy Institute, 1998).

countries should not be this high. Even if we consider that the United States uses a higher share of high transmission lines (which would mean less losses) the numbers should be closer. If we were to put a prime of double the technical losses of Mexico as compared to the US, that would mean that 11.6% of losses in Mexico are technical and still 6% due to non-technical losses! Not being able to account for these losses has direct impact on the capacity of the electric system in Mexico. It is hard to plan generation needs if there is no clear understanding about how much is needed. Another problem has to do with the development of renewable energies. Since renewable energies are intermittent and non-technical losses cannot be accounted for, relying heavily on these technologies will have direct impact on reliability and productivity.

Energy prices in Mexico

One of the most important aspects of distribution in the electric value chain is the actual billing As for the electricity good. In open markets, the price of a good is a reflection of cost of production and the required rate of return. This is not the case in Mexico. Since CFE is a state-owned monopoly, the price is set for different reasons. The reasons are both economic and political. Economic reasons depend on the financial necessities of CFE *and* the financial needs of the country. This means that Secretaría de Hacienda (Department of Treasury) has the main responsibility for influencing prices in Mexico; in practice, energy prices are administered through a committee that includes SENER, Secretaría de Economía (SE), CFE, PEMEX and the office of the President.

The price of energy in Mexico depends on several variables. The prices of electricity in Mexico are classified by final use and voltage. Most tariffs are adjusted monthly (except some designated for the development of agriculture and adjusted annually). Domestic, public services, and agriculture tariffs are adjusted based on fixed factors such as type of service, demand, and volatility. The rest of the tariffs are adjusted to fit inflation and fuel price variability.

As mentioned before the prices of electricity are in part determined by political reasons. This has led to the fact that electricity prices are subsidized in Mexico. The subsidies are defined by the difference between actual generation cost and final price. These subsidies are given to the consumers through the price paid to CFE. This means that the final electricity "bill" includes the subsidy. The CFE is then reimbursed for the subsidy through tax discounts. As a result, the Federal Government never actually *gives* money to CFE. For 2008 this subsidy was of MX$148.52 billion pesos[17], or $13.32 billion dollars.[18]

It is reasonable to assume that the subsidies will remain in existence for a long time. The government will have no political incentives in the near future to eliminate these subsidies since it would be political suicide. The current system limits the possibility of allowing CFE to charge the average marginal cost of electricity to the user, and thus limits available revenue for the Federal Government. While the existence of these subsidies is understandable in political terms, they are, nonetheless, very aggressive on CFE's finances.

Renewable energies in Mexico

According to Mexican law the following sources of energy are considered renewable:

- Wind
- Solar radiation

[17] This subsidy is divided into $91.25 billion pesos for CFE and $57.27 billion pesos for the now extinct LFC. In the case of LFC the subsidy was direct, that is the government gave LFC a direct monetary transfer equivalent to the subsidy.
[18] At a $11.15 MXP to $1 USD. That was the average for 2008.

- Movement of water in channels
- Ocean energy
- Geothermal
- Biomass

In 2008, after months of public discussion, Congress finally approved an energy reform package. This was a major event in Mexican politics, and has direct repercussions in the country. The energy reform was a breakthrough because the subject is very touchy in political terms. Even though most of the public attention was aimed towards the oil industry, a good deal of attention was given to renewable energies. Among its many improvements, the so-called energetic reform calls for the creation of the National Counsel of Energy. This new body will oversee and coordinate all energy programs including those related to renewable energies. The current administration understands the importance of diversifying the sources of energy; the question is the best and most viable strategies for doing so.

The new law regarding renewable energies, Law for the Use of Renewable Energies and the Financing of the Energy Transition, actually consists of 31 clauses, and basically intends to:

1. Finance renewable energy projects
2. Promote the eventual substitution of fossil fuels
3. Regulate compensation for land use in renewable energy projects
4. Facilitate the interconnection of renewable energy projects to the national electric grid (Marcos 2008)

There is a very strong incentive, and considerable pressure from civil society and other groups, for the Government to promote renewable energy projects. As with any major country procurement of energy is vital for the nation's security. Mexico's fossil resources have been declining sharply. While current and prospective reserves are still enough to guarantee energy independence it is in the best interest of the nation to diversify its sources of energy. In early 2009 the President of Mexico, Felipe Calderon, inaugurated Eurus, the largest wind park in Latin America. Only a week later Parques Ecologicos de Mexico was opened. This will be the second largest wind project in the subcontinent. None of these parks will be operated by CFE; private investors under the self-supply regime developed both these facilities. It is hardly a triumph of the government[19]. Eurus was developed by CEMEX (the world's second largest cement producer) in order to cut down high electricity costs and volatility. According to the Secretary of Energy, Mexico expects to have an installed capacity of 2,500 MW by 2012. Only 500 MW will be administered by CFE. The government, however, will continue to promote this as an accomplishment of the administration. The Mexican government has found a way to allocate resources to other energy priorities while still allowing for diversification of energy sources and competiveness of the industry. As discussed before, the growth of the consumption of energy is higher than that of the economy. One of the two reasons for this is that the productive sector in the country is becoming more industrialized. Multinational companies need to reduce their risks as much as possible in order to effectively compete in a global market[20]. The 1993 reform was made in part because of the pressure the industrial sector put on the federal government to decrease volatility, and costs, in electric prices. Due to the lack of certainty CFE has offered these

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[19] These facilities were developed not because the government directly encouraged private investors, but rather because of the lack of investment and security CFE provided these companies.

[20] Local based companies are not as affected by volatility because the effects on the economy as a whole are the same for everybody. For example, if a company is selling only on the local market and suffers an unexpected rise in cost of ten percent due to a higher electric bill, if every other company suffers the same problem its relative price will not change. On the other hand, if the company faces that increase in costs but sells to an international market that did not suffer that increase, it will become relatively more expensive to its international consumers.

large consumers they have been investing in self-generation. This is why CEMEX developed Eurus. It could be that CFE is incentivized to be inefficient because large consumers are able to invest in self-generated energy while small consumers have no option to switch suppliers.

There is another reason of why the Mexican government is interested in promoting renewable resources, even if they are not officially administered by CFE. Mexico is a signatory, since the year 2000, of the Kyoto protocol. This shows that Mexico is genuinely interested in reducing the emissions of carbon dioxide (and other gases related to the greenhouse effect). National strategies aimed at GHG reductions are the promotion of renewable energies and a more efficient use of energy even if the Kyoto regime fails (Rubio 2008). The 2010 United Nations Climate Conference held in Cancun, showed that negotiations could eventually fail because of the discordance between science and economic realities, and the Kyoto protocol (or any variation of it) could cease to exist (Doyle, 2010).

Current production of renewable sources is provided mainly by geothermal and wind resources[21]. Yet, the potential for all resources is very large. According to documents from researchers at Universidad Autónoma Metropolitana (UAM), and Comisión Nacional para el Uso Eficiente de la Energía the potential for the main sources of renewable energies in Mexico can be classified as follows (UAM and SENER 2002):

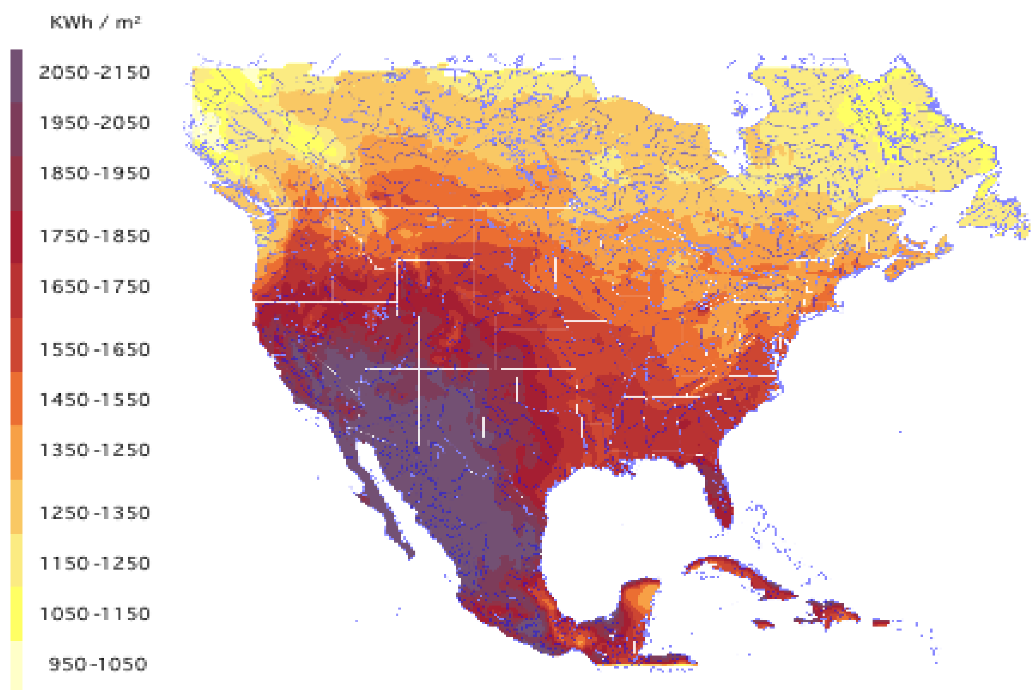
- Mini hydro electrical (under 10 MW): Current capacity is 479 MW. Potential is 3,250 MW.

[21] Due to the size of traditional hydroelectric generation it is not considered in this number.

- Geothermal: Current capacity is 965 MW. This makes Mexico the fourth largest producer in the world. Proved potential is of 1,300 MW, and it could be of up to 4,500 MW.
- Solar: Current capacity is not relevant and it is not connected to the grid. It is mainly used to provide electricity to small rural areas, where procurement of energy can be very expensive. There is no clear estimate of the potential capacity; however solar radiation averages 5 $kWh/m^2/day$ throughout the country[22]. This means that there is great potential from this source. The greatest potential comes from thermal solar plants (solar concentration). These plants require large areas to have economies of scale. Northern Mexico has a desert-like climate and is not densely populated. This opens the possibility to building large enough plants near industrial centers without having many concerns about the environmental impact on the landscape. Illustration 3 shows the average solar radiation for North America demonstrating the potential of such plants in Mexico. Unlike other developed countries there is enough demand, mainly industrial, in the northern part of the country where the plants would be installed to make transmission costs low enough to allow large scale thermal solar technology to be competitive.

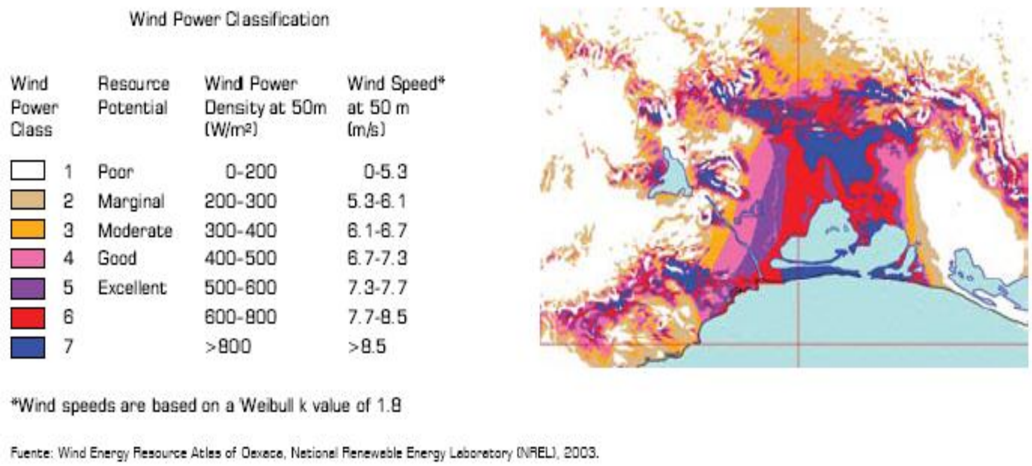
[22] This figure is nearly twice as big as that of the United States.

Illustration 3: Average solar radiation in KWh/m^2 in North America



- Wind: Current generation is of around 600 MW. The potential of wind energy in Mexico is estimated in 5,000 MW. The southern part of the country has splendid conditions to generate electric power. Most of current and proposed electric plants are in that area. Illustration 4 shows a map of the state of Oaxaca showing the wind potential for the region.

Illustration 4: Wind Power potential for the region of Tehuantepec in Mexico



FUTURE DEMAND AND CHALLENGES

CFE describes itself as “a world class company.” Recent publications appear to undermine that claim. According to a report from Banamex, Citigroup’s Mexican branch, CFE greatly underperforms international companies. CFE’s per capita output is of 1.75 GW per worker. As a comparison ENEL’s[23] output is of 7.5GW/worker, EnBW’s[24] is of 5.87 and Endesa[25] has an outstanding output of 17.39 GW per worker.

As big as Mexico’s energy sector is, output is still relatively small in per capita terms. The following table is built with information from the International Energy Outlook and SENER shows the consumption per capita of energy of select geopolitical regions along with Mexico (Energética 2006,EIA 2010).

[23] Italy
[24] Germany
[25] Spain

Table 4: Per capita energy consumption for selected regions in 2004 and 2015 (projected)

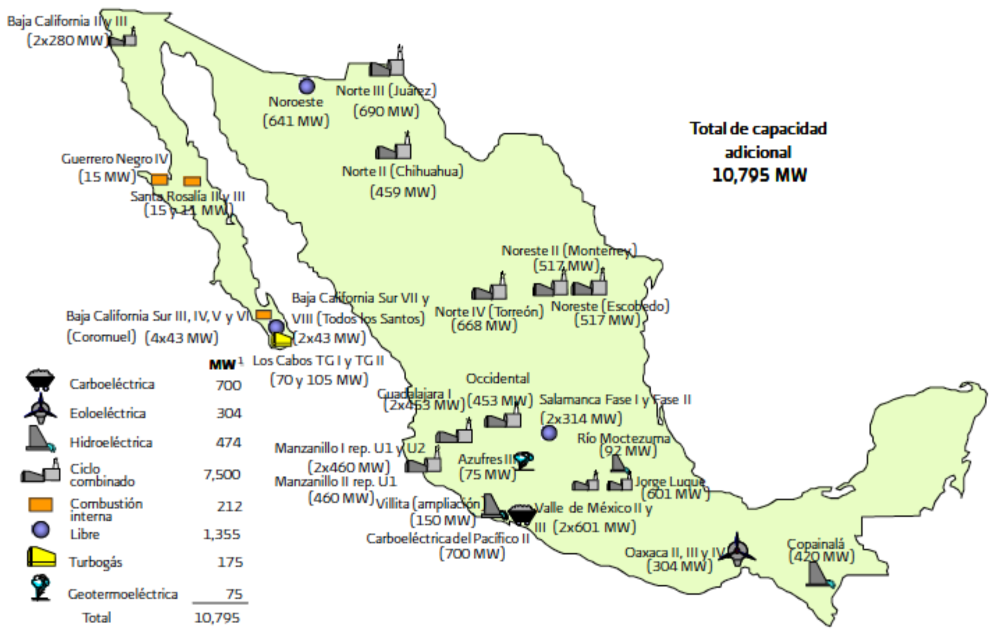
Region	2004	2015 (projected)
World	2,416	3,007
Mexico	1,786	2,332
OCDE Europe	5,713	6,398
OCDE Asia	7,412	9,167
OCDE North America	10,333	11,406
No OCDE Asia	975	1,559
Central and South America	1,830	2,627

For the period 2004-2015, Mexico's per capita consumption is expected to grow over 30%. This is higher than the World (24%) and all OECD countries (10%-24%). However, it will grow less than "No OCDE" Asia and Central and South America (59% and 43% respectively). While it comes as no surprise that per capita energy consumption in Mexico will grow higher than more developed economies it is interesting that it will grow slower than the average of its "closest" neighbor region: Central and South America.[26]

Mexico's electric system is expected to grow at an average of 3.6% until the year 2024. This means that in the following 14 years 38,698 MW are forecast to enter the grid. Some 5,113MW have either been constructed or assigned for construction and therefore technology is already fixed. Mexico then expects to have the capacity to generate 78,406MW. This figure includes all withdrawals from the system (10,315 MW). Illustration 5 shows the expected generation of electricity by technology, for the year 2017 for assigned technologies.

[26] It should be noted, as an anecdote, that Europe would be growing at a higher rate than North America, even considering that its population growth for the period will be close to zero.

Illustration 5: Projected new power plants by technology in Mexico for the year 2017



There are still some challenges for the development of renewable energies in Mexico. According to the World Bank's review of renewable sources of energy in Mexico, there are a few "constraints due to practical realities":

1. *Lack of governmental funds mainly due to the 'least-cost' procurement mandate.*
2. *A mandated market policy is of limited applicability for Mexico as the existence of essentially one monopoly utility provides limited options for effective trading among different utilities to pursue cost reductions.*
3. *Incentives would also require a clear set of policies, grid access terms and institutional capacity development to facilitate sustainable mainstreaming of renewable technologies.*

Because the generation and distribution of electricity are reserved nearly exclusively to the nation, decisions regarding the energy sector are as political as they are technical. This means that strong political negotiations have to take place before any structural decisions are made. The SENER has independence to operate only within its legal framework and a budget approved by Congress. Any reform, even one based solely on technical assumptions that SENER intends to pursue, is dependent upon successful political negotiation. Government owned enterprises are usually inefficient and have little access to market instruments.

The current system of subsidizing energy prices is dependent on revenue from PEMEX. As PEMEX's production declines, government's revenue will decrease. It will then be economically unviable to continue these subsidies. The government should, at least, decrease the subsidies in a percentage similar to the decrease in revenues from PEMEX.

How to effectively address these challenges?

Market strategies can be used to go around the least cost mandate. My thesis proposes a better approach to the design of an energy fuel mix.

Opening the market to private investors will help reduce costs and prices. This could allow the consumer to choose which kind of energy he or she wants to use. It will also allow producers to better take advantage of international market incentives to produce energy with renewable energies.

The new energy law tries to address the issues of institutional incentives. There are several limitations to the law but the spirit of it is valid: political will could help incentivize the use of these energies without the need to impose the use of them. It is believed that an advantage of the new energy law is that as it was discussed under the shadow of the oil reform, it was not part of the public debate and therefore it was not subject to as much political pressure (Shields, 2009). The far left wing parties of the country do not approve of this reform as they are opposed to any form of private investment in strategic activities and propose other mechanisms to promote the electric sector such as using oil derivatives as fuel (Obrador, 2007). However, it is generally agreed that this reform will incentivize the deployment of renewable energy plants (Marcos, 2008) (Shields, 2009).

There is no way to effectively address these challenges without political will. None of the above constraints are impossible to overcome. They depend solely on the public agenda and public support. In Mexico it would be political suicide to open electricity to private investment. Such an action could cause mobilizations and riots throughout the country. Even the fact that a government owned company takes over another, clearly more inefficient entity caused lots of controversy[27]. However, it is possible to eventually overcome these challenges and a possible objective must be kept in mind.

[27] People opposed to the decision of the government agreed with the fact that LFC was more inefficient than CFE (LFC was also nearly insolvent). They opposed the action of the government because they felt that firing workers is illegal and because they believe that the government purposely abandoned LFC in order to force bankruptcy In fact, LFC had been in difficult financial straits for many years.

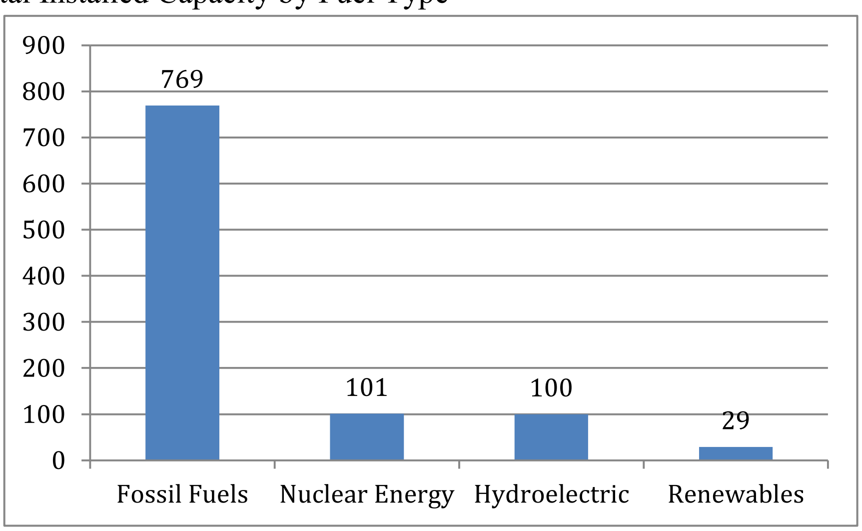
Chapter 4: A Review of International Policies and Statistics

Countries like Mexico, with a heavily centralized government structure, are sovereign in determining the policies that guide their electric sectors. In order to successfully plan electricity portfolios it is important to determine the priorities of the nation. It is through the definition of these priorities that policy makers determine and enforce the norms and regulations that shape the world's electricity portfolio. What are the guidelines that determine the path that the electricity sector around the world follows? Each country is different and this chapter will compare the basic principles for a few select cases.

United States

The United States is the world's largest economy and as such it is also the largest consumer and producer of energy in the world. It has an installed capacity of nearly 1,000,000 MW. The following figure details the breakdown of total installed capacity for the United States by fuel type (Energy Information Administration, 2010):

Figure 6: Total Installed Capacity by Fuel Type



The United States electricity market is very competitive but also highly complex. All parts of the energy value chain are open to private investment although investor owned utilities remain dominant entities, controlling generation through distribution in most states. The United States government oversees interstate electric power transmission and associated generation, as well as federal power authorities (such as Tennessee Valley Authority), many associated with large, federally constructed hydroelectric facilities. State public utility commissions (PUCs) oversee generation, transmission and distribution of electricity within state boundaries and thus are the dominant regulatory entity in the US electricity sector. Only a few states, such as Texas, have implemented broad restructuring programs to create competition in both the wholesale (bulk) and retail (final end user) markets. The state PUCs, in concert with state energy offices also have most influence over laws and regulations associated with renewable energy development and use. The Energy Independence and Security Act of 2007 objective (Public Law, 2007):

> To move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes.

Overall, the main objective of the United States government is to guarantee supply and promote environmental protection. Most attention is paid to efficiency and modernization of infrastructure. A great deal of emphasis is placed on research and development of renewable energies and carbon sequestration. In practice, renewable energy projects have most often been launched where state renewable portfolio standards (RPS) regimes exist with considerable federal subsidies and other support, such as loan guarantees. Little agreement exists about how and whether to implement a national RPS.

Little agreement and substantial conflict exists about how best to cover the cost of large scale new transmission projects that would be needed to ship electricity from remote renewable energy sites to final customers. Order No. 1000 from the Federal Energy Regulatory Commission (FERC) requires public utility transmission providers to allocate the costs of new transmission facilities to the beneficiaries of such facilities (Barnett, 2011). This debate is centered on the location of renewable sources of energy. Should they be located where they could most efficiently generate electricity, or near consumption centers (Opalka, 2011)? The answer to this question depends on who is willing to pay more for renewable energy.

European Union (EU)

The European Union has defined a series of challenges and objectives that must be followed by every Member State. The EU assumes that these directives are the best tools to address these issues. In any case these directives are generic, so each member is autonomous as to how they meet these directives. The following table exemplifies this fact. It summarizes total EU electricity capacity and the technologies used to generate that capacity from some select countries (European Commission, 2010):

Table 5: Fuel Mix for Total Electricity Capacity of the EU and Some Select Countries

	TOTAL	Conventio nal	Nuclear	Wind	Geo-thermal	Hydro
EU27	779,192	449,129	132,829	56,270	698	140,266
Share		58%	17%	7%	0%	18%
Denmark	12,608	9,475	3,124	0	9	0
Share		75%	25%	0%	0%	0%
Germany	128,789	77,738	20,208	22,247	0	8,587
Share		60%	16%	17%	0%	7%
Spain	88,246	47,412	7,365	15,097	0	18,372
Share		54%	8%	17%	0%	21%
France	116,284	25,672	63,260	2,220	0	25,132
Share		22%	54%	2%	0%	22%
Italy	93,198	68,708		2,702	671	21,117
Share		74%	0%	3%	1%	23%
Netherlands	23,677	21,382	510	1,748	0	37
Share		90%	2%	7%	0%	0%
United Kingdom	81,998	64,273	10,979	2,477	0	4,269
Share		78%	13%	3%	0%	5%

This freedom to choose national and local energy policies is within the legal framework of the EU. The guiding principles for the EU are (European Union, 2007):

- The development of an effective interconnected competitive market
- Secure energy supply
- Reduce greenhouse emissions

The EU has also set a series of targets and standards that will help achieve these goals. These standards are normally aimed towards efficiency, competition, and environmental responsibility. The EU's targets for the year 2020 are (Communities 2007):

- 20% of energy must come from renewable resources
- 10% of transportation needs must be supplied by biofuels
- 20% reduction in Greenhouse gas emissions

- 20% increase in energy efficiency

As a net importer of energy (fuel imports are of nearly 60% of total consumption) the EU is greatly concerned with supply security. It imports nearly 40% of its coal and 60% of its gas. Their need to reduce consumption and promote renewable sources is evident: they depend heavily on foreign fuels from Russia (European Commission, 2010) and it is desirable to reduce this dependence.

Brazil

Brazil is Latin America's largest economy and country and holds the largest population in the region. In terms of electricity generation it has, as expected, the largest installed generating capacity with a little over 106 GW. Brazil has experienced rapid economic growth during the last decade. This led to an increase in the total demand for energy as well as the growth rate at which this energy is demanded[28].

The electricity market in Brazil is open to private investment. There is a growing participation from private sector interests in all sectors of the energy value chain. However the government is still a major player in all areas, except distribution. The following figure details the contribution of each fuel to the energy mix (Ministerio de Minas e Energia, 2009).

[28] This is a classic sign of improvement in quality of life. This is something also experienced by Mexico and all developing countries.

Table 6: Generation of Electricity in Brazil by Source

Source	**Installed capacity (MW)**	**% Total**
Hydroelectricity	78,610	73.94%
Fossil Fuels	18,003	16.93%
Biomass	6,103	5.74%
Nuclear	2,007	1.89%
Wind	1,589	1.49%
Total installed capacity	106,312	

Brazil depends on nearly 8% in imports for its electricity sector. This means that securing a supply of energy is a major driver of national policy. Another important factor is Brazil's high dependence on hydroelectric power that is subject to sharp wet and dry cycles. Since Brazil also needs to keep up with its growing demand, priorities would be directed towards growing without endangering supply. This sets up a trade-off between fossil fuels (imported) and nuclear fuels (long term).

India

The government largely dominates the Indian electricity sector although there is private participation (13.5%). The electricity sector is responsible for the generation of 164,835 MW. Fossil fuel is responsible for 65% of the generation while hydro is the second largest used technology with 25%. As a rapidly growing economy with high levels of poverty, the priority of the Indian government is to have its electricity sector keep up with the growing demand as well as to grant universal access to electricity. India's policy is dominated by the following principles (Ministry of Power, 2010):

- Taking conducive measures to develop electricity industry
- Supply of electricity to all users
- Promotion of efficient and environmentally sound policies

- Economic Viability of the Electricity Sector

Energy security is a traditional guiding principle for a country's energy policies. In the case of India it is not a critical issue, not because it is not important, but because the country is mostly self-sustainable. India has enough coal reserves to meet internal demand for over a century (Allianz Knowledge, 2009). In addition to this 25% of its electricity is produced by local hydro plants. Even though considered in the national policy report, it is clear Indian policy emphasizes the possibility of being self-sustainable (Planning Commission, 2006). The biggest threat comes from low uranium and natural gas reserves that make it necessary for India to import these products. In any case the development of new nuclear reactors, following the Canadian model, that use thorium instead of uranium could make India independent from foreign supplies.

Subsidies

There are different reasons governments use subsidies in the electric sector. In some cases it is with the intention of promoting a certain technology, in other cases it is because electricity is perceived as a social good that should be easily available to every citizen of such country. There are different kinds of subsidies, but they can all be grouped in two categories: producer and consumer subsidies (Steenblik, 2009). This makes it difficult to compare subsidies across countries, since each country allocates its resources differently, and most importantly, they report these subsidies in a different matter. In free market economies, where electricity prices are not regulated, subsidies are usually in the form of producer subsidies through the form of tax credit, production incentives, research and development and/or feed-in tariffs. Even though it is believed that the U.S. government subsidizes traditional energy sources, recent studies show that the latter is not true. The largest beneficiaries of federal subsidies between 1950 and 2006 have been renewables. In 2006 subsidies for solar and wind power was of about four times the average cost of electricity. Subsidies for other kind of technologies were between 2% and 7% of the average cost of electricity (Gary M. Sandquist, 2010). The EU traditionally uses feed-in tariffs to support the development of renewable energy. Feed in tariffs consist of establishing a prearranged price for the electricity, thus ensuring that the investment is profitable. Current economic crisis might affect the rate at which these subsidies are given. The Spanish situation exemplifies this effect. Driven by a remarkable economic growth, the Spanish government decided to subsidize renewable energy (especially solar) through high feed-in tariffs. Today, the government is considering cutting these subsidies (Bernd Radowitz, 2010). Even though this retroactive measure will most probably don't go through, it is clear that the economics of renewable energy is still too dependent on subsidies to reasonably substitute fossil fuels.

The importance of this chapter is to illustrate that all countries face different needs when designing their electricity portfolios. Each country's situation is unique and that is why every portfolio is approached in a different fashion. This chapter showed that level of economy, local resources and environmental concerns are different for each country and as such its directives also change.

Chapter 5: Mexico's Approach to Electricity Planning

SENER regulates the energy sector of Mexico. It is through this department that all electricity planning is regulated. The mission and vision of SENER are defined as:

> **Mission**
>
> To guide the energy policy of the country, within current constitutional framework, to guarantee a competitive, sufficient, high quality, economically viable, and environmentally sustainable supply of the energy required to the development of the nation
>
> **Vision**
>
> To have a population with full access to energetic inputs, at competitive prices; with world-class public and private companies, operating within a legal and adequate regulatory framework.
>
> With a firm impulse to an efficient use of energy and to the research and technological development; with a broad promotion of the use of renewable resources; and with energetic security.

GUIDING PRINCIPLES

Currently, the development of energy in Mexico is subject to three major guiding principles. These guidelines are used to define all national energy strategies. These principles are intended to give coherence to the development of infrastructure and programs in the nation:

1. National Security
2. Environmental Sustainability
3. Economic and Productive Efficiency

With these guiding principles in mind, the SENER developed a series of objectives for 2024. While these objectives are broad in terms of energetic needs of the country, this thesis is only interested in those that have to do with electric generation. These objectives are:

- Diversify energy sources, with emphasis on renewable sources of energy
- Improve efficiency
- Reduce environmental impact of energy consumption
- Operate the energy infrastructure in an efficient, safe, and trustworthy way
- Execute investments in a timely fashion so as to reduce the cost of energy
- Provide energy to remote population centers
- Provide human and technological development to the energetic sector

These general guidelines imply different decisions. It is common to use these guidelines as a topic. Topics are useful because they require little analysis. In this case it is important to define these topics so as to know what these guidelines imply in terms of designing an electricity portfolio.

1. For National Security:
    - Diversify sources of fuel
    - Reduce dependence on foreign inputs
    - Guarantee supply for current and future needs
2. For Environmental Sustainability:
    - Reduce environmental impact of generating electricity
    - Reduce contribution of fossil fuels
3. For Economic and Productive Efficiency:
    - Reduce transmission losses
    - Lowest possible cost

It is not possible to attain all goals in a single solution bundle. The first two guidelines broadly imply a diversification of sources of energy (implying a higher capital cost) while the third guideline procures for the lowest possible source of electricity. It is necessary to clearly define what following each strategy implies in terms of benefits and losses. The following table describes the implication of each goal in terms of the portfolio experiment. It also assesses the level of risk to the country and the level of feasibility. Is it really a threat to depend on the United States for the supply of natural gas? Is it feasible to fully substitute fossil fuels in the mix? While some of these answers seem evident it is important to clearly state the level of risk and feasibility in order to take the best possible decision.

Table 7: Assessment of Optimum National Security Scenario

No importation of fuels	Level of risk: Low Level of feasibility: Medium	In this scenario the use of gas would be limited to local production. Uranium is also imported, but it could be mined in Mexico. There could be an increase in coal production but it would be reasonable to assume that an increase in production would mean an increase in imports. Since most of the supply comes from the United States, it is reasonable to assume that there will be no threats to the supply in the near future. This means that reducing the importation of inputs would imply development of renewable sources, and an increase of nuclear power in the share. Mexico has little official estimates on uranium reserves; however the latest estimate considers the possibility of locally mining enough uranium to power national plants.
Optimum diversification of energy sources	Level of risk: Medium–High Level of feasibility: High	"Do not put all your eggs in one basket." This implies an increase in other sources of energy: nuclear, coal, renewable. The recent example of Venezuela shows how it is necessary to diversify sources of energy. It is possible to diversify the mix if the conditions are adequate[29]. A correct estimation of financial risk could reduce the associated cost of the portfolio making it feasible to diversify the portfolio.

[29] It should be noted that Venezuela is suffering a major electricity crisis due to a lack of diversification and a lack of public investment derived from nearly free electricity.

Table 7 (continued)

Minimum depletion of fuels so as to guarantee supply for future needs	Level of risk: Medium-Low Level of feasibility: Medium	Increase of renewable sources that do not deplete. Increase of the share of nuclear energy whose supply is expected to last over 120 years without considering technology improvements that would at least double the availability of the resource (World Nuclear Association, 2010). There is no chance of depletion in the short or medium term. It would be advisable to begin preparing for it but it is not indispensable at this moment.

Table 8: Assessment of Optimum Environmental Sustainability Scenario

No CO_2 emissions	Level of risk: Medium Level of Feasibility: Low	This would require, ideally, reducing the share of fossil fuels to zero. This is not only impractical, but also quite impossible. The dependence on fossil fuels is far beyond availability or cost; it also includes reliability and accessibility. In any case it is possible to reduce dependence on fossil fuels for electricity generation. France generates nearly 80% of its energy with nuclear power plants. For the case of Mexico it would be impossible to do this in the near future. The goal should be to reduce the share of fossil fuels in the generation as much as possible. The country depends too much on fossil fuels to rapidly switch to nuclear power. Other renewable sources have technical constraints that make it impossible to fully substitute fossil fuels. The 2011 nuclear crisis in Japan will further hinder support for this technology, as public perception about nuclear technology has been negatively impacted.
Increase plant efficiency	Level of risk: Medium Level of Feasibility: Low	Increasing plant efficiency not only has an impact in the environment, but also reduces the cost of generating electricity. New technologies for CO_2 sequestration make new generation fossil power plants much cleaner than older plants even though it reduces their efficiency.

Table 9: Assessment of Economic and Productive Efficiency

Optimize grid connections and reduce consumer demand	Level of risk: Medium Level of Feasibility: Medium-Low	Mexico suffers many non-technical losses in the grid. With CFE's absorption of LFC these losses increased. This requires stricter vigilance and monitoring of the company's operation. Current subsidies disincentive and efficient use of electricity from the agricultural and residential sector. The strong political ties to subsidies make it very difficult to eliminate them.
Procurement of energy at the lowest cost	Level of risk: Medium Level of Feasibility: High	Currently the country follows the low cost mandate. This explains the high contribution of fossil fuels into the electricity mix. This measurement does not take into account diversity and fuel variability risk.

The following chapter will analyze feasible portfolios. This will allow us to determine the impact each technology has in the portfolio and decide, in terms of what the priorities are, which the best configuration of the mix is.

Currently the Federal Government is promoting the development of renewable energies. This raises a question: why would Mexico be interested in developing renewable energies? There are several reasons of why Mexico should address these issues (Antonius, et al. 2006). The following list does not intend to be exhaustive, but rather to justify why any government (Mexico in this case) would be interested in developing renewable energies. There should be clear benefits to the development of these technologies in order to successfully develop them. It is arranged in a similar order to the table recently shown, but with clear benefits from renewable sources. The government, through the report *Renewable Energies for Sustainable Development in Mexico* presents some of these benefits as reasons to push for the development of renewable energies in the country.

- National Security: Mexico depends heavily on fossil fuels. Diversifying through renewable sources means that the country will not rely on foreign raw materials to generate electricity. This, is, in any case more a political threat than a real security problem. As stated before the level of risk from this situation is low. On the other hand, if grid reliability is not improved, the introduction of intermittent energy sources could affect national security.
- Diversification: In the previous bullet diversification was suggested in order to prevent the possibility of depending heavily on a foreign supplier. Yet, diversifying should be addressed for more practical reasons. The old proverb "do not put all your eggs in one basket" hints at the importance of diversifying, and the related goal of reducing risk. Yet high investment costs, urgency, or ease of use makes policy planners take decisions against this logic. It should be noted, again, that a reliable grid is needed to properly accommodate intermittent energy sources.
- Connectivity: While Mexico does provide electricity to nearly 98% of all Mexicans, it is a reasonable aspiration to want to provide it to all its citizens. The size of traditional energy sources and the capital investment needed to transport energy to any of the many small towns along the country makes it very hard to

reach 100% coverage.[30] It is extremely costly and difficult to provide electricity under these conditions. Renewable energies, however, provide the tools necessary to effectively provide electricity to these communities, provided they know how to sustain them.

- Environmental: It is reasonable to assume that it is in the best interest of the country to develop and define greener energy sources. It has also internationally committed to help improve the environment. It is a signatory of the Kyoto Protocol and is an active spokes country in favor of the environment.
- Research and Development: The opportunity to become a pioneer in the development of green energies will open the door to Mexico to greater research. If properly funded, a group of energy research facilities could be developed. This could generate an inertia that could lead to more research. According to official government documents the country will allocate funds in order to develop technologies that will capture CO_2. This means that, unlike previous times, the project as a whole considers the development of technology as integral to the development of the country.

RECOMMENDATIONS

The nature of renewable energies is different than those of traditional sources of energy. The location and size of an electricity generation plant that uses renewable sources depend on the location and availability of such sources. This means, that unlike traditional plants, several considerations must be taken into account that are additional to those already considered for the electric industry. For example, one advantage is that plants can be of very small scale. The main disadvantage is their intermittency, with all

[30] According to the 2005 census, there were 187,938 communities of fewer than 2.500 people in the country. They account for over 20% of the total population.

the problems it raises in terms of hidden costs, monitoring, and grid connections. Unless this reality is taken into account when developing public policies funding for these projects will not be available.

Since private participation is expected, the government must provide as little uncertainty as possible with reliable long-term projects. One possible strategy is to set defined prices for the plants. This will reduce the risk associated with the fluctuation of price. Since the cost of the resource is nearly zero, it is reasonable to assume that with an adequate cost of capital all projects will become profitable[31]. This price must consider the costs of managing variability, or else incorporate this added cost as a subsidy and recognize it as such.

Considering the experience of the Spanish model, economic incentives should be the ones more strongly encouraged by the government. Market instruments are useful but the government has little control over these. Since cap and trade systems are globally used the role of the government should be limited to not interfering with these solutions. While these instruments provide an incentive to pollute less as a national strategy it makes little difference. If the goal is to generate energy the government is indifferent to the source of this energy. If the goal is to generate clean energy then the government should take an active role into promoting the use of renewable resources. For this matter fiscal and economic incentives are most useful.

It is also recommended to develop a complete assessment of the potential of renewable resources in Mexico. Official information available does not know precisely the potential or quality of wind and solar sources. These two sources are of very high potential. It is unbelievable that the Mexican government has not yet assessed the full

[31] This is, of course, constrained to a reasonable predefined price for the electricity.

potential of these sources. Even though there is an estimate of the amount of average solar radiation in the country, and the potential of the Oaxaca region for wind energy, it is not clear how big the contribution of these sources could be. The government should develop, either through SENER or through an academic institution, a real assessment of the potential of these two energy sources.

More important, an assessment of the grid should be developed. How prepared is the grid to handle an increasing amount of electricity from renewable sources? CFE and SENER should develop an assessment of the grid in order to better understand which regions are more suitable for the development of renewable energy sources.

Attention on Efficiency

Increasing efficiency in the electric systems is another great way of mitigating the effects electricity usage and generation has on the environment. Even though energy efficiency programs can be as effective as the development of the infrastructure for renewable energies they are not as popular in the public's eye. It is much easier to see a windmill constructed than to be aware of a new norm in the country regulating commercial refrigerators (SENER, Tercer Informe de Labores 2009)[32].

Nonetheless SENER has set up several programs designed to increase efficiency in the end use of electricity. These programs are divided into four areas: creation of norms designed to improve efficiency, industrial and commercial, residential, day light saving. During 2008 these programs contributed to save over 23,000 GWh. The contribution of these programs to the total was of 87.3%, 6.1%, 1.7%, and 4.8% respectively. The most popular of these programs is one aimed towards reducing waste in residential use of the electricity. This effort is called "Programa de Sustitución de

[32] This activity had, by 2005, saved over 700 GWh and 85MW.

Equipos Electrodomésticos para el Ahorro de Energía" (Program for the Substitution of Electric Appliances to Save Energy)." Consumers are able, through either rebates of financing opportunities, to substitute old refrigerators (the largest residential application for electricity in Mexico) with new ones that meet the new standards of efficiency[33].

The government, and specially SENER, should address the issue of efficiency more publicly. While there are several programs that have proven to be very effective they have not received enough publicity. There is a catch to promoting these achievements. Promoting efficient technologies could push people to spend more electricity to offset the savings, neutralizing the benefit of efficiency.

Energy efficiency programs have failed to reach its full potential. There are several reasons that explain why the results from efficiency programs are not as high as expected. The main reason has to do with a "rebound" effect. An increase in the efficiency of energy consumption will effectively result in lower per unit cost of energy leading to an increase in consumption, thus, creating a "rebound" effect (Lorna A. Greening, 2000). This effect causes lower marginal gains in efficiency as time increases and people become immune to price signals. Other reasons are: high initial investment costs, maintenance costs and the difficulty of replacing a country's whole stock (H. Hens, 2001).

A very important aspect of efficiency should be centered in subsidies. In Mexico, subsidies amount to about 29% of the real cost. The following figure shows a breakdown of the subsidy and the real price for agricultural, residential sectors, and the weighted total (SENER, 2010).

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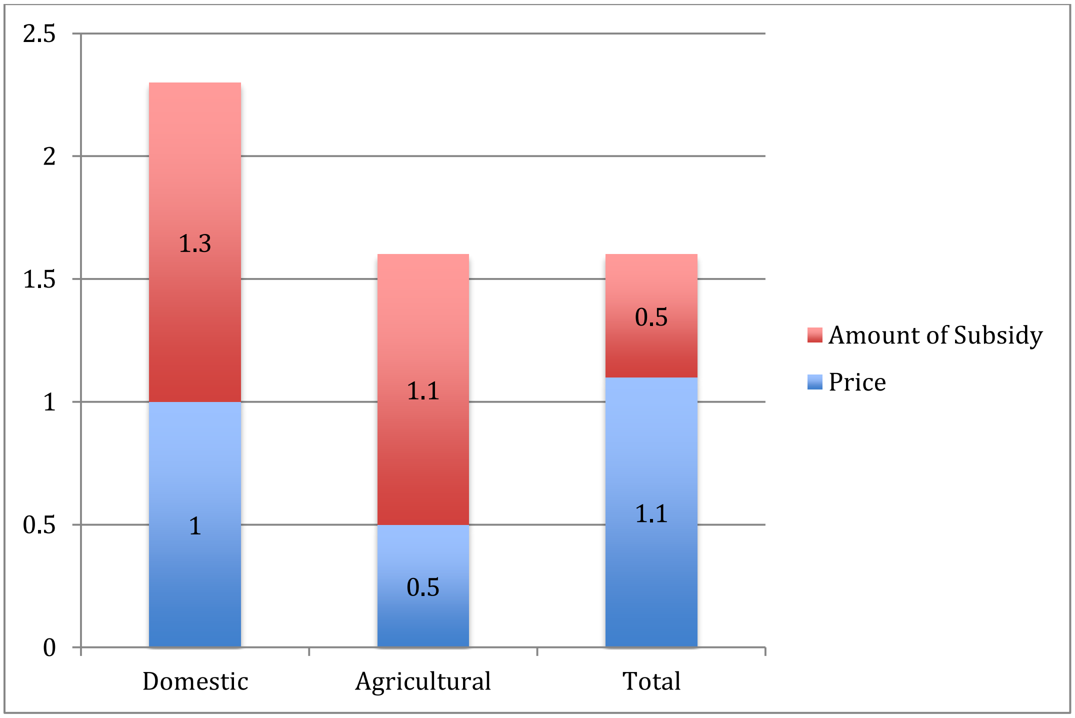
[33] With this program over 100,000 refrigerators have been substituted. Because of the subsidy given to the price of electricity, this program is also intended to save the government money.

Figure 7: Breakdown of price and subsidy as part of the total cost of electricity in 2009 pesos/Kwh



It is recommended to reduce subsidies in a gradual way in order to focus those resources on other priorities. The subsidies could be better focused to assist the lowest income families and producers and be reduced to the higher end consumers. This will lead to an increase in revenue for CFE, and an increase of efficiency in terms of a reduced demand. The development of efficiency programs, while useful, should not be considered the "silver bullet" to improve the electric power system. The development of cleaner and more efficient technologies and the improvements in the transmission and distribution systems are more relevant over the long term.

Chapter 6: A Modern Portfolio Theory Approach

It was discussed earlier that CFE is constrained by a 'least cost mandate.' This limits the range of action of CFE towards the construction of new generating capabilities. In addition to this constraint an emerging market country needs to develop electric generating capacity at a *higher than average* rate when compared to developed economies. This sets up a critical problem: What is the best way to generate electricity in the country? Or to be even more precise: How can the country meet its future energy demands with the lowest possible overall cost?

A portfolio management approach could help us solve this issue. In Chapter Two I described modern portfolio theory (MPT). I discussed how the introduction of a less risky asset could, through diversification, reduce the overall cost of the portfolio. This concept could be applied when designing electric portfolios. If we understand the generation mix as a portfolio of different technologies, then we could use a portfolio management approach to more efficiently develop it. The question then is, is it possible to introduce assets with lower risk and a higher cost in order to reduce the overall risk-cost of the portfolio? In other words, can we increase the share of renewable energy to the Mexican generating mix and reduce the overall cost to the country?

It is possible to reduce the overall cost of the mix as well as reduce the risk associated with this portfolio. When analyzed on a cost-alone basis, renewable energy performs lower than traditional fossil fueled plants. It is no exception for the case of Mexico. Even hydro, a traditional power source in the Mexican generation mix shows higher costs than combined cycle gas turbines or coal. However, when the analysis takes risk into account, the situation changes. Depending on how risk is defined, it can not only level the playing field, but work as an advantage for renewable energy. Previous efforts to show this effect have been done, especially for the portfolios of the United States and Europe (Awerbuch, 2003).

A map is a model of reality. No one expects the land to be brown everywhere and the oceans pale blue. Just as a map models reality in order to explain something this thesis intends to prove a point: it is possible to reduce overall costs of a portfolio through the use of financial tools and rationale. Nonetheless it is critical to use correct inputs. Going back to the map analogy it is not expected that land be brown everywhere, but the shape of the country should be the correct one. My thesis will introduce assumptions that will help to simplify the problem, make the results feasible, and to limit the infinite nature of restrictions that could arise when designing an electric generation portfolio. Nonetheless, the assumptions made here are justified and explained. This permits the solutions to be logical within the presented framework. In order to solve this problem I used the SOLVER program for EXCEL and Crystal Ball software.

ASSUMPTIONS

Selecting Technologies

The objective of this thesis is not to offer a final solution for the energy generating portfolio for Mexico, but rather to offer an illustrative idea of how to approach an existing problem. Previous work has *packaged* renewables in a single bundle. Due to the fact that hydroelectric power is a big component of the Mexican mix, I find that it is unreasonable to simply add it to the renewable bundle[34]. In order to generate a realistic scenario for the portfolio six different "technologies" were chosen to integrate the mix.

[34] All papers done by Awerbuch consider hydro as part of the renewable mix. Awerbuch has studied mainly the United States and European cases, where hydroelectric power can easily be considered an alternative source of energy. His work for the Mexican case was done as a guidance of how his previous work could be used. Beltran considered hydro as a separate source, but he did not consider a bundle for renewable energies as he only used wind.

The six technologies were Combined Cycle Gas Turbine (CCGT), Hydroelectric, Coal, Nuclear, Geothermal, and Renewable. CCGT is the most common power plant type in the country. In order to simplify this analysis, CCGT is used as a bundle of all technologies based on fossil fuels (except coal)[35]. This is done because of the importance of CCGT to the mix when compared to other technologies, and because of the similarities in terms of risk and correlation it shows with the other fossil based technologies. Another reason is that thermoelectric generation, despite its current contribution, would be removed gradually from the mix in a strong GHG reduction scenario; current plans to build more plants fueled by natural gas consist almost entirely of CCGT technology (SENER, 2010). Hydroelectric power includes mini hydro just as the SENER defines it. The renewable bundle consists of wind and solar only[36]. However, because availability of renewable sources is limited to their location, a "bundle" of renewable sources could increase the possible share in the portfolio as opposed to a restricted wind only contribution.

Expected Costs

As explained before, a portfolio consists of two variables: the expected return and the standard deviation. There are two ways to approach the definition of expected return in this case. Since the objective is to minimize the costs of generating electricity, an analysis can be made using expected generation costs. The costs used for this analysis are levelized costs. Levelized costs are the present value of the cost of building and operating a power plant. They are normally expressed as adjusted dollars over electric generation. They make it possible to compare different technologies in a tangible manner.

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[35] These are Traditional Thermoelectric, Gas Turbines, Internal Combustion, and Dual technology.

[36] Wind = 65.67%, Solar PV = 34.33%.

The costs used in this thesis come from two sources: The U.S. EIA (EIA, 2010) and the paper, "Modern Portfolio Theory Applied to Electricity Generation Planning" from Beltran (Beltran, 2009). The EIA report uses costs for electric generation in the United States. They use a discount rate of 20%. The Beltran paper uses information for Mexican power plants. His analysis uses information for 20 years provided by CFE. For his analysis he uses a discount rate of 12%. Both scenarios can be considered as low and high cost with different embedded assumptions regarding intergenerational priorities and effects as well as opportunity costs.

The objective of the MPT is to maximize the expected performance of the portfolio E (P). Because E (P) = π/σ minimizing it when using a cost-based scenario will yield an inefficient result: higher expected costs for the same associated risk. An alternative is to use a "return." Since cost is expressed in [$/MWh] and return is expressed as [MWh/$] to get the inverse of the cost will be equivalent to obtaining a return for the investment (Awerbuch and Berger 2003). In this case it is possible to do the analysis as a best performance portfolio by maximizing the expected portfolio performance. Table 3 summarizes the generating costs and their "return" (or inverse) for the technologies used in the analysis (Beltran) for Case 1. Table 4 shows the costs for Case 2 (EIA).

Table 10: Expected Generation Costs and Return (Inverse) for Case 1

Power Plant	Expected Cost ($/MWh)	Inverse
Hydro	91.35	0.010946
Combined Cycle	70.74	0.014136
Nuclear	74.48	0.013107
Coal	76.29	0.013426
Renewables	93.06	0.010745
Geothermal	80.24	0.012462

Table 11: Expected Generation Costs and Return (Inverse) for Case 2

Power Plant	Expected Cost ($/MWh)	Inverse
Hydro	119.90	0.008340
Combined Cycle	83.10	0.012033
Nuclear	119.00	0.008403
Coal	110.5	0.009049
Renewables	234.02	0.004273
Geothermal	115.70	0.008643

Risk: Standard Deviation

The main idea behind the design of the Modern Portfolio Theory is that reducing risk can in fact lead to reducing the overall cost of the portfolio. Because of this concept risk becomes the most important factor of the MPT. Unlike financial assets physical assets (like power plants) have several elements of risk: fuel risk, transmission and voltage risk, political, environmental, investment, operations and maintenance (O&M), etc. Because this analysis is based on the cost of generating such technology, fuel cost risk is the most important part of the composition of risk (Awerbuch and Berger 2003). Because this analysis focuses on generation, I will consider that the two other main sources of risk are investment and O&M risks. Because the information for the expected generation cost considers a present value approach investment risk could be discarded leaving the composition of the cost with only fuel and O&M (Awerbuch and Berger 2003)[37]. Renewable energies have the advantage of having zero fuel cost risk and zero depletion risk (fossil fuels incorporate this risk directly into the price); however, they are subject to other sources of risk such as availability and consistency of the resource[38]. Because of this feature, a 10% prime risk has been added to the composition of risk for

[37] For the purpose of this project the contribution of fuel and O&M risk contributed to 100% of the risk. Beltran uses a different methodology for the measurement of the total risk.
[38] It could be possible that for a given moment no wind blows at all.

renewable and hydro sources for this analysis. This is important because it takes into account higher transmission costs and any voltage issues. Since the MPT penalizes higher risk this prime will help un-bias the results. The correlation between different technologies has to do primarily with price. Because of this fact, correlation between zero cost fuel and any other technology is zero (the cost of generating wind power is the same despite the price of gas; while it becomes less expensive in relative terms, its absolute price is the same[39]). In the case of other fuels there is a correlation of some sort when fuel prices of one-technology moves. This is particularly true for fossil fuels. The information used to build this table comes from the work of Beltran as well. However some of the assumptions are revised in order to un-bias the results. The following table summarizes the technology risk associated with each source used for this thesis.

Table 12: Total Technology Risks

Power Plant	**Total Risk**
Hydro	11.79%
Combined Cycle	37.60%
Nuclear	21.80%
Coal	36.70%
Renewables	14.40%
Geothermal	21.80%

Feasibility

Unlike financial assets, real assets have technical constraints: they might not be fully available. In the case of electric plants there is a limited potential for them. This is especially true for renewable energies; it is impossible to force the wind to blow anywhere we want, and it is not possible to transport the wind to a certain location. Furthermore, it is unreasonable to assume that the Mexican government will substitute all

[39] The prime risk is used to consider back up generation risk as well.

energy sources for the most efficient portfolio. It will make little sense to provide results that were not feasible so technical constraints are considered.

This MPT analysis was done under the assumption that only 33,583 MW are available to be built. This comes from the country's necessities as stated in the Prospectiva del Sector Eléctrico 2009-2024. This means that there have to be limits based on the potential of some sources. It is also unreasonable to believe fossil-fueled technologies will disappear from the share, as they are critical to the mix and absolutely necessary. There also is a set limit for nuclear energy. Current capacity is 2,730 MW. The limit is set to up to two times the current capacity. The following table summarizes the limits set to the technologies modeled.

Table 13: Capacity Constraints

Technology	Limit %	Limit MW
Hydro	13.32% (Upper)	4,474
Combined Cycle	50% (Lower)	16,792
Nuclear	8.13% (Upper)	2,730
Renewables	19.95% (Upper)	6,700
Geothermal	10.53% (Upper)	3,535

Portfolio analysis

There are an infinite number of combinations available when constructing a portfolio. Constructing a six-asset portfolio presents a yet more compelling challenge. The following figures represent the efficient frontiers. As explained before, the efficient frontier line represents all the possible combinations of portfolios that are efficient. In the case of the Expected Cost scenario any portfolio above the efficient frontier is considered inefficient. This is because we are looking for the lowest cost alternative, which is to the bottom of the vertical axis. The higher the risk the closer to the right the portfolio will be. Traditional efficient frontiers work with expected returns, the curve of which is opposite to that of the expected costs. This means that when we are looking for the highest return, any portfolio under the curve is considered inefficient.

The Optimization Problem

In order to know which the best possible portfolio is, it is important to set up an optimization problem. Depending on the objective it must be set either to maximize or minimize a defined objective function (Kwan 2002).

For the Expected Return scenario the objective is to maximize the expected performance of the portfolio and the optimization problem becomes:

Maximize:
Max

$$P = \frac{E(\Pi)}{\sigma_P}$$

s.t.

$$\sum_{i=1}^{6} \omega = 1$$

for i=1,2,3,4,5,6
and $\omega_i \geq 0$

The objective is to ultimately reduce risk as much as possible, in the most efficient manner. This optimization problem seeks to maximize the expected performance of the portfolio. The expected performance is measured as Expected Return over standard deviation. Since it is a division the optimization problem should be resolved by reducing the standard deviation as much as possible. This will lead to a possible assignation of lower risk technologies despite their higher costs (higher expected returns).

Sensitivity Analysis

In order to better evaluate the results I present a sensitivity analysis that will be compared to a base case. In a previous section I described Case 1 and Case 2. These scenarios use data on costs of generating electricity. Case 2 costs are considerably higher than those of Case 1. This gives enough margin to understand how the portfolio models work under different scenarios. The base case runs under the assumption that all technology is available to be built. A second base case considers only resource availability limits. That means that there will be no constraints to minimums and maximums except for resource availability. The purpose of this is to compare "ideal" results with practical results.

Base Case 1 and 2 Results and Comments

Free Technology Scenario

Table 14: Optimum Portfolio Weights for Base Case 1

Technology	Weight
Hydro	62.51%
Combined Cycle	4.69%
Nuclear	10.74%
Coal	0.00%
Renewables	14.22%
Geothermal	7.84%

Portfolio's Expected Return	
0.011453	$87.31

Portfolio's Standard Deviation
7.19%

Table 15: Optimum Portfolio Weights for Base Case 2

Technology	Weight
Hydro	77.53%
Combined Cycle	5.07%
Nuclear	8.62%
Coal	0.00%
Renewables	1.97%
Geothermal	6.81%

Portfolio's Expected Return	
0.008473	$118.02

Portfolio's Standard Deviation
7.41%

This set of results favors low risk technologies. This is because the optimization problem shows the performance of the portfolio in terms of cost/risk. The higher the risk is the lower the performance of the portfolio is. The better cost-risk ratio performance of Hydro makes it the most attractive technology. The higher risk of fossil fueled technologies makes them outperform against lower risk technologies. The high correlation of CCGT and coal tends to leave coal out of the mix.

The Base Case 2 results are more extreme. The higher costs for renewables make them an unattractive technology despite their lower risk. Their share is mostly taken by Hydro, which makes up for the *increased* risk of the portfolio due to the lower share of Renewables and Geothermal.

It can be concluded that current high costs of Renewables are not enough to compete against fossil fueled technologies despite their lower cost even if we use an analysis that *punishes* high fuel variation risk[40].

Resource Availability Restrictions Scenario

[40] The definition of risk that I use for this work basically considers fuel risk as the prime source of risk for the generation of energy. In order to have unbiased results, I also added a 10% risk prime to renewables. This considers transmission and voltage issues. If these assumptions were to be changed, then the results presented here would be different.

As explained before there is a limit to how much renewable fueled plants can be built. There is only a certain capacity available in each country with current technology. This last scenario takes these limitations into account. The assumptions that will be used consider practical restrictions for CCGT and Nuclear. In this case these assumptions are not considered because the objective is to know the *ideal feasible* mix.

Table 16: Optimum Portfolio Weights for Base Case 1 with Resource Availability Restrictions

Technology	Weight
Hydro	13.32%
Combined Cycle	16.85%
Nuclear	39.35%
Coal	0.00%
Renewables	19.95%
Geothermal	10.53%

Portfolio's Expected Return	
0.012580	$79.49

Portfolio's Standard Deviation
10.43%

Table 17: Optimum Portfolio Weights for Base Case 2 with Resource Availability Restrictions

Technology	Weight
Hydro	13.32%
Combined Cycle	18.69%
Nuclear	37.51%
Coal	0.00%
Renewables	19.95%
Geothermal	10.53%

Portfolio's Expected Return	
0.008275	$120.85

Portfolio's Standard Deviation
10.47%

As explained before efficient portfolios are limited to feasible combinations. These combinations yield different results from the optimum portfolios. This is very much expected since the optimum portfolio allocated nearly half of the expected generation technology as hydroelectric. Since hydroelectric maximum capability is of only 13.32% we would expect to see a big shift in the mix.

Not surprisingly the portfolio maximizes the possible use of low risk technologies. Since Hydro is so constrained, allocating the highest possible share of low risk technologies into the mix compensates the performance of the portfolio. The share of Nuclear becomes most important. This makes sense since it offers a much better cost-risk ratio than fossil fueled technologies.

Case 1 and 2 Results and Comments for Feasible Scenarios and Cost Variation

To better conduct the sensitivity analysis I used a dynamic approach rather than a static one. This element of analysis is called Cost Variation. Portfolio optimization uses static (fixed) values to determine the optimum portfolio. In this case the results presented are based upon the expected value of the cost; that is, the final results come from a series of simulations of the costs. The ranges on which the costs vary are 10% for all technologies but renewable, which is analyzed with a 20% variation for the Low Cost Variation scenario. A second scenario is presented where all technologies vary by 20% but renewable, which has a 40% variation. This scenario is called High Cost Variation. These will be considered the optimum results for this analysis.

Case 1 Low and High Cost Variation Results

Table 18: Optimum Portfolio Weights for Case 1 Low Cost Variation

Technology	Weight
Hydro	11.42%
Combined Cycle	50.00%
Nuclear	8.10%
Coal	0.00%
Renewables	19.95%
Geothermal	10.53%

Portfolio's Expected Return	
0.012867	$77.72

Portfolio's Standard Deviation
18.86%

Figure 8: Efficient Frontier for Case 1 Low Cost Variation

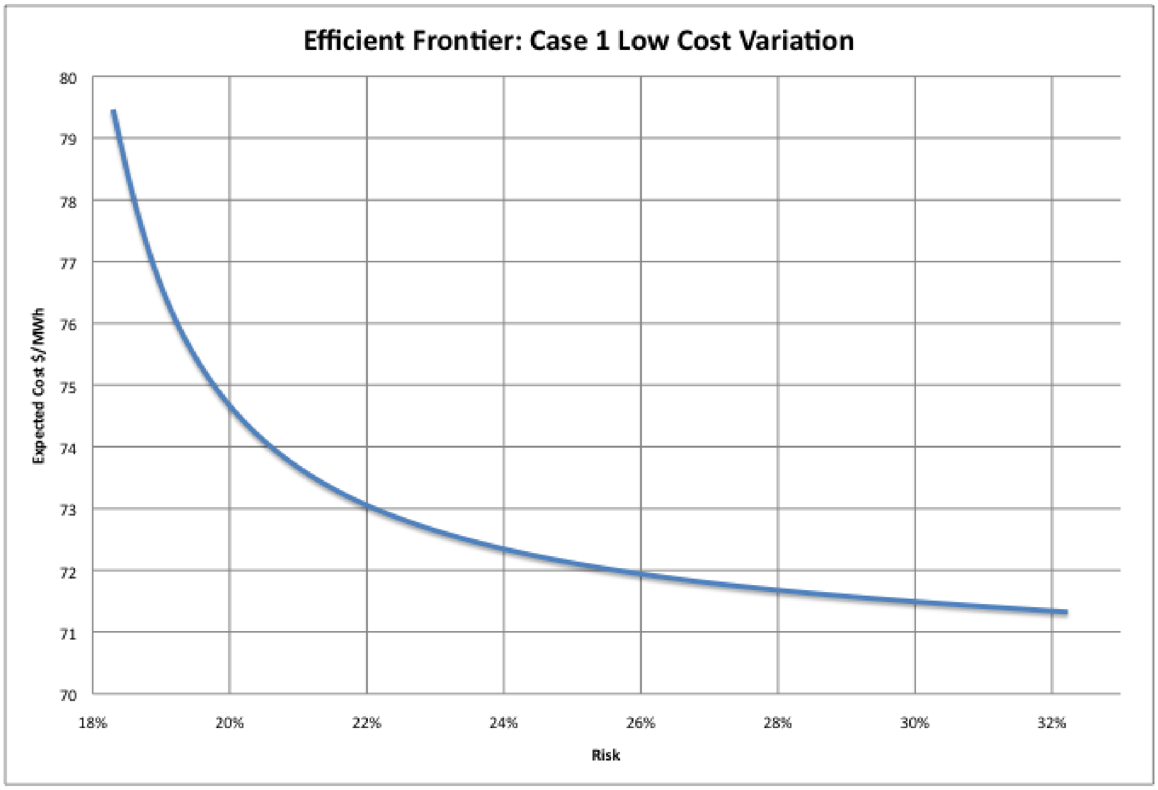


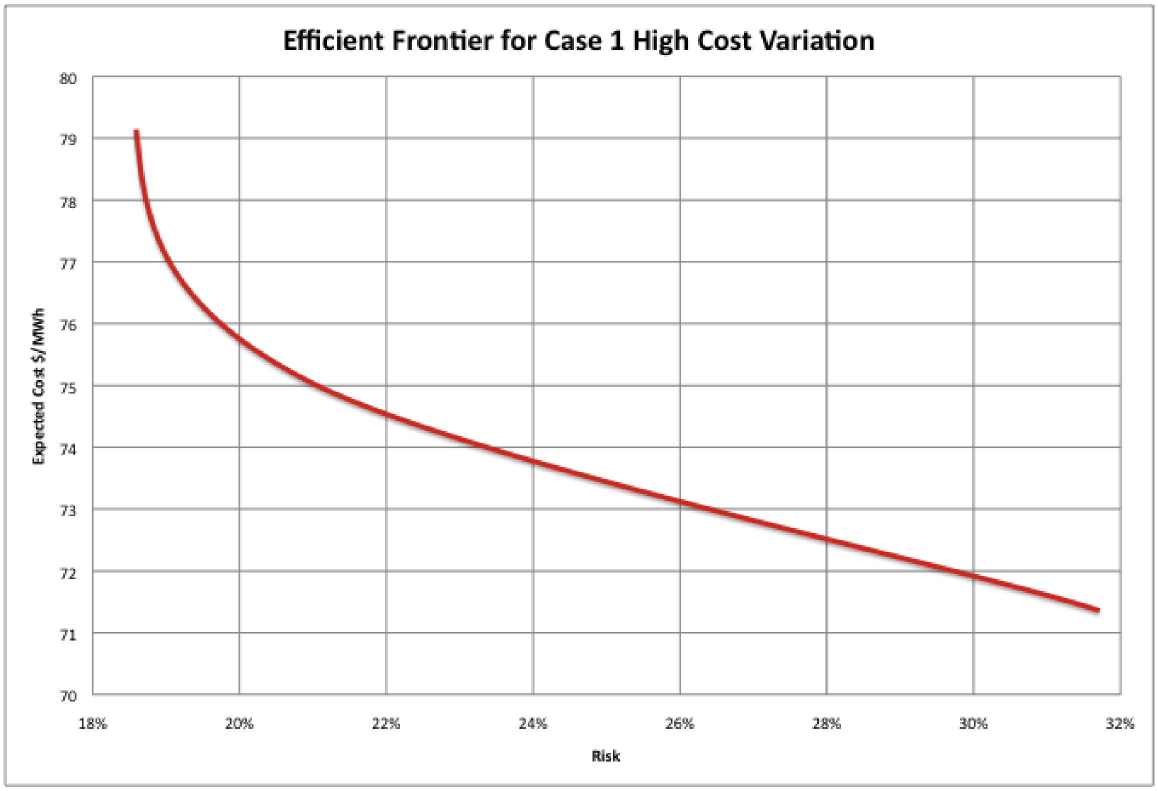
Table 19: Optimum Portfolio Weights for Case 1 High Cost Variation

Technology	Weight
Hydro	12.89%
Combined Cycle	50.00%
Nuclear	7.83%
Coal	0.00%
Renewables	19.33%
Geothermal	9.95%

Portfolio's Expected Return	
0.012840	$77.88

Portfolio's Standard Deviation
18.85%

Figure 9: Efficient Frontier for Case 1 High Cost Variation



The Case 1 scenario yields a portfolio using almost 58% traditional energies and 42% of renewable sources. The most notable aspects of these results are:

- The expected cost of generating electricity was nearly the same for Low Cost Variation and High Cost Variation ($77.72 and $77.88 $/MWh). I would have expected a higher difference as the price variation was twice as high.
- The risk of the portfolio was nearly the same in both cases (18.86% vs. 18.85%). This is expected, as the weight of each technology in the mix is nearly identical.
- Optimum results entail the smallest allowed use of Combined Cycle Technology (50%).
- Allotted capacity for Hydro was not used exhaustively.
- No Coal was used.

- The Low Cost Variation Scenario maxed out Nuclear, Renewable and Geothermal allowance, while the High Cost Scenario nearly did.

Case 2 Low and High Cost Variation Results

Table 20: Optimum Portfolio Weights for Case 2 Low Cost Variation

Technology	Weight
Hydro	13.32%
Combined Cycle	50.01%
Nuclear	8.10%
Coal	0.02%
Renewables	18.02%
Geothermal	10.53%

Portfolio's Expected Return	
0.009492	$105.36

Portfolio's Standard Deviation
18.85%

Figure 10: Efficient Frontier for Case 2 Low Cost Variation

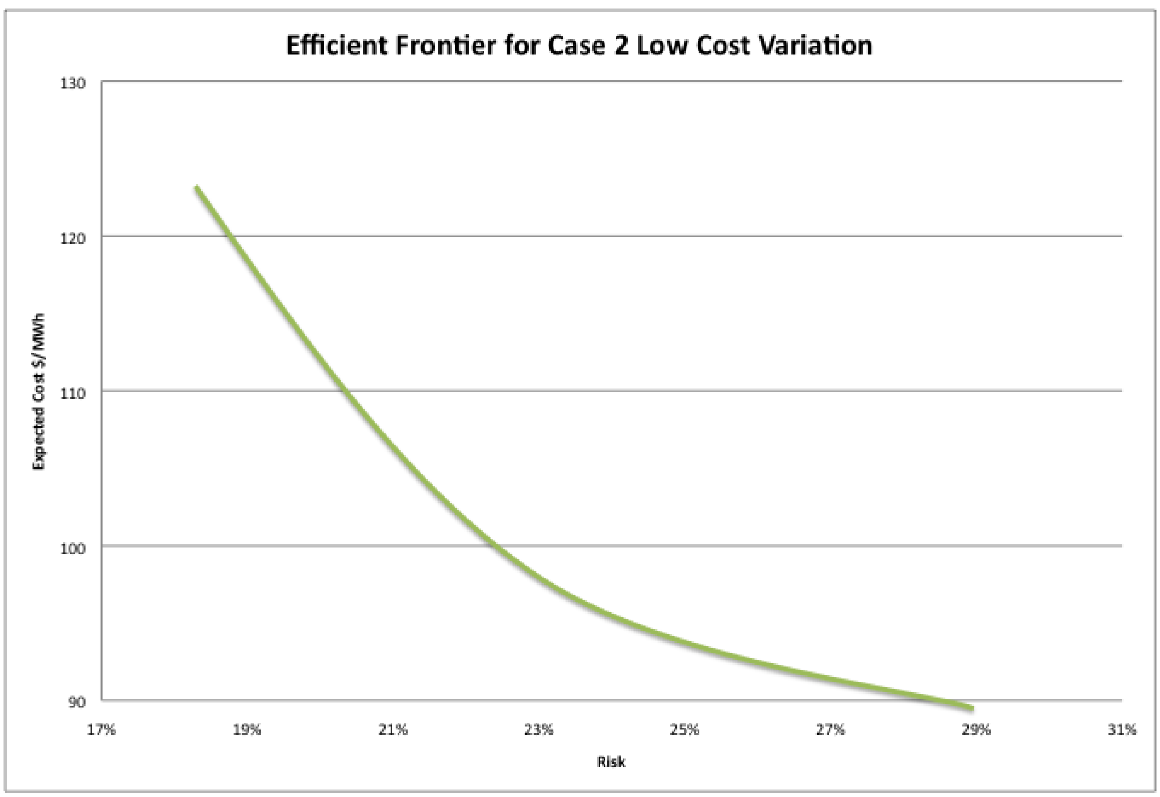


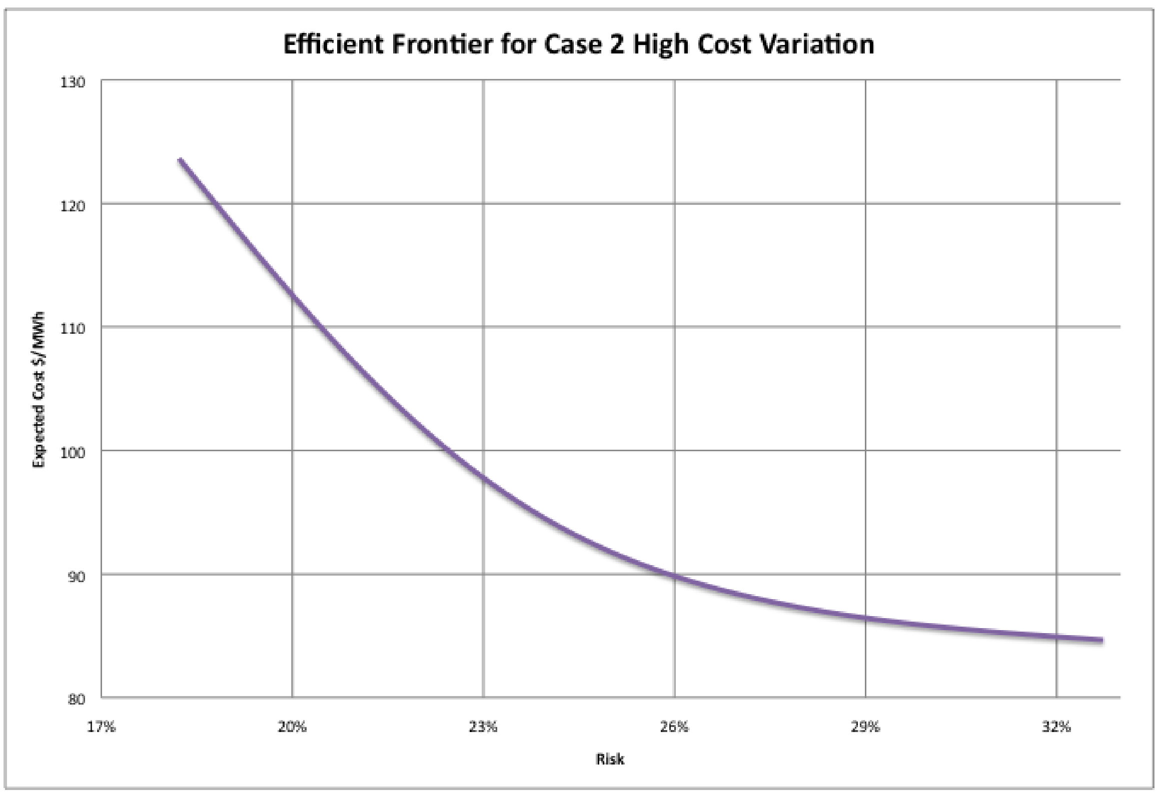
Table 21: Optimum Portfolio Weights for Case 2 High Cost Variation

Technology	Weight
Hydro	13.32%
Combined Cycle	50.00%
Nuclear	8.10%
Coal	0.00%
Renewables	18.05%
Geothermal	10.53%

Portfolio's Expected Return	
0.009484	$105.44

Portfolio's Standard Deviation
18.84%

Figure 11: Efficient Frontier for Case 2 High Cost Variation



Case 2 Scenario yields slightly different results. The share of renewable and traditional technologies remains as 42% and 58% respectively. The most notable results of Case 2 are:

- The expected cost of generating electricity was, again, nearly the same for Low Cost Variation and High Cost Variation ($105.36 and $105.44 $/MWh). In this case, the difference was even smaller than in the previous case, only 0.07% as compared to the Case 1 difference of 0.2%.
- The risk of the portfolio was nearly the same in both cases, both having similar results (18.85% vs. 18.84%). The notable thing is that it is, even by a minimum margin as is the expected cost, lower than in Case 1.
- Optimum results use the least allowed use of Combined Cycle Technology of 50% (Low Cost Variation used 50.01%).
- Allotted capacity for Hydro, Nuclear, and Geothermal was used exhaustively.
- Nearly no Coal was used (Except for a 0.02% in the Low Cost Variation Scenario).
- The share of renewables was of 18.02% and 18.05% respectively. This makes sense because prices are considerably higher for Case 2.

Conclusions

Some interesting conclusions can be drawn from this exercise:

- It is important to incorporate risk into planning any kind of investments. Hedging can be expensive, and there are costs associated to high volatility in energy planning. This volatility could be as much as 0.40% of GDP (Awerbuch, 2006).
- It is possible to reduce overall cost of a portfolio with the introduction of presumed low risk technologies, despite their higher cost. This is possible because portfolio optimization considers cost-risk ratio. However, when there are

no restrictions, the Case 2 base case shows that the lower risk might not be enough to compensate their higher cost.

- Generating energy is not only about reducing costs but there are many other factors and assumptions that have to be taken into account.
    - This exercise considers the overall cost for each technology. It does not take into account factors such as high/low initial investment cost and actual construction period. These two factors underlie the rapid growth of CCGT technology in Mexico. The limitations of this model are the limitations SENER would face when actually building the portfolio. Budget constraints and catching up with growing demand will work as a handicap against the development of high initial cost technologies or with a long construction period.
    - The assumptions could be extended to other factors like emissions, diversification, location, peak demand, employment, etc. All of these factors could be built into the model in the same way as the other assumptions were introduced.
    - Grid and voltage considerations are critical. Wind and solar energy are not constant. This means that there is a cost to managing voltage variations and to provide backup generation. My thesis incorporates this cost by increasing the risk associated with the use of these technologies. However, my assumed risk prime may not be enough. In Mexico the development of renewable technologies has been done near industrial areas in order to compensate for this problem. Such a strategy, on a national scale, would not solve the issue of using all possible resources

(for instance, it would not make sense to move enough heavy industry to Oaxaca to optimize the available wind resource in that region).

- Nuclear power is a most interesting technology. Its low cost/low risk return makes it an attractive option, as the renewable energies are limited to their potential. Currently there are three big drawbacks to the development of nuclear capacity. The first one is the higher initial investment needed despite its possible lower overall costs. As explained before CFE is restrained to a budget and to meeting growing demands. Even though private investment is allowed to produce electricity in the country, this figure does not consider the nuclear option. Nuclear technology is considered a national security issue. The handling of nuclear material for the generation of electricity is allowed only to the federal government. This means that not only must the legislation change to openly accept private investment in the generation of electricity, but also to allow for the use of nuclear power. This would seem difficult to accomplish. As a result, a nuclear option is attractive but it is not a priority for CFE. The second drawback has to do with the perception of the safety of the nuclear technology. The Japan disaster of 2011 nuclear technology has reopened the debate about nuclear safety. Even though the accident could be considered an "act of god," the debate is centered about if the risk is worth taking. In any case, the most important thing will be to understand how this accident will affect future design and economics of nuclear plants (assuming public perception could be ignored and becomes irrelevant in the decision). Finally, nuclear technology is seen as disruptive for the environment. Nuclear technology has strong impacts on water and as radioactive waste if reprocessing to reduce high level waste is not an option. On the other hand this technology is quite clean, reliable and has no emissions. Since one of the goals of the government is to reduce emissions developing nuclear technology could help achieve this goal in an efficient matter.

- It is important to remember the limitations of renewable energies. The feasible potential of these technologies and resources directly affects the available mix. This analysis considers the maximum proven potential. If this potential were to be less effective it would considerably affect the mix.

My model offers a way to go around the "least cost" mandate. It has shown that under certain conditions it is most advisable to encourage the use of renewable energies. My model does not consider the level of emissions, which is a benefit of developing these technologies. I only explicitly experiment with reduced overall cost and risk of the portfolios with specific assumptions regarding priorities and risk factors. Implicitly, as programmed, the model tries to solve for sustainable development by reducing the environmental impacts of generating electricity. Traditionally it is assumed that cleaner technologies are more expensive so that trade-offs are mainly between economical cost and environmental cost. With the use of a model approach of the type I devised here it is possible to merge these two goals in an efficient way.

Chapter 7: Cost-Benefit Analysis

This chapter summarizes the most relevant aspects of my research and experimentation. Here I re-cast my results in terms of the cost-benefit analysis defined in Chapter One. So as not to be redundant I will be brief and I will use only the most necessary summary statements.

SIX STAGE ANALYSIS

Stage 1: Definition of project

The project is the design of an electricity portfolio in Mexico. Mexico needs to add 33,583 MW to its electric grid by 2024. In order to do so it should consider the different available technologies and how they fit within these major guiding principles.

Stage 2: Identification of Project Impacts

The design of the portfolio should be done considering the following guiding principles:

1. National Security
2. Environmental Sustainability
3. Economic and Productive Efficiency

Stage 3: Which Impacts are Economically Relevant?

As stated before, these principles will guide the design of the real portfolio for Mexico. This means that economical relevance of these impacts is analogous to the economical relevance of the different fuel and technology alternatives used to design the electricity portfolio. As the price is predefined the most important aspect is the levelized cost of generating energy. As explained before my model experiment considered two different base cases. The levelized costs for the different technologies considered in my analysis for the two cases are:

Table 22: Expected Generation Costs for Case 1

Power Plant	Expected Cost ($/MWh)
Hydro	91.35
Combined Cycle	70.74
Nuclear	74.48
Coal	76.29
Renewables	93.06
Geothermal	80.24

Table 23: Expected Generation Costs for Case 2

Power Plant	Expected Cost ($/MWh)
Hydro	119.90
Combined Cycle	83.10
Nuclear	119.00
Coal	110.5
Renewables	234.02
Geothermal	115.70

Stage 4: Quantification of Relevant Impacts

The quantification of these impacts is done in two ways. The first method is the assessment of risk associated with each technology. This risk considers fuel volatility, O&M risk, and in the case of renewables a prime related to the low maturity of the technology and its low reliability. The second assessment is directly associated with the major guidelines in force for Mexico. These principles imply certain preferences when designing the nation's portfolio; these preferences have different levels of risk and feasibility associated to them. This risk defers from the other type of risk. Technology risk is associated with variability in cost, while risk assessment has to do with how I perceive the possibility of a negative outcome if the event described was not achieved.

Table 24: Technology Risks

Power Plant	Total Risk
Hydro	11.79%
Combined Cycle	37.60%
Nuclear	21.80%
Coal	36.70%
Renewables	14.40%
Geothermal	21.80%

Table 25: Assessment of Risk and Feasibility for Principle Guidelines

Optimum National Security Scenario	**Level of risk**	**Level of Feasibility**
No importation of fuels	Low	Medium
Complete diversification of energy sources	Medium–High	High
Minimum depletion of fuels so as to guarantee supply for future needs	Medium-Low	Medium
Optimum Environmental Sustainability Scenario		
No CO_2 emissions	Medium	Medium
Increase plant efficiency	Medium	Medium
Economic and Productive Efficiency		
Optimize grid connections and reduce consumer demand	Medium	Medium-Low
Procurement of energy at the lowest cost	Medium	High

Stage 5: Applying Net Present Value (NPV)

The portfolio analysis performed in Chapter Six considers levelized costs. Levelized cost of energy generation discounts future cash flows associated with each power plant and incorporates investment, fuel, operations and maintenance, and transmission costs for the expected lifetime of the plant. These results compare the absolute expected cost of that portfolio. It is important to remember that this is not the lowest possible cost, but the cost associated with the optimum performance of the portfolio. This means that this analysis takes risk into account.

Table 26: Optimum Expected Cost of the Portfolio for Case 1 Low Cost Variation

Portfolio's Expected Cost
$77.72

Table 27: Optimum Expected Cost of the Portfolio for Case 1 High Cost Variation

Portfolio's Expected Cost
$77.88

Table 28: Optimum Expected Cost of the Portfolio for Case 2 Low Cost Variation

Portfolio's Expected Cost
$105.36

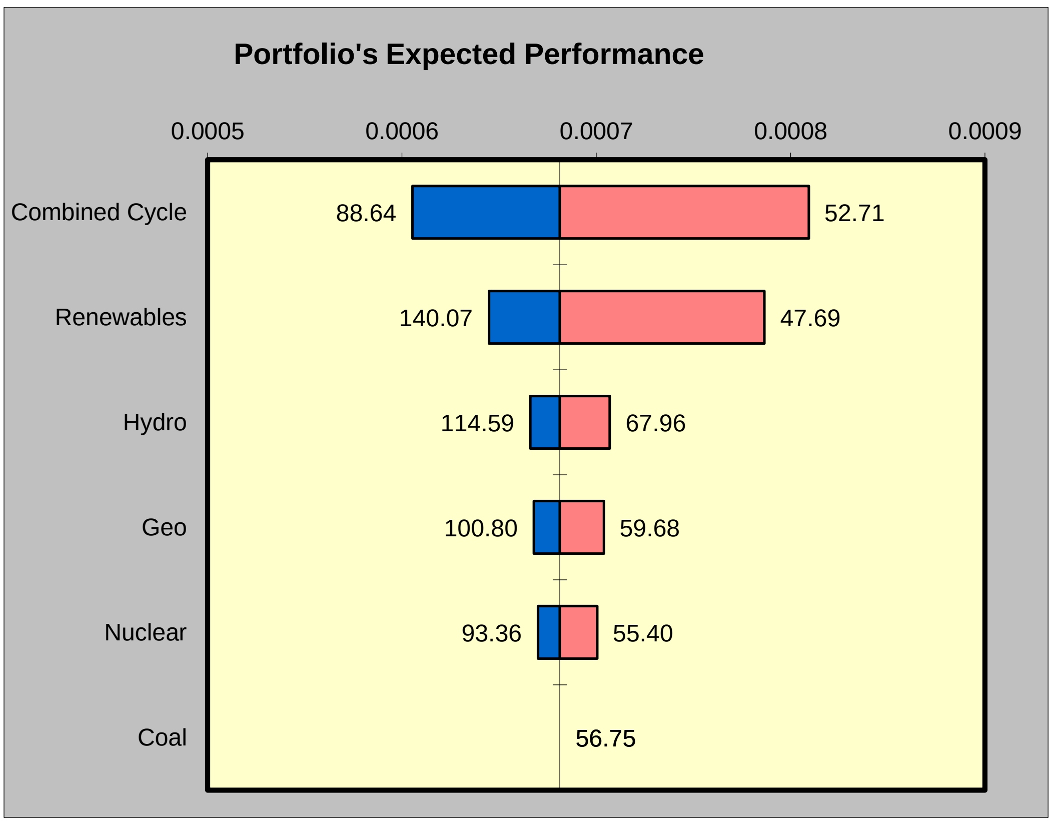
Table 29: Optimum Expected Cost of the Portfolio for Case 2 High Cost Variation

Portfolio's Expected Cost
$105.44

Stage 6: Sensitivity Analysis

The analysis of the guiding principles in chapter five make it clear that it is not possible to choose a single solution that will satisfy all guiding principles. Depending on the principle adopted as highest priority, the decision to design the portfolio would be different. The following charts show the impact of each technology in the final cost. This means, how will an increase or decrease in the price of a certain technology, considering the technical constraints described in the previous chapter, affect the portfolio's cost? A useful tool to address this question is a tornado chart. Tornado charts show how much the value of an asset changes if one of the variables that make up this asset changes. Used here, a tornado chart shows how any change in the share of a given technology will affect the overall cost of the portfolio. The two following figures show the tornado charts for both cases I modeled[41]. This is useful because it can help understand the importance of each variable. How will the portfolio be affected by volatility? What will be the performance of the portfolio under this new condition? A tornado chart helps us understand the *flexibility* of the portfolio in terms of the expected performance.

Figure 12: Tornado Chart for Case 1 High Cost Scenario



[41] I decided not to include the low cost scenario because results are too similar and conclusions would be redundant.

Table 30: Results for Tornado Chart for Case 1 High Cost Scenario

	Portfolio's Expected Cost		
Variable	Downside	Upside	Base Case Cost
Combined Cycle	65.55	87.63	70.71
Renewables	67.45	82.28	93.44
Hydroelectric	75.04	79.65	91.32
Geothermal	75.36	79.43	80.24
Nuclear	75.74	79.18	74.43
Coal	77.87	77.87	76.28

Figure 13: Tornado Chart for Case 2 High Cost Scenario

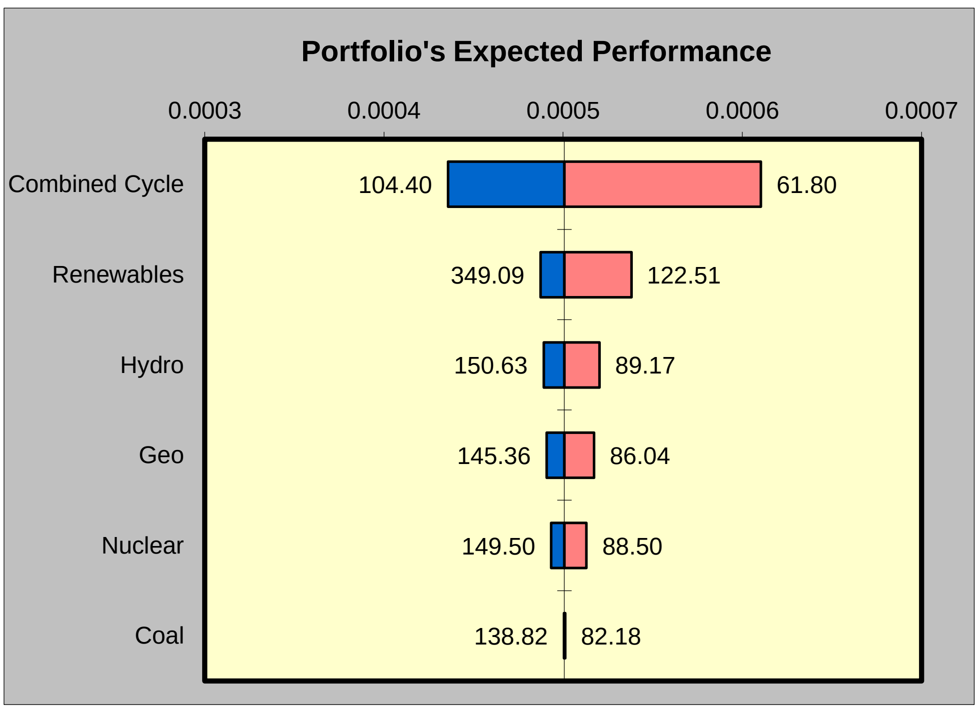


Table 31: Results for Tornado Chart for Case 2 High Cost Scenario

	Portfolio's Expected Cost		
Variable	Downside	Upside	Base Case Cost
Combined Cycle	86.97	121.79	83.1
Renewables	98.65	108.91	234.83
Hydroelectric	102.03	108.52	119.9
Geothermal	102.62	108.13	115.7
Nuclear	103.46	107.58	119
Coal	105.92	106.07	110.5

These charts show the impact the cost of each technology will have on the overall portfolio. As expected the technologies that have the largest share in the mix have the largest impact in the portfolio's expected cost. It is interesting to see that the portfolio is more sensitive to a reduction in technology costs than to an increase in them. This is important because, in general, we can expect technologies to decrease price as performance of these technologies improves. This is especially true for renewable energies as these are technologies still maturing and may decrease their cost at a higher rate, assuming key improvements to manage inherent risks. In the most optimistic interpretation, the tornado charts from my simulations suggest that in the near future renewable technologies could be competitive enough to be considered even if the costs do not go as low as traditional energies' costs. This is contingent, of course, on factors I could not incorporate into my modeling, such as transmission and grid operations.

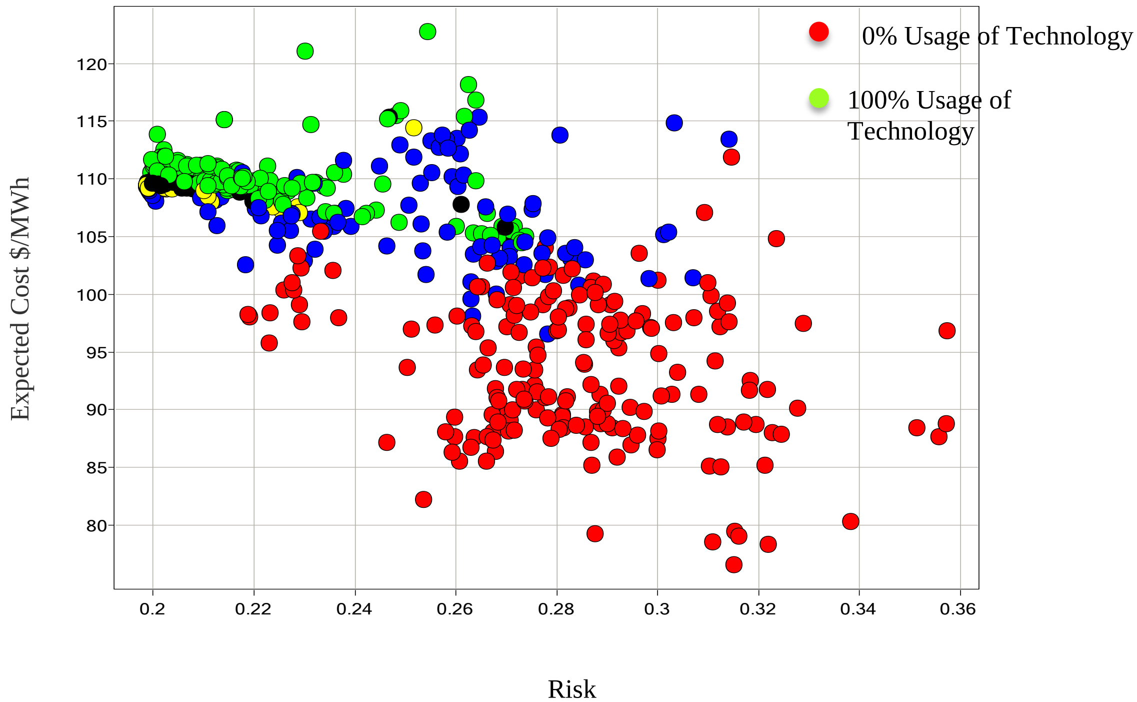
TRADE-OFFS

The objective of this chapter is to show that prioritizing one guiding principle over the other has implications affecting the cost of the portfolio. This does not help answer the question of which guiding principle is most important. It does help to answer the question of what it will cost to choose one priority over the other. The following figures show how important the contribution of each technology is to the share of the portfolio[42].

These charts show a number of possible combinations for the Case 2 High Variation Scenario. As explained before, it is possible to build an enormous array of possible portfolios by allocating different weights to each technology. This can lead to the generation of highly inefficient portfolios. In any case it is possible to see how important the contribution of each technology is to each portfolio. Each point in the following graphs represents a different possible portfolio. These points are color-coded. The green points show the portfolios where all of the allotted capacity for a certain technology was used, while the red points show where the technology was used at minimum. This means that for technologies with an upper bound restriction, green points are close to that upper restriction and red points are near zero. For technologies with a lower bound restriction the red point is that restriction while the green point shows near 100% use. In other words, the green points show what the cost of the portfolio would be if all of the allotted technology of a certain technology is used, while the red dots show the opposite. This will help us answer such questions as, for example, how will my portfolio be affected if I decide to prioritize the Environmental Sustainability guiding principle that would recommend using the greatest possible allotment of renewable resources? Or, on the other hand: what if I prioritize the Economic and Productive Efficiency principle thus removing the highest cost (renewable) technology from the mix?

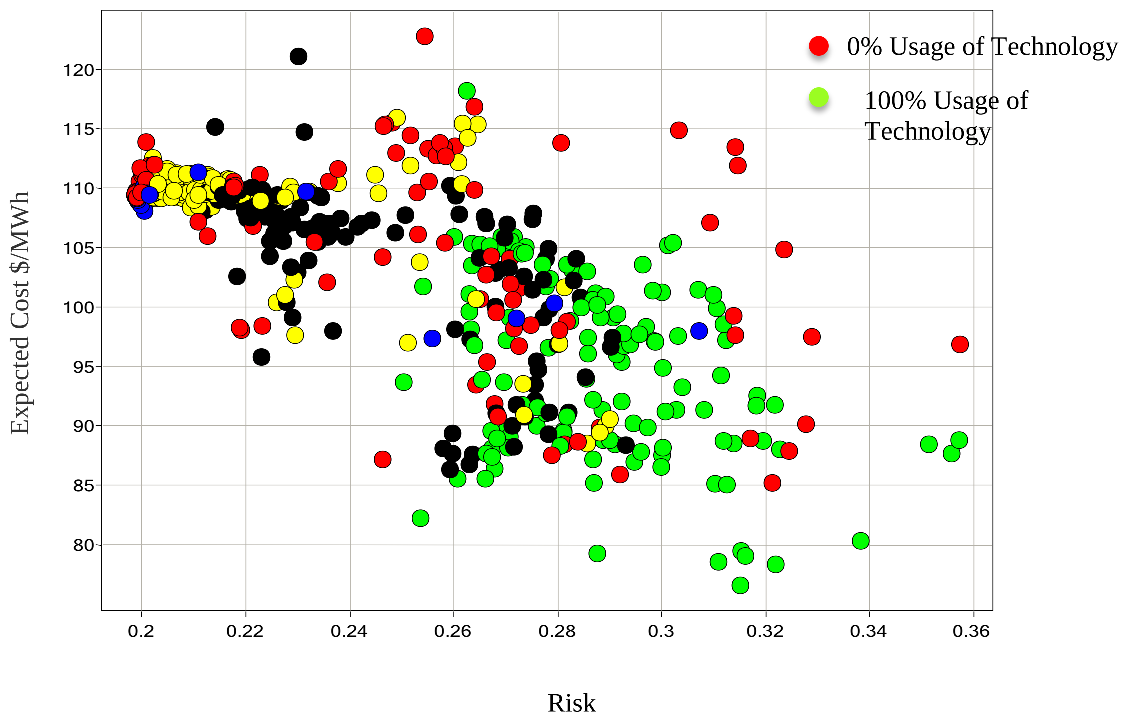
[42] I only included Renewable, Combined Cycle, and Nuclear. Since the share of the other technologies is smaller, the conclusions that are drawn from these three charts can be applied to the excluded technologies.

Figure 14: Importance of Renewable Fuels in the Portfolio



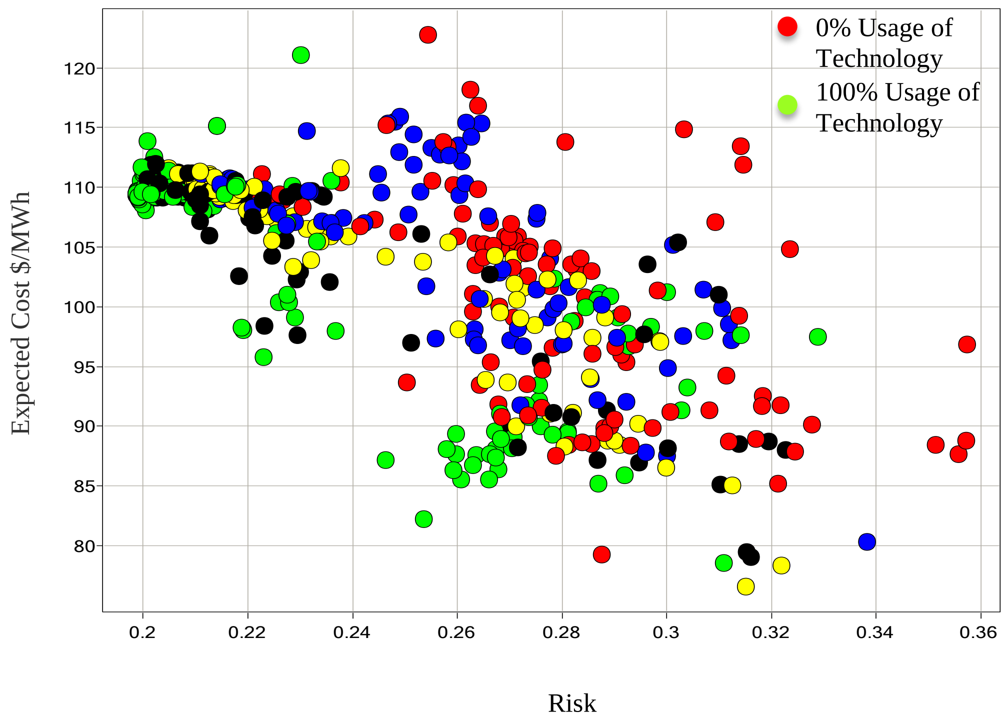
The chart above clearly shows the contribution of renewables in the portfolio. The renewables bundle clearly reduces risk and raises overall costs. This can be seen from the colored dots. The green dots in the upper left corner show what the cost and risk of the portfolio is when all of the allotted contribution of renewables is used (19.95%). On the other hand, the red dots show the cost and risk of the portfolio when no renewables are used. This helps us understand the contribution of renewables in the portfolio better. These results suggest that if a guiding principle prioritizing the use of renewable fuels is used, then the electricity portfolio of the country will have a higher associated cost.

Figure 15: Importance of Combined Cycle in the Portfolio



This second chart shows in a very clear way that introducing Combined Cycle technologies into the mix reduces the overall cost of the portfolio. CCGT also raises the risk of the portfolio, because of how is risk defined, thus reducing the performance. My depiction shows that a principle prioritizing low cost technologies over all other criteria should increase as much as possible the share of combined cycle in the portfolio.

Figure 16: Importance of Nuclear in the Portfolio



This third chart is important because it shows that nuclear technology increases the efficiency of the portfolio. The green points move along the efficient frontier showing that it is better to include nuclear technology than to not include it under all principles.

It is hard to do a cost benefit analysis when it comes to government actions. How do you properly quantify priorities? What is the choice of discount rate – how do we feel about intergenerational effects? It is, however, of the utmost importance to know what the trade-offs are associated with each decision. In the case of electricity planning these trade-offs come in the form of choosing priorities. A freely elected government can decide, with appropriate representation, what is best for the country and act accordingly. What it cannot do is improvise and try to make every stakeholder happy because that is not possible. The objective of the analysis presented above is to show how prioritizing any technology (in terms of the guiding principles) would affect the cost of the portfolio. With this accomplished, I suggest that decisions are not free and choosing in favor of any principle is possible but it certainly has implications.

Conclusions

The ideal goal of pursuing development for a country is to generate economic growth in order to increase the quality of life of its citizens with as little negative impact on the country's natural resources and environment as possible at the lowest possible cost. In order to do this, a cost-benefit approach has to be taken to electricity planning.

Currently, Mexico has three guiding principles regulating the nation's energy strategy:

1. National Security
2. Environmental Sustainability
3. Economic and Productive Efficiency

The trade-offs associated with the generation of energy have to do primarily with the choice of fuel and associated technology. Each fuel has certain advantages and disadvantages in terms of cost, supply, and environmental impact. The selection of an electricity portfolio depends on the priorities of the nation. In other words, what are the costs and benefits of each technology? Given that generation of electricity is a must, what is the priority of the nation? For the case of Mexico, these priorities are set by the guiding principles. The problem lies in the trade-offs of these principles, as they would prioritize once choice of fuel/technology over another.

The work presented in my thesis shows some of the trade-offs associated with the generation of energy. It shows the cost of generating technologies, the environmental impact, and, in the case of Mexico, availability. The reason this is done is because it is important to be clear about what the implications are when generating electricity.

My approach uses portfolio theory as a tool to choose portfolios. With financial theory it is possible to incorporate risk into the design of a portfolio. This allows for a more efficient portfolio. My thesis also recognizes technical constraints to the construction of the portfolio, that is: it is not possible to create a portfolio consisting solely of renewable fuels. The objective is to analyze what would be the best *possible* portfolio.

Finally I show the implications of prioritizing one technology over the other considering the guiding principles. Since each principle implies a different ideal choice of fuels, then it is important to know what impact increasing or decreasing each fuel will have in the cost of a feasible portfolio.

Limitations

The electricity industry is very complex. This is true especially for a country like Mexico, where electricity generation is restricted to the government domain. This means that every decision has political implications, complicating choices. Such a circumstance makes it difficult to propose a single solution to solve the energy mix, as opposed to a market-determined outcome. Designing financial models to approach the problem is innovative, yet incomplete. It is, for example, nearly impossible to mathematically represent the political effects of substantially augmenting the share of nuclear power in the country. However, a financial model affords a great tool to help understand that it is possible to explore the choice problem from a different perspective. In order to offset political vagaries, a cost-benefit approach is used. This allows one to know, once the priority is defined, what are the implications of choosing certain technology over the other. It is important to clarify that my model and assumptions do not attempt to demonstrate which guiding principle is more important. My goal has been to demonstrate a method for exploring what the most efficient portfolios are or could be, and what the impact of choosing one technology over the other is.

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