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Master Thesis in Engineering

Application of the Portfolio Theory to the Power Sector in Mexico

February 2016

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Application of the Portfolio Theory to the Power Sector in Mexico

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Abstract

Energy planning has become a most relevant subject due to its economic implications and the social welfare commitment of ensuring access to affordable energy. Over the last decades, Mexico's energy planning priority was to achieve universal access to electricity, thus least-cost optimization criteria has been the tool used to assess the expansion of power capacity. As a result of this policy, the energy mix relies heavily on fossil fuels.

Nevertheless, a new paradigm in energy planning is expected to emerge from important changes in Mexican energy regulation, institutions and market mechanisms. In this context the portfolio theory is applied to find energy planning alternatives based on the risk minimization of generation technologies. Historical data on the cost of generation was used to quantify the risk, which is based on fuel fluctuation prices and investment

costs. Additionally, the notion of realized generation capacity was used to find the most efficient mix of generation technologies in terms of risk, then, the best technological options to enhance energy security were identified.

The results show that geothermal and hydropower plants are key technologies for decreasing risk due to fuel price volatility. Wind power is risky in terms of realized capacity. Nuclear and coal power plants are stable in capacity and operation costs. Thermal and gas technologies are the most vulnerable to fuel price variability. Finally, the key findings and implications for decision making when selecting generation technologies are presented.

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Chapter 1. Introduction

1.1. Background

During the last century, energy played a major role in the industrialization of nations. Energy supply, especially oil and coal, marked the pace in the 20th century, when major manufacturing powers grew, transitioning into sophisticated, less machine and energy intensive service economies. Entering the 21st century, the rise of billions of people into an immense new middle class is expected. In the same fashion as the last century, we are witnessing the destruction of old industries and the creation of new ones through innovation like information and communication technologies. The Internet is the backbone sustaining and shaping the new paradigms.

Nevertheless, the consequences of the apparent success and abundance of industrialization are catching up in all contexts of society, regardless of geographical or economic position.

These results come as humanity faces huge challenges like climate change, environmental degradation, inequality and stagnant development in some regions.

This transition into knowledge economies requires energy, especially electricity, (which is the fuel that keeps technology moving forward and shaping our new reality), from consumer electronics to industrial robots, and from children's games to smart infrastructure. Thus the need for reliable sources of power has never been so evident.

The several dimensions of energy reliability measurement in conjunction with indigenous growth, resources, purpose and vision comprise the principles and basis of energy planning. While for some countries the main objective is to ensure a constant flow of foreign fuels, others look into ways to reach their rich natural resources.

In the case of Mexico the energy supply vision over the last century has focused on social welfare, led by the state-owned

Federal Commission of Electricity (CFE). With over 98% of the Mexican population having access to electricity, the social purpose of this big company can be considered a success.

Nevertheless, a new wave of liberalization is pushing the state-owned utilities beyond government budgets, control and support into a free market, limiting their participation in the planning process and establishing clear boundaries of influence. As a consequence new opportunities for environmental and operational efficiency are arising.

On the other hand, awareness of the new environmental dimension has been taking incremental relevance over the last decades, challenging the way we think about least-cost criteria. In addition, production and reserves of oil have plunged significantly over the last decade throwing Mexican planners into new landscapes of uncertainty.

1.2. Research Problems

Mexico's energy generation capacity is expected to double over the next 15 years. This implies vast investment in new power plants, decommissioning of old ones and complementary infrastructure like transmission lines, pipelines and roads. During this expansion, according to Mexico's official energy forecast combined cycle gas turbines are to be expanded by over 50% by 2028 (SENER 2014). At the same time the country has been increasing its gas import from US, mainly for power generation (SENER 2014g), increasing exposure to fuel availability and consequently price volatility.

With plenty of renewable energy potential in Mexico, further development of these technologies is necessary and worth and considering.

1.3. Research Question

This study seeks to answer the following specific research

question: “What are the optimal energy technology combinations considering fuel price volatility and capacity variability in Mexico?”

To answer this question, a Markowitz Portfolio Approach is taken using the variance in daily generation costs by technology and capacity cost in Mexico. These variables represent variability in O&M costs, fuel costs, and constraints in system operation.

1.4. Research Objectives

The objectives of this study are:

1. To identify the risk associated with selected energy technologies evident, especially with fuel price variability.
2. To determine an efficient frontier of optimal generation mixes along risk-free and risk-seeking profiles, considering fuel price volatility and the variance in

realized capacity and its investment cost.

3. Finally, policy recommendations for future energy generation selection based on the results.

.

1.5. Organization of the thesis

This study is organized in six chapters. The first chapter presents the introduction, background, research questions, objectives and problems. Chapter 2 is an overview of the energy situation in Mexico; presenting resource potentials, energy consumption and the new institutional structure for energy planning. Chapter 3 reviews the literature about portfolio theory and its applications to the energy sector. Chapter 4 presents the model and its variables. Chapter 5 presents the data description, analysis and results. Chapter six presents conclusions and recommendations.

Chapter 2. Energy Situation in Mexico

Mexico's total energy consumption in 2014 consists mostly of petroleum (45%), followed by natural gas (NG) (40%). Petroleum mainly supplies the transport sector while NG is mainly used in the power generation sector. Due to environmental regulations and system modernization the latter is increasingly replacing heavy fuel oil in power generation. Currently, Mexico produces more than half of its NG consumption to keep up with power generation and industrial expansion, but higher levels of natural gas will likely depend on more pipeline imports from the United States or liquefied natural gas (LNG). All other fuel types contribute relatively small amounts to Mexico's overall energy mix. The country also has growing geothermal and wind energy capacity for electricity generation. (U.S. EIA 2014)

Recently, the government of Mexico has implemented several

measures for energy diversification and access including expansion of gas transportation infrastructure, pro-renewables regulations and investment in oil reserves exploration.

Nevertheless, great challenges are still ahead. From 2000 to 2011, the annual average growth rate of energy consumption was 2.08%, higher than that of GDP. The annual average growth rate was 1.82% for the same period, while primary energy production decreased to an annual rate of 0.3%. (SENER 2013)

According to the Ministry of Energy (2013), if these conditions continue, by 2020 Mexico will have an energy deficit turning the country into a net energy importer. This situation is critical for the power sector as the growth rate is even higher than the national energy average.

2.1.Energy Resources

Mexico has abundant natural fossil and non-fossil energy

resources. According to the Ministry of Energy, in January 2014 proved oil reserves were 9,812.1 million barrels. The assessed potential capacities for renewable sources generation as of March 2014 were 1,119 GWh/y for biomass; wind 15,307 GWh/y, geothermal 45,720 GWh/y, ocean including tidal and wave 1,057 GWh/y and solar 8,171GWh/y, with no proved information available for mini hydro. (SENER 2014h)

2.2. Oil and Gas

According to the Ministry of Energy and the National Oil Company, PEMEX, in January 2014 Mexico's oil reserves were 9.8 billion barrels. Over the last 10 years, the reserves level has decreased at an annual average rate of -1.3%, which means a reduction of 5,882.6 thousand barrels compared with 2004.

The reserve/production ratio up to 31 December 2013 was 10.1 years for proved reserves. With proved and possible reserves the figure was 18.6 years. Finally for the total reserves 3P the

ratio was 31.6 years. (SENER 2014d)

2.3. Renewable Energy

The recent development of the renewable industry in power generation began in late 2008 when Mexico's government enacted the Law for the Use of Renewable Energies and the Financing for the Energy Transition (Ley para el Aprovechamiento de las Energías Renovables y el Financiamiento de la Transición Energética, LAERFTE). Its objective was to regulate the use of renewable energy sources and clean technologies generating electricity not meant for public service (i.e., self- supply outside the CFE grid). Since then, private sector interest in developing renewable energy has increased, as indicated by the rise in applications (IRENA 2015).

The theoretical potential capacities for renewable sources presented in the Energy National Strategy (SENER 2013b) are

20GW for wind generation, 10GW for geothermal, 6.6 GW for mini hydro, 6 GW for solar PV and 3 GW for biomass.

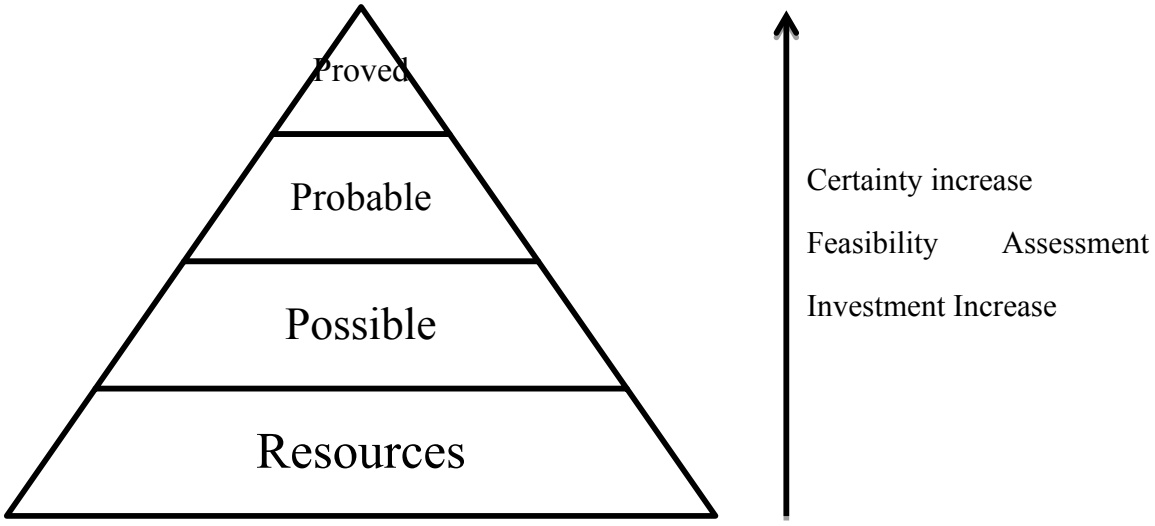
Assessments of these potentials adding technical, environmental and social restrictions are presented in the National Inventory of Renewable Energies, a tool developed and maintained under SENER's responsibility as stipulated in the Renewable Energy Law.

The Inventory presents the generation potentials for each renewable energy source classifying them in proved, probable, possible and resources.

- Resource: Theoretical potential not considering environmental, technical, economic or social restrictions, the result of a generally well accepted international methodology.
- Possible: Theoretical capacity and power generation potential based on indirect assessments, using assumptions with no field studies to prove technical and economic feasibility.

- Probable: Available direct and indirect in-field assessments without corroborated technical and economic feasibility.
- Proved: Enough technical and economic assessments prove its power generation feasibility.

Figure 1: Renewable energy potential classification.



The National Inventory consists of information provided by different institutions, universities and the private sector. The generation potentials according to the National Inventory are presented in Table 1:

Table 1: Proved and probable generation potential. March 2014.

Resource	**Potential (GWh/a)**
Biomass	1,119
Wind	15,307
Geothermal	45,720
Mini hydro	No information available
Ocean (waves and tidal)	1 057
Solar	8 171

2.3.1. Solar Energy

According to the Ministry of Energy (SENER 2013c) the development of solar PV projects for power generation will be the main growth engine for solar energy use. The average solar insolation in Mexico is 5.5 kWh per square meter, with the northern part of the country receiving around 25 kWh per square meter. With these measures it is estimated that the

radiation received in 1% of the northern Sonora desert would be enough to meet Mexico's power demand (Sanchez 2014). According to the Mexican Solar Energy Association in 2012 there were around 60 thousand PV panels whose installed capacity reaches around 14 MW.

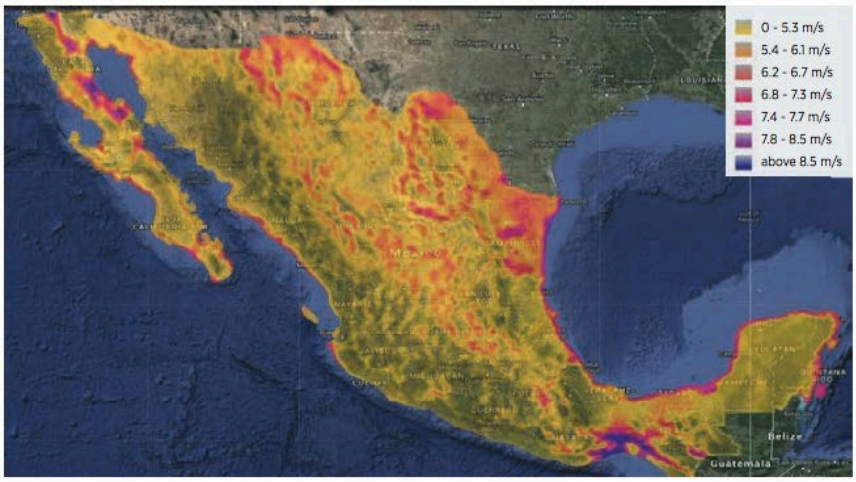
2.3.2. Wind Energy

The biggest renewable energy resource relies on wind power technology as this source has the highest economical potential (INER, SENER, AMDEE). According to the Mexican Wind Energy Association (AMDEE for its acronym in Spanish), in 2014, on top of the 1.9 GW wind power plants already in operation, there are 5 GW in different stages of development.

Thus this industry, which was born in 2008 with the enacting of the Renewable Energy Use and Energy Transition Financing Law, has shown great dynamism and competitiveness. The private sector through the Independent Power Producer scheme

has led this new development. Surprisingly enough, not many of these initiatives have been taken by power generation companies. Other types of industry and consumers have demonstrated that the price of generating power with renewable energy technology has become competitive even against fossil fuels (AMDEE 2014).

Figure 2. Annual mean wind speed at 50m height



Source: IRENA 2015

The highest wind power potential of the country is concentrated in the southwest and northwest parts of the

country where capacity factors can be up to 40%. While low resource areas average 27% and the rest of the potential areas average 35% (IRENA 2015).

2.3.3. Geothermal Energy

Geothermal energy contributed 2.35% of overall generation and 1.54% of installed capacity in Mexico in 2013. It is the only renewable technology that is considered base load by the system operator in Mexico. The development of this technology started in 1973 with the Cerro Prieto I 30 MW project developed by the CFE. Since then, the use of this technology has grown to 823.4 MW in 2013. Until 2013 the geothermal development was exclusive to the state owned utility. In 2013, as part of new legislation in the Mexican Energy Sector, a specific Geothermal Law was enacted allowing private companies to develop geothermal wells for power generation and giving certainty for the investment

process. (IRENA 2015)

Mexico's geothermal potential is estimated to be around 10 GW, one of the highest in the world (IADB 2014). One of the main barriers to the development of geothermal resources in Mexico is associated with exploration risks. Efforts have been implemented through international cooperation to make further geothermal development possible. For instance in May 2013 the Ministry of Energy, with the support of the Inter-American Development Bank, designed and approved financial loans and risk mitigation instruments to foster geothermal energy development.

2.3.4. Hydropower

Hydropower is the main renewable source of power generation in Mexico. In 2013 it contributed 10.63%, a decrease from 12.41% in 2012.

Hydropower accounts for 21.51% of installed capacity. In 2014 a 375 MW hydropower plant started operations increasing renewable generation in the country. Hydropower now accounts for 77.65% of renewable power generation in Mexico. (SENER 2014a)

The utility CFE operates an installed capacity of 286.6 MW of mini hydro power plants in 42 centers concentrated in 14 states. Some have been operating nearly 100 years. (CFE 2014)

2.4. Current Situation of Power Generation

In 2014 98.33% of the population in Mexico has access to electricity, the result of rural electrification programs started over 50 years ago (CFE 2015). During this period the power generation supply mix has changed to cover demand in Mexico. Combined cycles gas turbines deliver the most power today, making natural gas the main fuel for power generation.

By the end of 2013 total power generation was 258.6 TWh. From this total 53.4% was produced using natural gas. Other generation fuels and sources were heavy fuel oil (15.3%), hydroelectric (10.6%), coal (12.2%), uranium (4.2%), geothermal steam (2.3%), diesel (0.8%) and wind (0.8%). (SENER, 2014)

In terms of technology, by the end of 2014 generation with CCGT accounted for 49.2% of the total, followed by thermal

plants that burn fuel oil (18.2%), hydroelectric (10.6%), coal (8.1%), nuclear (4.6%), dual GT-thermal (4.2%), geothermal (2.3%), OCGT and internal combustion (2.1%), wind power (0.7%) and solar PV (less than 1%) (SENER 2014a).

Mexico has started making big reforms in the energy sector including the oil, gas and electricity sectors. Following a major reform of the Mexican Constitution approved on 20 December 2013, 21 secondary legislative dispositions were enacted in August 2014.

Inside this secondary laws package the new Law of Electricity Industry, the Geothermal Energy Law, and the Petroleum Law as the new Regulatory Framework were included. These legislative changes have opened the oil, gas and power sectors to private investment after decades of monopoly. Mexican Petroleums (PEMEX) and the Federal Commission of Electricity (CFE) were the state-owned monopoly utilities that became State Productive Enterprises (EPE for its acronym in Spanish) (OECD 2015).

The new legal framework liberalizes power generation and commercialization, while keeping the transmission and distribution system operator controlled by the state. Nevertheless new schemes allow the private sector to participate in finance, installation, maintenance and expansion of the grid. The package of secondary legislation includes creating the CENACE system operator, the interconnection criteria for power plants, market guidelines for the wholesale electricity market, social impact assessment guidelines and a new fiscal regime guideline for the hydrocarbon sector. (IRENA 2015)

A clean energy certificate system is also being implemented through the clean Energy Certificate Guidelines (DOF 31-10-2014). The Mexican government will determine the portfolio for the implementation of the certificates on a yearly basis three years in advance of the compliance period. The first of these periods ends in 2018, and the quota has been fixed as 5% of total energy use.

The clean energy target for Mexico by 2018% is 24.9% of total power generation. Clean energy is defined as wind, solar, geothermal, hydropower, combined heat and power, nuclear, fossil fuels with CCS and "other low carbon technologies" (SENER, 2014c). The set targets by 2018 in terms of capacity include hydropower (13 GW), wind (8.9 GW), geothermal (1 GW), bioenergy (784 MW) and solar (627 MW).

Previous to the 2014 reform, the legal frameworks for the energy sector were the Law of Electricity for the Public Service, the Law of CFE and the Law for the Development of Renewable Energy and Energy Transition Financing (LAERFTE). The main rule for the expansion of the grid was least-cost generation. The main instruments for renewable energy development were a self-supply regime and 20 years of PPA auctions.

Other legislation supports renewable energy development as well. For instance in 2012 the Congress of Mexico enacted one

of the world's most ambitious laws to mitigate climate change, implementing and enforcing the Special Program for Climate Change Mitigation in which the energy sector plays a main role.

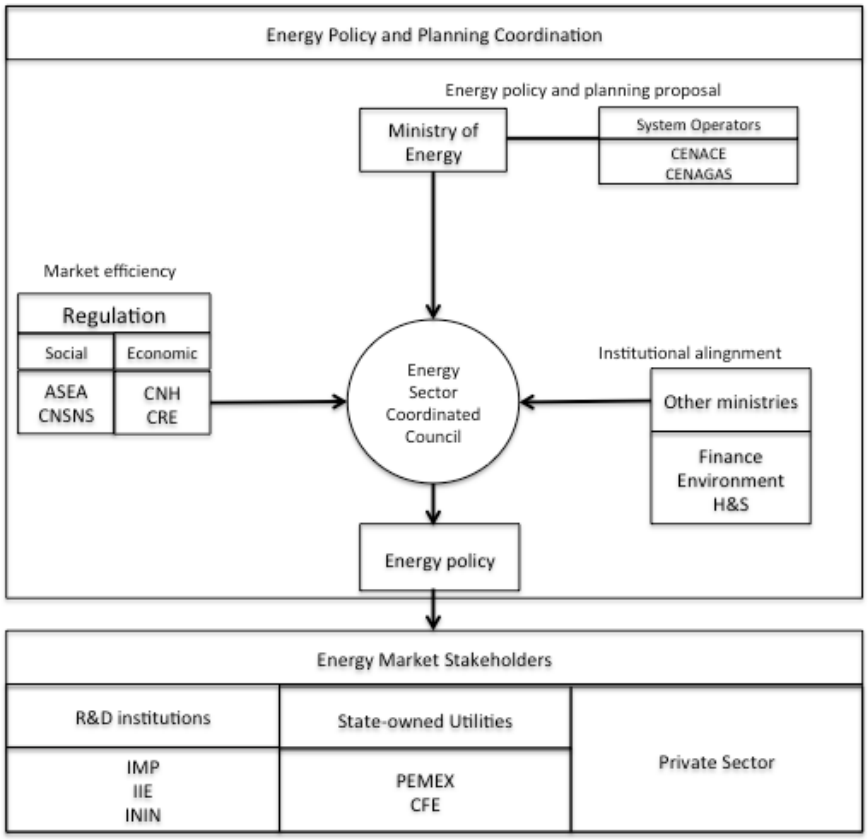
2.5. Energy Sector Structure in Mexico

The main institutions involved in the energy sector in Mexico are the Ministry of Energy (SENER), Ministry of Finance (SHCP), Energy Regulatory Commission (CRE), National Hydrocarbon Commission (CNH), National Commission for the Efficient Use of Energy (CONUEE), the Electric System Operator CENACE, the Gas System Operator CENAGAS, the Safety, Energy and Environment Agency (ASEA), the National Commission of Nuclear Safety (CNSN), the private sector and the state productive enterprises Mexican Petroleums (PEMEX) and Electricity Federal Commission (CFE).

The R&D institutions operating in the sector are the National Nuclear Research Institute (ININ), the Electricity Research

Institute (IIE) and the Mexican Petroleum Institute (IMP).

Figure 3 Institutional framework for energy planning



According to the Federal Public Administration Organic Law

Act of 1976 Amendment (13/05/2015), the Ministry of Energy is in charge of:

- Defining, conducting and coordinating the country's energy policy, watching over its compliance priorities, energy security and diversification, energy savings and environmental protection (for which it can make programs, projects, assessments and research on matters of competence).
- Carrying out mid and long term planning relating to the following criteria: energy sovereignty and security, improving energy productivity, hydrocarbons reserves restitution, fuel sources diversification, progressive reduction of environmental impacts caused by energy production and consumption, increasing renewable energies in the national energy balance, satisfying the population's basic energy needs, enhancing efficiency and energy savings in production and use, strengthening productivity in state enterprises (PEMEX and CFE), and supporting national R&D in the energy

sector.

- Establishing coordination mechanisms with the gas and power system operators (CENAGAS and CENACE), for compatibility with the sector programs.
- Fixing energy efficiency policy in the electricity industry and establishing the new power plant policies to fulfill the country's needs and efficiency policy, and establishing the mandatory requirements in clean energy power generation.

In the same law the Coordinated Energy Regulation Organs are created, separate from the Energy Ministry, with their own legal, technical and managerial identities.

The Coordinated Energy Regulation Organs Law of 11/08/2014 rules the regulation entities. These entities are the National Hydrocarbon Commission (CNH), and the Energy Regulatory Commission (CRE).

The CNH is in charge of:

i. Regulating and overseeing hydrocarbons recognition and swallow exploration, exploitation and extraction, including collection from production sites until integrated in the transport and storage system.
ii. Bidding and assigning contracts for hydrocarbons exploration and extraction;
iii. Managing the technical aspects of the assignations and contracts for the exploration and extraction of hydrocarbons, and
iv. Giving technical consultancy to the Ministry of Energy.

The CRE is in charge of promoting the efficient development of:

i. Transportation, storage, distribution, compression, liquefaction and regasification, as well as public oil expenditure on natural gas, LP gas, and other oil products;
ii. Pipeline transportation, storage, distribution and public expenditure on biofuels and
iii. Power generation and transmission and power distribution

for public services, as well as transmission and distribution which is not part of the public service and electricity commercialization.

The Energy Sector Coordination Council was created to coordinate regulation and policy alignment between the Regulation Organs, the Ministry of Energy and other ministries of the Federal Public Administration. The Council is composed of the minister of energy, the presidents of the Regulation Organs CNH and CRE, the vice ministers of the Energy Ministry and the general directors of the power and gas systems operators CENACE and CENAGAS. Other ministries and institutions from the energy sector such as CONUEE, ASEA and CNSNS, can attend if they have a previous invitation from the Ministry of Energy.

The Energy Sector Coordination Council is in charge of:

- Presenting energy policy established by SENER to the Regulation Organs;
- Issuing, when necessary, recommendations about aspects of federal energy policy and programs to be

included in the Regulation Organs' annual work programs;

- Analyzing, when necessary, recommendations and proposals made by the Regulation Organs about the federal energy policy and programs;
- Establishing the rules of operation;
- Implementing shared information and institutional cooperation systems and
- Analyzing specific cases which can affect the development of federal public policies related to energy and proposing coordination mechanisms.

It is also specified that the Energy Council will abstain from knowing any procedures or regulatory aspects of the state productive enterprises.

In comparison with the legal framework before 2014, CFE and PEMEX have undergone a fundamental change, moving from a state in which the government intervened directly in order to achieve a range of social and economic goals to a regulatory

state which seeks to control and influence through a mix of contractual arrangements, rules and regulations (Windholz 2012).

Before the new reform took place the two massive state-owned utilities were in charge of energy policy through the planning and proposal process. Then SENER was acting just as a mediator between the interests of the two giants and other stakeholders such as the Ministry of Environment and Finance.

The new planning and policy making process seems more inclusive and open to different views. Good communication between the different institutions will be critical for successful design and implementation of national energy policy, especially when different institutions plan to influence the same policy. For instance very clear directives on energy generation fuel policy should be defined.

The current landscape offers the possibility of defining a new Mexican energy sector paradigm. Whether the policy strongly

supports the development of clean technologies or continues through the less risky fossil fuel paradigm, technological development should be supported.

Decentralized R&D institutions for technological catch-up and innovation are key to defining the country's energy future. The technological aspect of energy planning does not seem to be very strong in the new institutional framework. For this reason clear mechanisms that ensure the participation of the current research institutes in the decision- making process should be designed and implemented.

Chapter 3. Theoretical Framework

3.1. Theoretical Background: Markowitz Portfolio Theory

In classic portfolio theory it is assumed that asset diversification automatically leads to risk minimization. Introduced by Harry M. Markowitz[1] in 1952 in his paper "Portfolio Theory", modern portfolio theory states that diversification is important but won't necessarily solve the problem of risk management. This approach looks deeply at the relationship between assets. Accounting for correlations or co-movements allows us to construct an efficient portfolio. Then the main problem faced by investors is a selection problem, in other words figuring out the weight percentages of assets in the portfolio

1 The foundation of portfolio theory was laid by Markowitz (1952). The basis of the theory states that by diversifying a portfolio of assets, the overall risk can be lowered compared to the risk of the individual assets. (Delarue 2011).

Based on Markowitz's theory, a portfolio is efficient if no other portfolio exists with the same variance and a higher expected return, or, on the contrary, if no other portfolio exists with the same expected return and lower variance. The efficient frontier is the set of efficient portfolios for a given problem. (Arnesano 2012)

Eventually his work in financial portfolio theory resulted in Markowitz winning the Nobel Prize for economics in 1990. Markowitz shared the prize with William F. Sharpe and Merton H. Miller. Sharpe and Merton's contribution was based on their theory of financial economics.

The application of portfolio theory to energy planning has been widely accepted and confirmed by numerous studies. (De-Llano Paz 2014).

Simon Awerbuch is one of the major scholars to apply the Markowitz Theory to the electricity mix. He applied the

methodology to the USA energy mix (Markowitz 2000), highlighting important aspects of a portfolio approach especially noting the impact of renewable sources: Renewable energies decrease risk by providing diversification to the energy matrix. Traditional engineering/economic models of valuing power generation assets, and the least-cost optimization widely used in most utilities, do not account for this effect, hence potentially under valuing renewables (Awerbuch 2003)

For financial investors, on the other hand, the idea of portfolio diversification is deeply embedded in the way they assess opportunities. This might explain why some financial investors, such as insurance companies and pension funds, have become more proactive than utilities when it comes to investing in renewable energy assets. (Wustenhagen et al. 2012)

Awerbuch and Berger (2003), evaluated the portfolio theory as an application to the development of efficient or optimal power generation portfolios for the European Union (EU-15). The

result of the study is that a portfolio of energy technologies with differing financial characteristics could be less costly over time than a portfolio constructed exclusively from fuel-based systems.

Huang and Wu (2008) applied portfolio theory in Taiwan as a case study. They minimized the "risk-weighted present value of total generation cost". Both the present value of generating cost and risk (variance of the generating cost) were considered. Risk was measured with the variance in fuel prices and uncertainty of technological change and capital cost reduction. The authors included technical constraints related to the dispatch regime and renewable energy potential. Their results introduced renewable energy participation of up to 15%. They recommended carefully evaluating nuclear policy.

Muñoz et al. (2009) made the analysis for the Spanish case by evaluating only the optimal portfolio for renewable energies. The analysis was performed from the investor's view taking the Real Return of Investment standard deviation and its mean

as the risk measure. They used a model for minimizing investment risk and maximizing the return of a portfolio of renewable energies. Their findings included that increased external financing increased the risk with negative or close to zero correlation between the technologies.

Delarue et al. (2011), presented an application of portfolio theory on the electricity generation mix, accounting for the difference between installed power capacity, generated electric energy and instantaneous power delivery. Taking into account actual load patterns, and corresponding dispatch issues such as ramping constraints, their results show that the introduction of wind power can lower the risk on generation cost, albeit to smaller levels than typically reported in the literature. This wind power deployment further requires the need for sufficiently rampable technologies, to deal with its fluctuating output.

Arnesano et al. (2012), made an extension of the Awerbuch approach detailing, in particular, the financial characteristics of

the renewable sources for their whole life cycle, and then considering the aspects connected to the realization and utilization phases (Life Cycle Assessment, LCA) for the Italian case. This allowed the authors to focus the application to a territorial extent and account for technological change. The results obtained in the analysis suggested investing more in technologies based on renewable sources. In this way, a reduction in total generation cost can be reached with the same level of risk.

Wustenhagen et al. (2012) pointed out three important portfolio aspects to be considered in the application of the Markowittz portfolio theory to energy assets. First: adding renewable power generation assets to a portfolio of conventional power generation assets may provide a diversification effect. Second, there is diversification among different renewables. The risk-return ratio of a wind park and a solar power generation facility together is likely to be more favorable than the risk of either facility on its own.

De Llano-Paz et al. (2014) evaluated the efficiency of the projected IEA.EU-27 scenarios in terms of proximity to the efficient frontier. The analysis includes a broader perspective that includes not only production costs but also externality costs (SO2, NOx and particulate matter emissions, land use, plant accidents or radioactivity). The results demonstrate how the "efficient minimum risk path" (economical and environmental) for EU-27 is essentially based on an increasing share of renewable sources in the power generation portfolio.

Gao et al. (2014), made an analysis for the energy structure in China using the MPT approach assessing different energy resources using their thermal costs and the use intensity of the power plants. The learning curve model has been applied to the prediction of price change trends in renewable energy. The results show that the expected return in portfolio will decrease with the share of renewable energy increasing.

Sunderkötter and Weber (2012) pushed forward the Markowitz application including conceptual elements of classic capacity

planning models providing easily interpretable analytical optimality conditions for efficient generation portfolios from a societal point of view. Results show that fuel mix diversification can considerably influence the total standard deviation of generation costs and fuel-mix diversification does not provide reduced risk characteristics per se. Blind diversification without consideration of technology costs and price risks as well as the correlation risks may even be counterproductive.

Ahn et al. (2015), examined scenarios that can be considered more realistic for sustainable energy planning in the Korean electricity power generation industry via: least-cost and cost-risk optimization, and combined both methodologies. Applying the least-cost optimization model, the author determined projections of the energy mix for electricity generation to meet electricity demand considering environmental externalities and the particular Korean conditions. The study extended this to cost-risk optimization and determined electricity generation mixes for 2030 that consider the risks associated with each

energy source. Results show that increasing nuclear energy generation is inevitable, as is increasing renewable generation to achieve the optimal mix in order to meet Korea's sustainability goals.

Marrero et al. (2015), applied the Markowitz theory to electricity and fuel. The authors introduce the Capital Asset Pricing Model (CAPM) framework to compute systematic and non-systematic risks. For the electricity case they found that there is a strong trade-off between average costs and total risk.

An examination of the bibliography shows that there is no single approach to defining the type of efficient frontier lines. Studies based on economic and electricity production criteria can be found. Economic studies present many return-risk frontiers, as well as cost-risk frontiers. The definition of return is equally diverse, having been defined as: the reverse of the cost of generation (kWh/cent$), the Net Present Value (NPV) for the technology of generation, the Internal Rate of Return (IRR), and as the relative measure of profitability. On the other

hand, studies based on production criteria have used the expected value of the average production as a reference (De-Llano Paz 2014).

3.2. Research Methodology

The model for this thesis is based on De-Llano Paz et al. (2014) as an optimization structure with restrictions. It is an approach to portfolio theory that incorporates an objective function for risk minimization, subject to any given level of portfolio cost. It is based on the technological costs of generation and the cost of risks (standard deviations and correlations between the several cost components).

From Delarue et al. (2011), a distinction is made between fixed and variable costs. The fixed costs are expressed in terms of [$/MW] and fixed costs are expressed in terms of installed capacity. No technology specific load factor has to be assumed, as this variable will result from the integrated model optimization.

3.3. Technology selection

The selected generation technologies are consistent with those expected by the government in 2028 in Electricity Outlook

2014-2028 published by the Ministry of Energy. These are conventional thermal (fuel oil), combined cycle gas turbine (CCGT), open cycle gas turbine (OCGT), coal power plants (coal), internal combustion (diesel) and nuclear. The renewable technologies considered are geothermal (geo), solar PV (solar), hydro and wind power (wind). In total ten technologies are analyzed.

3.4. Power generation costs

The costs of electricity production by technology are taken in the form of variable costs (dependent on production; V/MWh). The variable generation has mainly two components: fuel costs and O&M costs as shown in Equation 1.

$$VPC_t(\tfrac{\$}{MWh}) = O\&M_t + Fuel_t \qquad (1)$$

Fixed costs are transformed into variable costs per day by weighting these by the daily capacity realized, as shown in

Equation 2 where j is the period, in this case one day.

$$F_{t,j} = Capacity_{t,j} \bullet Investment_{t,j} \quad (2)$$

The total generation cost per technology (TGC_t) is obtained by adding together the two large concepts of production costs as shown in Equation 3.

$$TGC_t(\frac{\$}{MWh}) = VPC_t + Fixed_t \quad (3)$$

$$t \in T = \{Thermal, CCGT, OCGT, Coal, IntComb, Nuclear, Geo, Solar, Wind, Hydro\}$$

3.5. Technology Risk

Portfolio theory assumes that past volatility can serve as a guide for the future. Thus the risk for each technology is obtained from data on the variability of the different cost components. The risk is determined by the standard deviations and the possible relationships between the elements (correlations).

The technology risk is obtained by adding the variances for the several types of costs considered, as shown in Equation 4.

$$\sigma_t = (\sigma^2_{VPC_t} + \sigma^2_{F_t})^{\frac{1}{2}} \quad (4)$$

The risk of technology t then depends on the variances of the fuel costs, O&M and the capacity.

$$\sigma_t = (\sigma^2_{Fuel_t} + \sigma^2_{O\&M_t} + \sigma^2_{Capacity_t})^{\frac{1}{2}} \quad (5)$$

3.6. Expected portfolio risk

The portfolio risk (σ_p) takes into account individual technology risks, each consisting in turn of several cost components, and their interaction between each pair of elements as seen in Equation 6.:

$$\sigma_P = \{\sum_{t=1}^{10} x_t^2 \sigma_t^2 + \sum_{t_1=1}^{10} \sum_{t_2 \neq 1}^{10} (\Sigma \forall C_1 \Sigma \forall C_2 \sigma_{c_1 t_1} \sigma_{c_2 t_2} \rho_{c_1 t_1} \rho_{c_2 t_2}) x_{t_1} x_{t2}\}^{\frac{1}{2}} \quad (6)$$

Where X_t represents technology share t as parts per unit in the portfolio p, σ is the standard deviation of the technology t cost stream and Cti is cost component k of technology t.

This general Equation (6) can be expressed as shown in Equation (7). This is due to the zero value assumption associated with most of the possible correlations for the different technology cost components.

$$\sigma_P = \{\sum_{t=1}^{10} x_t^2(\sigma_{O\&M_t}^2 + \sigma_{Fuel_t}^2 + \sigma_{Capacity_t}^2)^{\frac{1}{2}} + \sum_{t_1=1}^{10} \sum_{t_2=1, t_1 \neq t_2}^{10} (2\sigma_{O\&M_{t1}}\sigma_{O\&M_{t2}}\rho_{O\&M_{t1}}\rho_{O\&M_{t2}}x_{t_1}x_{t2} + 2\sigma_{Fuel_{t1}}\sigma_{Fuel_{t2}}\rho_{Fuel_{t1}}\rho_{Fuel_{t2}}x_{t_1}x_{t2})\}^{\frac{1}{2}} \quad (7)$$

3.7. The model

The model is based on the minimization of the generation portfolio risk, which forces the cost to be equal to a certain value. For each of the horizons, the initial cost established for the portfolio will be that of Mexico. Its mathematical expression is shown in the following Equation 7.

$$Min\{\sigma_P\} = Min\{\sum_{t=1}^{10} x_t^2 \sigma_t^2 + \sum_{t_1=1}^{10} \sum_{t_2 \neq 1}^{10} (\Sigma \forall C_1 \Sigma \forall C_2 \sigma_{q_{t_1}} \sigma_{c_{2t_2}} \rho_{q_{t_1}} \rho_{c_{2t_2}}) x_{t_1} x_{t2}\}^{\frac{1}{2}}$$

$$= \{\sum_{t=1}^{10} x_t^2 (\sigma_{O\&M_t}^2 + \sigma_{Fuel_t}^2 + \sigma_{Capacity_t}^2)^{\frac{1}{2}}$$

(8)

Subject to:

$$E(C_p) = \sum_t X_t E(TGC_t) = \sum_t X_t E(VPC_t + F_t)$$

$$= \sum_t X_t (O\&M_t + Fuel_t + Investment_t \bullet Capacity_{t,j}) \quad (9)$$

$$= C_{PortfolioMx}$$

3.8. Constraints

The model assumes that every technology should have participation in the generation mix and no import exports are being considering. Thus the addition of the mix its constrained to the unity.

$$\sum_t X_t = 1 \quad (10)$$

$$\forall t, X_t \geq 0 \quad (11)$$

Chapter 4. Analysis and Results

4.1. Summary of the Input Data

Main data for the generation costs including variable costs (O&M and fuel) as well as daily capacity per power plant and technology[2] are taken from the power system operator, which publishes the information on a monthly basis. The data for the analysis consist of the average daily variable costs and the added realized capacity for technology[1]. These data consist of 708 daily observations of 10 variables, from 27-09-2013 to 31-07-15. This period was selected because previous to this date the participation of all the technologies selected for the analysis was not present.

The utility document Reference Costs and Parameters for Power Generation Projects 2012 is the source of investment

Available in http://app.cfe.gob.mx/Aplicaciones/OTROS/costostotales/ConsultaArchivoCostosyCapacidades.aspx

costs. All costs are annualized to U.S. Dollars (2013). The daily exchange rates are taken from the Bank of Mexico (Appendix A).

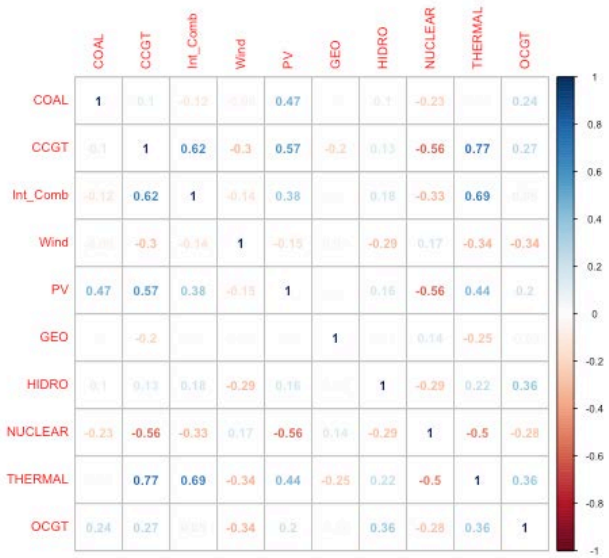
Table 2 Average generation costs (returns) and standard deviation (risk) by technology

Technology	**Tech.Risk (SD)**	**Technology Costs (Return)**
Coal	50.91	492.06
CCGT	305.21	1997.27
Int_Comb	83.51	280.92
Wind	116.02	176.71
PV	3.86	6.96
Geo	4.02	70.23
Hydro	151.34	2517.49
Nuclear	71.09	284.80
Thermal	609.99	2494.56
OCGT	815.25	1814.94

For the model the main components are the technology costs or returns. In this case the mean value of the historical data and the risk calculated as the cost standard deviation for the used data set the values presented in the Table 2. The correlation values between the technologies is shown in Figure 4. The portfolio optimizations are performed in R, using a modified version of the software Systematic Investor Toolkit, developed by Michael Kapler[3].

[3] Available in https://github.com/systematicinvestor/SIT

Figure 4 Total generation costs correlation



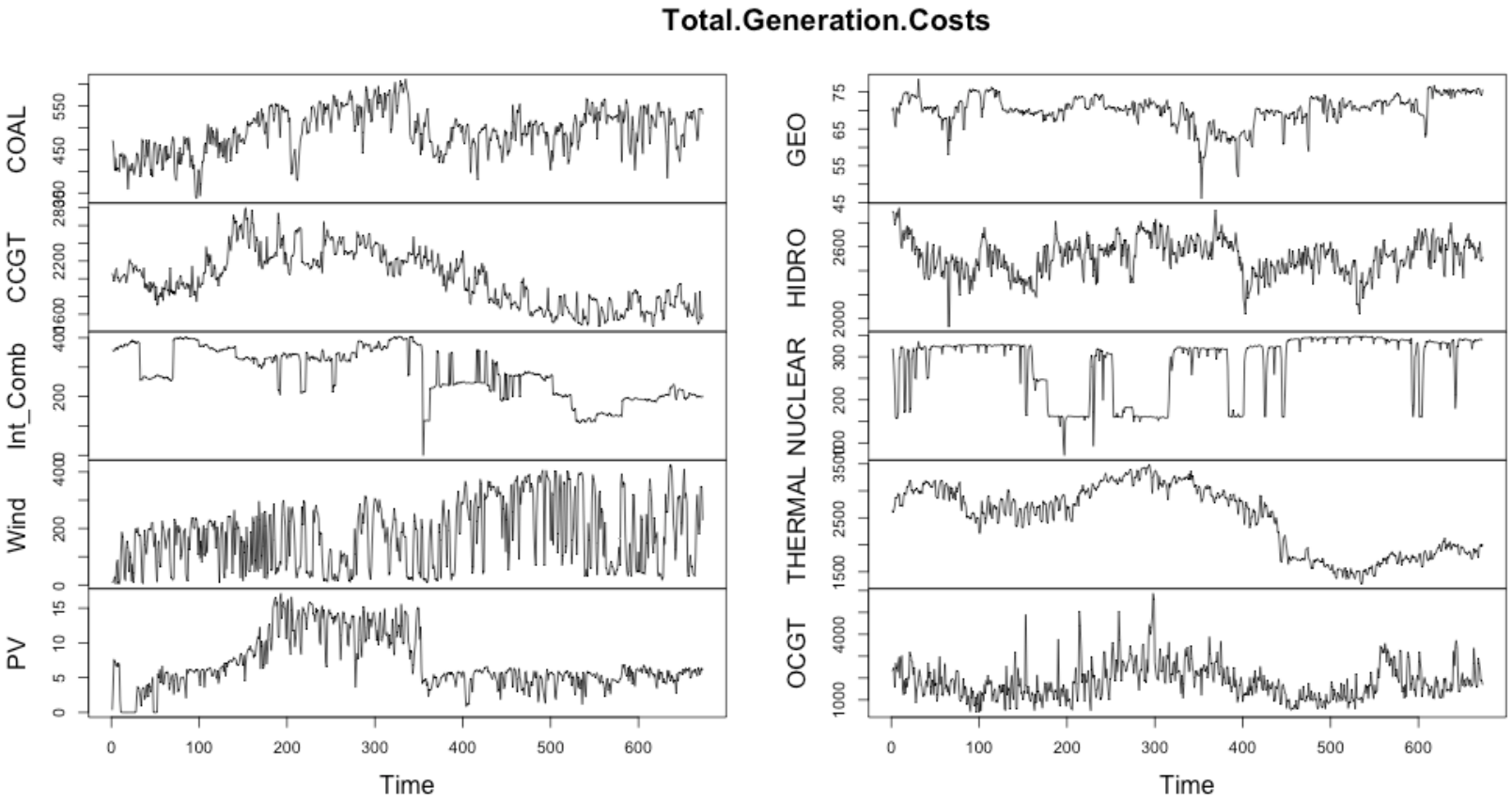


Figure 5 Total generation cost per technology

Table 3 Technology data summary									
708 obs. of 10 variables:									
Coal	**CCGT**	**Int_Comb**	**Wind**	**PV**	**Geo**	**Hydro**	**Nuclear**	**Thermal**	**OCGT**
Min. :112.7	Min. :34.73	Min. : 0.00	Min. : 0.090	Min. :0.00	Min. : 6.60	Min. :22.73	Min. : 71.13	Min. : 58.03	Min. : 9.45
1st Qu.:152.4	1st Qu.:41.78	1st Qu.: 44.22	1st Qu.: 2.105	1st Qu.:0.81	1st Qu.: 9.82	1st Qu.:28.57	1st Qu.:247.24	1st Qu.: 84.35	1st Qu.: 26.61
Median :164.7	Median :49.50	Median : 75.28	Median : 6.835	Median :1.04	Median :10.07	Median :29.80	Median :320.39	Median :123.24	Median : 36.98
Mean :163.9	Mean :48.69	Mean : 72.37	Mean : 6.606	Mean :1.54	Mean :10.02	Mean :29.70	Mean :285.58	Mean :114.62	Mean : 39.61
3rd Qu.:176.2	3rd Qu.:54.11	3rd Qu.: 91.80	3rd Qu.:10.510	3rd Qu.:2.55	3rd Qu.:10.39	3rd Qu.:30.85	3rd Qu.:333.29	3rd Qu.:137.80	3rd Qu.: 50.12
Max. :203.8	Max. :69.99	Max. :134.93	Max. :14.650	Max. :3.90	Max. :11.21	Max. :34.82	Max. :347.48	Max. :158.24	Max. :136.74

Table 4 Correlation Matrix										
	Coal	**CCGT**	**Int_Comb**	**Wind**	**PV**	**Geo**	**Hydro**	**Nuclear**	**Thermal**	**OCGT**
Coal	1.000	0.102	-0.120	-0.058	0.466	0.004	0.098	-0.228	0.028	0.243
CCGT	0.102	1.000	0.621	-0.302	0.569	-0.201	0.131	-0.562	0.769	0.267
Int_Comb	-0.120	0.621	1.000	-0.138	0.380	0.005	0.181	-0.332	0.689	0.052
Wind	-0.058	-0.302	-0.138	1.000	-0.150	0.033	-0.291	0.169	-0.337	0.343
PV	0.466	0.569	0.380	-0.150	1.000	-0.007	0.164	-0.561	0.443	0.203
Geo	0.004	-0.201	0.005	0.033	-0.007	1.000	0.021	0.138	-0.251	0.031
Hydro	0.098	0.131	0.181	-0.291	0.164	0.021	1.000	-0.288	0.221	0.363
Nuclear	-0.228	-0.562	-0.332	0.169	-0.561	0.138	-0.288	1.000	-0.501	0.278
Thermal	0.028	0.769	0.689	-0.337	0.443	-0.251	0.221	-0.501	1.000	0.365
OCGT	0.243	0.267	0.052	-0.343	0.203	-0.031	0.363	-0.278	0.365	1.000

4.2. Results

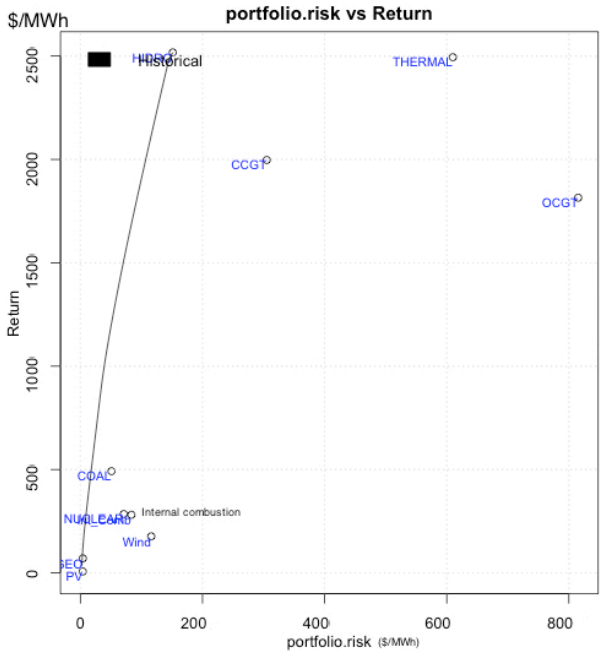
Two cases are discussed. First is the reference case where no constraints are added to the model in contrast to the second in which technological constraints are presented.

4.3.No-Constraints Optimization Scenario

The non-constrained optimization scenario ignores technology factors like fuel mix, resource availabilities and other potential constraints, intentionally over idealizing each power system to show the technological risk behavior of capacity and operating costs. On the less risky side, geothermal and solar photovoltaic are nearly risk free in terms of fuel volatility, operation costs and the consistency of the realized loads. Natural gas turbines and thermal systems based on heavy fuel oil are found on the opposite, more risky side. These technologies are used as peak load suppliers reflecting variability in generation costs mainly due to fuel prices.

Among the other technologies coal and nuclear plants are on the low risk and low cost side, mainly because of the stability of coal and uranium prices and their reliability as base load technologies. A particular behavior can be found in wind power plants, considered risk free in terms of fuel and operation costs. The risky nature of wind power comes from the variability of its realized capacity when looking at the power mix as a whole.

Figure 6 Pure Markowitz efficient frontier



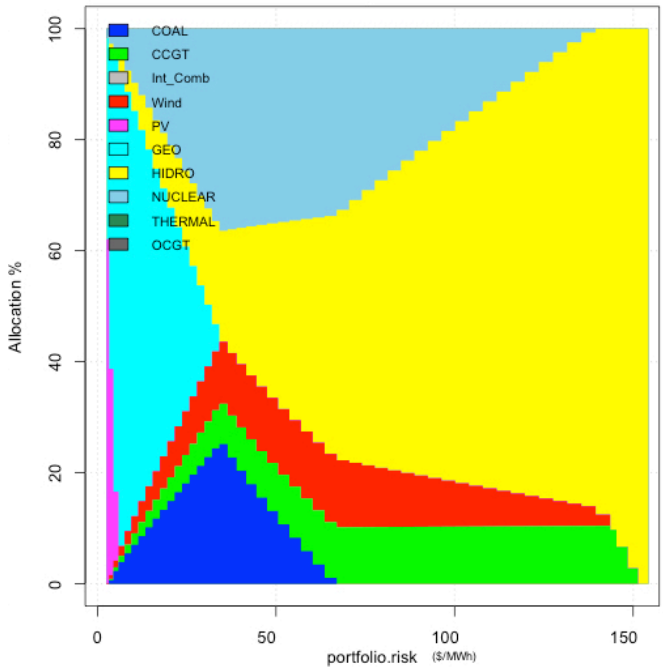
The calculated efficient frontier for power generation in the non-constrained optimization case is presented in Figure 6. Based on the covariance characteristics of generation costs for Mexico, higher risk aversion leads mainly to the increase in geothermal and nuclear energy as well as coal. The risk transition for this first case map is presented in the Figure 7 where it is clear that hydropower dominates the efficient portfolio.

This result is mainly driven by the fact that heavy investment costs are required to build up the big dams' installed capacity. But once installed, the technology, despite its dependence on meteorological conditions, is as reliable as the technologies operated with gas. Thermal and open cycle gas turbines do not appear in the efficient frontier due to their variability in capacity and high costs of operation. Although gas turbines are necessary to the power system for peak load alleviation and thermal plants are in the system due to the historical availability of fuel in Mexico, these characteristics are not reflected in this analysis. The optimization steps can be found in Appendix B.

These last analyzes shows how important geothermal, hydropower

and nuclear technologies are in cost-risk efficient scenarios, especially on the risk aversion side. Although there is great potential for geothermal energy in the country, it is still geologically and geographically constrained. Sites for new big hydropower dams are also constrained. Further developments are unlikely as environmental regulations are getting stricter. Nevertheless further development of mini hydro is possible.

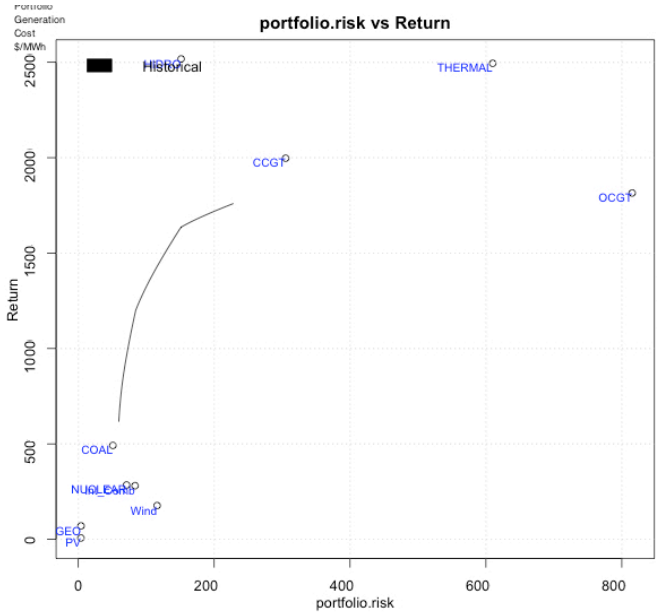
Figure 7 Pure Markowitz optimization risk transition map



4.4. Constrained Optimization Scenario

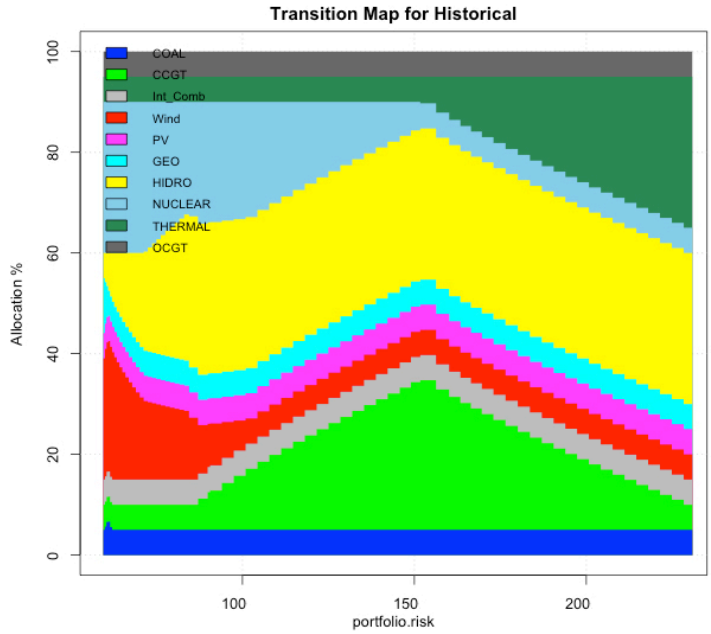
A constrained scenario is a slightly more realistic approach. The constraints assume that no technology capacity can be lower than 5% of the mix and no technology can be higher than 40% in the generation portfolio. Optimization steps can be found in Appendix C.

Figure 8 Constrained optimization efficient frontier



The estimated constrained efficient frontier is composed of more balanced portfolios. Figure 8 shows efficient generation mix portfolios, where no portfolio is composed of solely one generation technology but a mix of all of them. In this second approach hydropower is still present in all the efficient portfolios, nevertheless constraints make it more realistic. It is impossible to completely overtake hydropower at any point.

Figure 9 Constrained optimization risk transition map



The risk transition map for this constrained optimization is presented in the Figure 9. In this approach the combined cycle technology takes a more relevant place along the efficient frontier showing that constraints on the risk free assets leads to increases in mainly fossil fuel technologies. In the case of this efficient frontier the risk goes very high until the point where thermal energy is considered as an important part of the energy mix. Nevertheless it is very unlikely if not impossible that this could happen as such level of risk would not represent any benefit.

On the low risk side nuclear still represents an important asset worth exploring in the future. From the planning point of view this second optimization approach represents two paradigms. On the less risky side the portfolio is composed mostly of nuclear energy and wind power with less participation of the other technologies, while at the mid risk portfolio it is composed mainly of hydropower and combined cycle gas turbines. Taking further risk does not represent any significant advantage.

Compared with the previous analysis it is worth noting that at the level of 150$/MWh risk, the composition is mostly hydropower and combined cycle gas turbines compared with 100% hydropower in the non-constrained approach, showing a more realistic result.

Chapter 5. Conclusion and recommendations

5.1. Conclusion

This study has analyzed the effect of fuel variability and capacity in the diversification of long-term generation portfolios. By applying the Markowitz portfolio theory and system operation characteristics, an optimization problem was formulated to derive cost-risk efficient generation portfolios. Two approaches were taken for the analysis.

The non-constrained approach showed an idealized energy mix where the risk characteristics of each technology are very clear. According to the results low risk low cost portfolios are based on geothermal energy and solar photovoltaic while the risk increases along the participation of hydropower in the mix.

The constrained approach showed a more realistic and clear view of the generation mix and its relation to risk, showing contrasting

paradigms in planning. On the low risk side the energy mix relies mainly on nuclear and wind power contrasting portfolios in moderate risk where they consist of combined cycles and hydropower.

The presented application demonstrates the function of a developed model. The framework can be applied to a specific region using proper data. Big limitations on the model exist as many variables like operation and financing are not taken into account. Nevertheless it demonstrates a good approach to show explicit risk characteristics of various technologies. For this reason it could be developed as a useful tool to foster public debates on energy issues.

5.2. Recommendations

The recent deregulation of Mexico's energy sector and expected growth in energy demand over the next fifteen to twenty years present a perfect opportunity to change the way energy planning is developed.

From the new institutional framework it is recommended

technology development could be considered in energy planning, perhaps even creating an institution for this sole purpose.

Derived from the portfolio analysis, accelerating the development of geothermal energy as a source of reliable and risk free generation is recommended, as Mexico has the resources available.

Analysis showed gas-based technologies are very risky. Thus looking for alternatives to imports, or aggressively pushing R&D technologies that allow the country access to indigenous resources is recommended.

The current global energy market presents opportunities in which Liquefied Natural Gas suppliers are in short supply. Mexico's geographical position and its development stage make exploring LNG exports to the Pacific markets viable. This would represent advantages in terms of energy security and growth.

5.3. Limitation of the study

This study is limited to generation systems, thus considerations about the availability of transmission and distribution capacities as well as grid expansion costs and associated infrastructure such as roads and services are not considered. The increasing cost of renewable expansion and the best potential sites for development are also not taken into account.

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Appendix A:

Table 5 Daily fixed costs

Technology	Average USD_{2013}
Coal	0.10
CCGT	0.05
Internal Combustion	0.18
Wind	0.22
PV	0.57
Geothermal	0.11
Hydropower	0.28
Nuclear	0.24
Thermal	0.11
OCGT	0.28

Appendix B

Table 6 No constraints Optimization Results

Portfolio Weight Optimization 1										Efficient frontier	
COAL	CCGT	Int_Comb	Wind	PV	GEO	HIDRO	NUCLEAR	THERMAL	OCGT	Cost $/MWh	Risk$/MWh
0.000	0.000	0.000	0.001	0.619	0.362	0.000	0.017	0.000	0.000	35.11	2.55
0.006	0.003	0.000	0.007	0.371	0.576	0.009	0.026	0.001	0.000	85.77	3.23
0.023	0.007	0.000	0.012	0.124	0.780	0.016	0.036	0.001	0.000	136.43	4.46
0.039	0.011	0.000	0.018	0.000	0.853	0.026	0.053	0.001	0.000	187.09	5.89
0.055	0.016	0.000	0.024	0.000	0.791	0.038	0.075	0.001	0.000	237.75	7.61
0.070	0.021	0.000	0.031	0.000	0.730	0.050	0.097	0.000	0.000	288.41	9.49
0.086	0.026	0.000	0.037	0.000	0.669	0.063	0.120	0.000	0.000	339.08	11.44
0.102	0.030	0.000	0.044	0.000	0.607	0.075	0.142	0.000	0.000	389.74	13.44
0.117	0.034	0.000	0.051	0.000	0.545	0.087	0.165	0.000	0.000	440.40	15.47

Portfolio Weight Optimization 1										Efficient frontier	
0.133	0.039	0.000	0.058	0.000	0.483	0.100	0.188	0.000	0.000	491.06	17.51
0.149	0.043	0.000	0.065	0.000	0.421	0.112	0.210	0.000	0.000	541.72	19.57
0.165	0.047	0.000	0.072	0.000	0.359	0.124	0.233	0.000	0.000	592.38	21.64
0.181	0.051	0.000	0.079	0.000	0.297	0.137	0.256	0.000	0.000	643.04	23.71
0.196	0.056	0.000	0.085	0.000	0.235	0.149	0.278	0.000	0.000	693.70	25.79
0.212	0.060	0.000	0.092	0.000	0.173	0.161	0.301	0.000	0.000	744.36	27.88
0.228	0.064	0.000	0.099	0.000	0.111	0.173	0.324	0.000	0.000	795.02	29.96
0.244	0.069	0.000	0.106	0.000	0.049	0.186	0.346	0.000	0.000	845.68	32.05
0.252	0.073	0.000	0.112	0.000	0.000	0.200	0.364	0.000	0.000	896.34	34.15
0.227	0.076	0.000	0.113	0.000	0.000	0.223	0.361	0.000	0.000	947.00	36.43
0.203	0.078	0.000	0.114	0.000	0.000	0.246	0.359	0.000	0.000	997.67	38.94
0.179	0.081	0.000	0.115	0.000	0.000	0.269	0.356	0.000	0.000	1048.33	41.64
0.155	0.084	0.000	0.116	0.000	0.000	0.292	0.353	0.000	0.000	1098.99	44.49

Portfolio Weight Optimization 1										Efficient frontier	
0.131	0.087	0.000	0.117	0.000	0.000	0.314	0.351	0.000	0.000	1149.65	47.47
0.107	0.089	0.000	0.118	0.000	0.000	0.337	0.348	0.000	0.000	1200.31	50.55
0.083	0.092	0.000	0.119	0.000	0.000	0.360	0.345	0.000	0.000	1250.97	53.71
0.059	0.095	0.000	0.121	0.000	0.000	0.383	0.343	0.000	0.000	1301.63	56.95
0.035	0.098	0.000	0.122	0.000	0.000	0.406	0.340	0.000	0.000	1352.29	60.25
0.011	0.101	0.000	0.123	0.000	0.000	0.429	0.337	0.000	0.000	1402.95	63.60
0.000	0.102	0.000	0.121	0.000	0.000	0.451	0.326	0.000	0.000	1453.61	67.00
0.000	0.102	0.000	0.116	0.000	0.000	0.474	0.309	0.000	0.000	1504.27	70.47
0.000	0.102	0.000	0.111	0.000	0.000	0.496	0.291	0.000	0.000	1554.93	74.02
0.000	0.102	0.000	0.106	0.000	0.000	0.518	0.273	0.000	0.000	1605.60	77.62
0.000	0.102	0.000	0.102	0.000	0.000	0.541	0.255	0.000	0.000	1656.26	81.28
0.000	0.103	0.000	0.097	0.000	0.000	0.563	0.238	0.000	0.000	1706.92	84.98
0.000	0.103	0.000	0.092	0.000	0.000	0.585	0.220	0.000	0.000	1757.58	88.72

Portfolio Weight Optimization 1										Efficient frontier	
0.000	0.103	0.000	0.087	0.000	0.000	0.608	0.202	0.000	0.000	1808.24	92.50
0.000	0.103	0.000	0.083	0.000	0.000	0.630	0.184	0.000	0.000	1858.90	96.31
0.000	0.103	0.000	0.078	0.000	0.000	0.652	0.167	0.000	0.000	1909.56	100.14
0.000	0.103	0.000	0.073	0.000	0.000	0.675	0.149	0.000	0.000	1960.22	104.00
0.000	0.103	0.000	0.068	0.000	0.000	0.697	0.131	0.000	0.000	2010.88	107.88
0.000	0.104	0.000	0.064	0.000	0.000	0.719	0.113	0.000	0.000	2061.54	111.79
0.000	0.104	0.000	0.059	0.000	0.000	0.742	0.096	0.000	0.000	2112.20	115.70
0.000	0.104	0.000	0.054	0.000	0.000	0.764	0.078	0.000	0.000	2162.86	119.64
0.000	0.104	0.000	0.050	0.000	0.000	0.787	0.060	0.000	0.000	2213.53	123.59
0.000	0.104	0.000	0.045	0.000	0.000	0.809	0.042	0.000	0.000	2264.19	127.55
0.000	0.104	0.000	0.040	0.000	0.000	0.831	0.024	0.000	0.000	2314.85	131.52
0.000	0.104	0.000	0.035	0.000	0.000	0.854	0.007	0.000	0.000	2365.51	135.50
0.000	0.105	0.000	0.020	0.000	0.000	0.875	0.000	0.000	0.000	2416.17	139.50

Portfolio Weight Optimization 1										Efficient frontier	
0.000	0.097	0.000	0.000	0.000	0.000	0.903	0.000	0.000	0.000	2466.83	143.56
0.000	0.067	0.000	0.000	0.000	0.000	0.933	0.000	0.000	0.000	2482.83	145.33
0.000	0.028	0.000	0.000	0.000	0.000	0.972	0.000	0.000	0.000	2502.99	148.48
0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	2517.49	151.34

Appendix C

Table 7 Constrained Optimization 1 Results

Portfolio weight optmization										Efficient frontier	
COAL	CCGT	Int_Comb	Wind	PV	GEO	HIDRO	NUCLEAR	THERMAL	OCGT	P Cost (Returns)	Risk
0.05	0.05	0.05	0.24	0.05	0.11	0.05	0.30	0.05	0.05	615.86	59.57
0.06	0.05	0.05	0.25	0.05	0.08	0.06	0.30	0.05	0.05	639.20	60.01
0.07	0.05	0.05	0.26	0.05	0.06	0.07	0.30	0.05	0.05	662.55	60.47
0.07	0.05	0.05	0.26	0.05	0.05	0.08	0.30	0.05	0.05	685.90	60.96
0.06	0.05	0.05	0.26	0.05	0.05	0.09	0.30	0.05	0.05	709.24	61.50
0.05	0.05	0.05	0.25	0.05	0.05	0.10	0.30	0.05	0.05	732.59	62.08
0.05	0.05	0.05	0.24	0.05	0.05	0.11	0.30	0.05	0.05	755.93	62.73

Portfolio weight optmization										Efficient frontier	
0.05	0.05	0.05	0.23	0.05	0.05	0.12	0.30	0.05	0.05	779.28	63.45
0.05	0.05	0.05	0.22	0.05	0.05	0.13	0.30	0.05	0.05	802.63	64.23
0.05	0.05	0.05	0.21	0.05	0.05	0.14	0.30	0.05	0.05	825.97	65.07
0.05	0.05	0.05	0.20	0.05	0.05	0.15	0.30	0.05	0.05	849.32	65.97
0.05	0.05	0.05	0.19	0.05	0.05	0.16	0.30	0.05	0.05	872.66	66.93
0.05	0.05	0.05	0.18	0.05	0.05	0.17	0.30	0.05	0.05	896.01	67.94
0.05	0.05	0.05	0.17	0.05	0.05	0.18	0.30	0.05	0.05	919.36	69.01
0.05	0.05	0.05	0.16	0.05	0.05	0.19	0.30	0.05	0.05	942.70	70.12
0.05	0.05	0.05	0.16	0.05	0.05	0.20	0.30	0.05	0.05	966.05	71.29
0.05	0.05	0.05	0.15	0.05	0.05	0.21	0.29	0.05	0.05	989.39	72.48
0.05	0.05	0.05	0.15	0.05	0.05	0.22	0.28	0.05	0.05	1012.74	73.71
0.05	0.05	0.05	0.15	0.05	0.05	0.23	0.27	0.05	0.05	1036.09	74.97
0.05	0.05	0.05	0.15	0.05	0.05	0.24	0.26	0.05	0.05	1059.43	76.25

Portfolio weight optmization										Efficient frontier	
0.05	0.05	0.05	0.14	0.05	0.05	0.25	0.26	0.05	0.05	1082.78	77.56
0.05	0.05	0.05	0.14	0.05	0.05	0.26	0.25	0.05	0.05	1106.12	78.89
0.05	0.05	0.05	0.14	0.05	0.05	0.27	0.24	0.05	0.05	1129.47	80.25
0.05	0.05	0.05	0.14	0.05	0.05	0.28	0.23	0.05	0.05	1152.82	81.63
0.05	0.05	0.05	0.14	0.05	0.05	0.29	0.22	0.05	0.05	1176.16	83.03
0.05	0.05	0.05	0.12	0.05	0.05	0.30	0.23	0.05	0.05	1199.51	84.46
0.05	0.06	0.05	0.10	0.05	0.05	0.30	0.24	0.05	0.05	1222.85	87.07
0.05	0.07	0.05	0.09	0.05	0.05	0.30	0.24	0.05	0.05	1246.20	89.87
0.05	0.08	0.05	0.08	0.05	0.05	0.30	0.24	0.05	0.05	1252.06	90.59
0.05	0.09	0.05	0.07	0.05	0.05	0.30	0.24	0.05	0.05	1278.89	94.01
0.05	0.11	0.05	0.06	0.05	0.05	0.30	0.23	0.05	0.05	1304.74	97.46
0.05	0.12	0.05	0.05	0.05	0.05	0.30	0.23	0.05	0.05	1329.55	100.90
0.05	0.14	0.05	0.05	0.05	0.05	0.30	0.21	0.05	0.05	1353.53	104.35

Portfolio weight optmization										Efficient frontier	
0.05	0.15	0.05	0.05	0.05	0.05	0.30	0.20	0.05	0.05	1376.75	107.79
0.05	0.16	0.05	0.05	0.05	0.05	0.30	0.19	0.05	0.05	1399.35	111.24
0.05	0.17	0.05	0.05	0.05	0.05	0.30	0.18	0.05	0.05	1421.43	114.68
0.05	0.19	0.05	0.05	0.05	0.05	0.30	0.16	0.05	0.05	1443.06	118.13
0.05	0.20	0.05	0.05	0.05	0.05	0.30	0.15	0.05	0.05	1464.30	121.57
0.05	0.21	0.05	0.05	0.05	0.05	0.30	0.14	0.05	0.05	1485.20	125.01
0.05	0.22	0.05	0.05	0.05	0.05	0.30	0.13	0.05	0.05	1505.81	128.46
0.05	0.24	0.05	0.05	0.05	0.05	0.30	0.11	0.05	0.05	1526.16	131.90
0.05	0.25	0.05	0.05	0.05	0.05	0.30	0.10	0.05	0.05	1546.26	135.35
0.05	0.26	0.05	0.05	0.05	0.05	0.30	0.09	0.05	0.05	1566.20	138.80
0.05	0.27	0.05	0.05	0.05	0.05	0.30	0.08	0.05	0.05	1585.77	142.22
0.05	0.28	0.05	0.05	0.05	0.05	0.30	0.07	0.05	0.05	1605.79	145.74
0.05	0.29	0.05	0.05	0.05	0.05	0.30	0.06	0.05	0.05	1624.02	148.98

Portfolio weight optmization										Efficient frontier	
0.05	0.30	0.05	0.05	0.05	0.05	0.30	0.05	0.05	0.05	1636.87	151.70
0.05	0.28	0.05	0.05	0.05	0.05	0.30	0.05	0.07	0.05	1646.07	156.32
0.05	0.26	0.05	0.05	0.05	0.05	0.30	0.05	0.09	0.05	1653.31	160.12
0.05	0.25	0.05	0.05	0.05	0.05	0.30	0.05	0.10	0.05	1659.32	163.40
0.05	0.24	0.05	0.05	0.05	0.05	0.30	0.05	0.11	0.05	1664.79	166.45
0.05	0.23	0.05	0.05	0.05	0.05	0.30	0.05	0.12	0.05	1670.33	169.63
0.05	0.22	0.05	0.05	0.05	0.05	0.30	0.05	0.13	0.05	1676.11	173.01
0.05	0.21	0.05	0.05	0.05	0.05	0.30	0.05	0.14	0.05	1681.99	176.52
0.05	0.19	0.05	0.05	0.05	0.05	0.30	0.05	0.16	0.05	1687.83	180.09
0.05	0.18	0.05	0.05	0.05	0.05	0.30	0.05	0.17	0.05	1693.52	183.62
0.05	0.17	0.05	0.05	0.05	0.05	0.30	0.05	0.18	0.05	1699.01	187.08
0.05	0.16	0.05	0.05	0.05	0.05	0.30	0.05	0.19	0.05	1704.37	190.51
0.05	0.15	0.05	0.05	0.05	0.05	0.30	0.05	0.20	0.05	1709.62	193.92

Portfolio weight optmization										Efficient frontier	
0.05	0.14	0.05	0.05	0.05	0.05	0.30	0.05	0.21	0.05	1714.82	197.34
0.05	0.13	0.05	0.05	0.05	0.05	0.30	0.05	0.22	0.05	1719.99	200.77
0.05	0.12	0.05	0.05	0.05	0.05	0.30	0.05	0.23	0.05	1725.12	204.22
0.05	0.11	0.05	0.05	0.05	0.05	0.30	0.05	0.24	0.05	1730.21	207.67
0.05	0.10	0.05	0.05	0.05	0.05	0.30	0.05	0.25	0.05	1735.25	211.12
0.05	0.09	0.05	0.05	0.05	0.05	0.30	0.05	0.26	0.05	1740.24	214.56
0.05	0.08	0.05	0.05	0.05	0.05	0.30	0.05	0.27	0.05	1745.17	218.00
0.05	0.07	0.05	0.05	0.05	0.05	0.30	0.05	0.28	0.05	1750.07	221.44
0.05	0.06	0.05	0.05	0.05	0.05	0.30	0.05	0.29	0.05	1754.95	224.88
0.05	0.05	0.05	0.05	0.05	0.05	0.30	0.05	0.30	0.05	1759.81	228.34

국문 초록

에너지 계획 수립은 각종 경제적 지표에 영향을 줄 뿐 아니라 적정 가격의 에너지 상품에 대한 접근성을 보장하는 것과 관련하여, 사회 복지에 대한 기여도와 밀접한 관계에 있다.

지난 몇 십 년간 멕시코의 에너지 계획 수립에 있어서 우선 순위는 보편적 전력 공급이었고, 따라서 최소 비용을 기반으로 한 최적화 기준을 토대로 전력망의 확대를 평가하였다. 그 결과, 화석연료를 중심으로 한 발생 기술 결합과 에너지 계획 수립에서의 주 고려 대상이었다.

그럼에도 불구하고, 최근 멕시코 에너지 관리 당국, 기관 및 시장 메커니즘의 변화에 의해 에너지 계획 수립의 새로운 패러다임이 도래하게 되었다. 이러한 상황에서, 발생기술의 리스크를 최소화하는 방향으로 포트폴리오 이론을 적용하여, 에너지 계획수립에 있어 기존 방법에 대한 옵션들을 고려해 보았다. 화석연료 가격 및 투자 비용의 변동성을 고려한 전력생산 가격의 연대적 자료를 이용하여 리스크를 정량화하였으며, 전력생산 능력을 경제적 가치로 환산한 값을 토대로 분석하였다. 발생기술의 효율적인 결합을 알아내기 위한 분석을 진행하여, 에너지 보안을 강화하기 위한 최적의 믹스를

구해보았다.

분석한 바에 의하면, 화석연료의 가격 불안정성에 의한 리스크를 감소시키기 위한 핵심기술은 지열, 수력 발전인 것으로 나타났다. 풍력 발전의 경우, 달성생산 능력 관점에서 보았을 때 리스크가 상당한 것으로 나타났다. 원자력 발전 및 석탄 발전은 생산 능력 및 운영 비용에 있어서 안정한 것으로 나타났다. 열/가스 발전 기술의 경우 화석연료 가격 변동에 가장 취약한 것을 볼 수 있었다.

이를 종합하여, 본 논문의 핵심적 결과들과 함께 이것이 발생기술 선택을 위한 의사 결정 과정에 시사하는 바를 서술하였다.