MODERN PORTFOLIO THEORY APPLIED TO ELECTRICITY GENERATION PLANNING

BY

HECTOR BELTRAN

Ingeniero, National Autonomous University of Mexico, 2008

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master in Science in Electrical and Computer Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2009

Urbana, Illinois

Adviser:

Professor Thomas Overbye

ABSTRACT

To meet electricity demand, electric utilities develop growth strategies for generation, transmission, and distributions systems. For a long time those strategies have been developed by applying least-cost methodology, in which the cheapest stand-alone resources are simply added, instead of analyzing complete portfolios. As a consequence, least-cost methodology is biased in favor of fossil fuel-based technologies, completely ignoring the benefits of adding non-fossil fuel technologies to generation portfolios, especially renewable energies. For this reason, this thesis introduces modern portfolio theory (MPT) to gain a more profound insight into a generation portfolio's performance using generation cost and risk metrics. We discuss all necessary assumptions and modifications to this finance technique for its application within power systems planning, and we present a real case of analysis. Finally, the results of this thesis are summarized, pointing out the main benefits and the scope of this new tool in the context of electricity generation planning.

ACKNOWLEDGMENTS

First, I would like to thank Professor Thomas Overbye for the guidance and support he gave me to finish my graduate studies here in this university. I would also like to thank to Consejo Nacional de Ciencia y Tecnología (Conacyt) from Mexico for their generous financial support throughout the master's program.

Next, I would like to thank my family, Mom and Dad and my beloved brothers Julio and Ricardo, for their unconditional love. You were my source of strength and inspiration to accomplish this goal in my life.

This list would be incomplete without my friends; I thank them for making my life easier during this time, for giving me the support and encouragement when I needed them the most.

Last but not least, I want to dedicate this work to my little child Crío, who has come to my family bringing immense joy and happiness.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

Electric utilities face the challenge to serve electricity demand for the coming years with acceptable reliability, safety and quality through the expansion in generation, transmission and distribution systems. To fulfill this commitment, electric utilities have traditionally developed growth strategies and programs based on least-cost methodologies. This may have worked for past years when there was not high uncertainty in energy prices and technological changes were somehow very predictable. However, nowadays there is a wide range of sources of uncertainty that have to be taken into consideration, a more dynamic competitive environment and more volatile fluctuations in fuel prices, so that trying to identify the least-cost strategy has become a very difficult task [1].

Traditional power systems planning focuses on finding the least-cost generation alternative simply by adding stand-alone resources instead of analyzing complete portfolios. For this reason, least-cost methodology is biased in favor of fossil fuel-based technologies, having as an outcome the lack of diversification for generation portfolios [2]. Diversification generally means greater use of renewable energies or other non-fossil sources; particularly, the inclusion of renewable energies has been underestimated and used mainly to meet environmental constraints and to supply electric energy to isolated places where the cost of transmissions lines would be too high [3]. Moreover, it is widely believed that electric energy from renewable sources is more expensive than that coming from conventional sources (which is not completely true). In fact, adding more renewable sources to a portfolio strongly based on fossil fuels may not increase the overall generation cost. Equally important, but widely unknown, is that renewable sources could reduce the risk associated with portfolios. For this reason, we introduce modern portfolio theory (MPT) as a complementary planning tool to assess portfolio risk, which is completely ignored in least-cost methodologies, causing generation portfolios to be needlessly exposed to volatility in fuel prices.

Within this context, it makes sense to shift electricity generation planning from its current emphasis on evaluating alternative technologies to evaluate alternative electricity generation portfolios. The main objective of this thesis is to provide a new tool to assess the impact of diversification for generation portfolios. To achieve this, we have designed a framework to apply a financial technique that will allow decision makers to have a more profound insight into the addition of more renewable energies as feasible options in the generation system expansion.

The remainder of this thesis is organized as follows. Chapter 2 provides the explanation of electricity resource planning concepts and also provides a description of the least cost methodologies used for power systems in the evaluation of generation alternatives. Chapter 3 discusses the fundamentals of MPT, explaining how rational decision makers should select securities to maximize portfolio performance. It also discusses the modifications and the new set of assumptions needed to apply this financial technique to power systems and provides an example of its application to a small hypothetical power system. Chapter 4 describes a real case of analysis; the portfolio model will be applied to the Mexican power system, and a revision to the target portfolio using business-as-usual strategies will be presented, demonstrating that this portfolio is not optimal in the MPT framework. Finally, Chapter 5 summarizes the key results of this work and explains the scope of the MPT model, its limitations, and the main benefits of its application within the power system framework.

CHAPTER 2: POWER SYSTEMS PLANNING

2.1 Electricity Resource Planning

Planning for the electric power sector encompasses generation, transmission and distribution systems. The scope of this work is focused exclusively on the generation system assuming that all necessary equipment for transmission and distribution is available and there are no constraints regarding the power than can be transferred between interconnected areas.

The main goal of generation planning is to meet the electrical energy needs of the customers at “least cost” with an acceptable degree of safety, reliability and quality. To meet this goal, electricity resource planning involves the determination of the “what, where, when and how much” aspect of adding new generation capacity into the system through supply-side management (SSM) programs, which involve the construction of new power plants and repowering existing plants. In addition to SSM programs, demand-side management (DSM) programs are incorporated to manage the customer load demand to achieve least-cost system operation [4].

Generation planning deals with future decisions that have to be made in an environment of uncertainty. The key sources of such uncertainty include electricity demand, fuel prices, investment costs, unit operation, regulatory developments, legislative initiatives, etc. Such uncertainties must be explicitly considered in the development of least-cost strategies [5]. Therefore, the planning basic functions should include energy and demand forecasting, SSM and DSM adjustments, analysis of alternative expansion plans, determination of the optimal strategy or portfolio strategies and the evaluation of financial implications and feasibility.

The planning process begins with the forecast of the energy that will be demanded by the costumers. The demand for electricity initiates action by utilities to add or retire generation capacity. Because of the long time required, from the licensing and construction of the power plant to the start of operation, decisions must be made from 2 to 10 years in advance of the need for this new power plant [6]. Since these decisions involve economic analysis of the operating and investment costs, the utility planning horizon may range from 15 to 30 years into the future. Forecasts within this context are a big challenge in light of the uncertainties in national, regional and local economic growth, coupled with uncertainties in electricity usage and technology trends.

Least-cost planning involves the assessment of resource additions to the existing resource mix, and once load and energy demands are adjusted, a resource addition is specified in terms of type of resource (what), location (where), timing (when) and capacity and number of units (how much). The various resource additions are used to construct expansion strategies which have to be analyzed based on fixed costs and variable costs. These strategies are a year-by-year trajectory that is the optimal strategy or portfolio to meet the forecasted load demand; this is the so-called *resource plan* [7].

Finally, when a resource plan has been selected, it is necessary to include a financial analysis to assess the impacts on utility finances; this analysis is an important part of the planning process. Financial analysis is based on investment decisions, rate structure and tax and depreciation considerations. The result is a yearly financial statement with projected figures for the yield, earnings and taxes for the utility.

2.2 Methodologies in Power Systems Planning

Least-cost strategy can use different methods, some simpler than others, but in general we can divide these methods into three: levelized bus-bar cost, screening curve analysis and the evaluation of power system reliability [7].

2.2.1 Levelized bus-bar cost

This method is based on the calculation of levelized generation cost (LGC) in $/MWh produced by different types of power plants (e.g., coal, nuclear, combined cycle, renewable, etc.). The method involves the direct economic comparison between these options to determine the cheapest one. For example, consider two options: a nuclear power plant (Technology A) and a combined cycle with gas turbine (CCGT) power plant (Technology B). All necessary information to compute the LGC for technologies A and B is presented in Table 2.1 and Table 2.2, respectively.

Table 2.1 Data for a nuclear power plant project

Capacity	1100	[MW]
Electric efficiency	34.54	%
Capacity factor	85	%
Discount rate	12	%
Project lifetime	40	years
Construction time	5	years
Investment cost	1980	[$/kW]
Fuel cost	0.00094	[$/MJ]
O&M cost	8	[$/MWh]

Investment Schedule	
year	%
-5	3.5
-4	16.1
-3	41.7
-2	30.7
-1	8

Table 2.2 Data for a combined cycle power plant project

Capacity	1000	[MW]
Electric efficiency	53	%
Capacity factor	85	%
Discount rate	12	%
Project lifetime	30	years
Construction time	2	years
Investment cost	768	[$/kW]
Fuel cost	6.45	[$/MMBTU]
O&M cost	33169	[$/(MW-year)]

Investment schedule	
year	%
-3	9.3
-2	71.8
-1	18.9

The cost of the MWh generated is compounded by three main components: investment cost, fuel cost and operation and maintenance (O&M) cost. The determination of each component involves various aspects depending on the type of technology, investment schedule, average capacity factor of the power units, economic life, discount rate, electrical efficiency of the plant, and so on [5]. The LGC is defined as the value which, multiplied by the present value of the power plant generation in MWh, and considering its lifetime, equals the present value of all costs incurred in both construction and operation stages. From this definition we can derive the following equation:

$$\text{LGC} = \frac{\left[\sum_{t=-N}^{t=-1} I_t (1+i)^{-t}\right] + \left[\sum_{t=0}^{t=n-1} (F_t + O\&M_t)(1+i)^{-t}\right]}{\sum_{t=0}^{t=n-1} G_t (1+i)^{-t}} \tag{2.1}$$

where:

LGC = Levelized generation cost in [$/MWh]

I_t = Investment made in year t in [$]

F_t = Fuel cost for year t in [$]

$O\&M_t$ = Operation and maitenance most made in year t in [$]

G_t = Generation for year t in [MWh]

N = duration of the construction stage in [years]

n = duration of the operation stage in [years]

i = discount rate [1]

The factor $(1 + i)^{-t}$ is known as the present value factor (PVF). Therefore, nuclear power plant results are presented in Table 2.3 and Figure 2.1, whereas results for the combined cycle power plant are presented in Table 2.4 and Figure 2.2.

Table 2.3 LGC Breakdown for a nuclear power plant

Investment	49.18	**$/MWh**
O&M	8.00	**$/MWh**
Fuel	9.80	**$/MWh**
Total	66.98	**$/MWh**

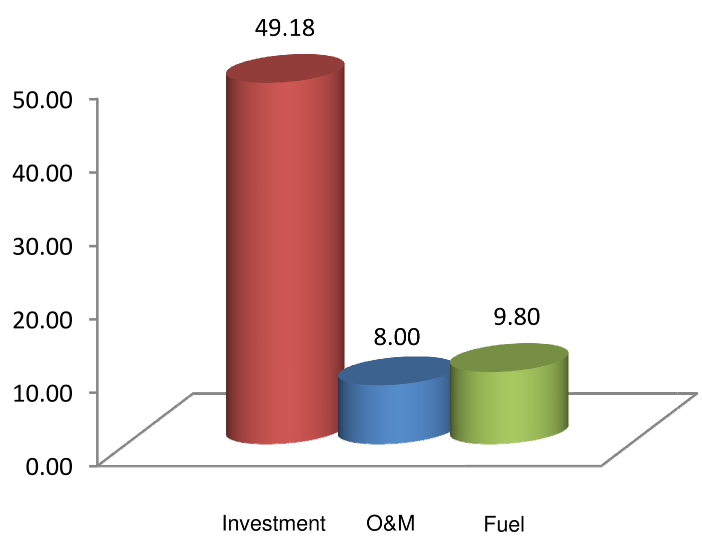

Figure 2.1 Levelized generation cost for a nuclear power plant

Table 2.4 LGC breakdown for a combined cycle power plant

Investment	16.86	**$/MWh**
O&M	4.45	**$/MWh**
Fuel	41.52	**$/MWh**
Total	62.84	**$/MWh**

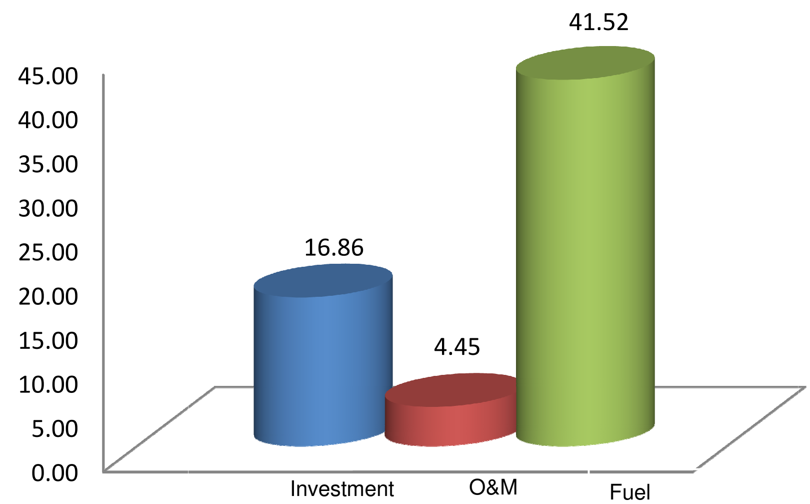

Figure 2.2 Levelized generation cost for a CCGT power plant

Based on the bus-bar cost analysis we should choose to build a CCGT power plant instead of a nuclear power plant. This method provides a general overview when comparing different technologies, and its main characteristic it is its simplicity. However, this method considers a constant capacity factor for both power plants and does not take into account the fact that different plants are dispatched in different order based on their marginal costs; as a result, they should have variable capacity factors and so other methods are needed.

2.2.2 Screening curve analysis

Screening curve analysis is very useful to obtain a first idea of an optimal mix and understand the relative economic merits of alternative generation types; it is appropriate for the identification of candidate resources [4]. The basic idea is to focus on the screening out of higher cost technologies, ignoring all sources of uncertainty and the interaction with the existing resource mix.

For example, suppose we want to determine the optimal mix of nuclear, coal and combustion turbines power plants for a hypothetical power system with a peak load of 10 000 MW. First, we have to consider the following screening curve expression:

$$C_T = c_g k_g + c_t k_t + f + (H c_f + v) t \tag{2.2}$$

where:

C_T = Total annual costs in \$/kW-year

c_g = capital cost of generation in \$/kW

c_t = capital cost of transmission in \$/kW

k_g = annual levelized carrying charge rate for generation capital in %/year

k_t = annual levelized carrying charge rate for transmission capital in %/year

f = fixed annual O&M costs in \$/kW-year

H = average heat rate in BTU/kWh

c_f = fuel costs in \$/BTU

v = variable O&M costs in \$/kWh

t = number of operating hours in h/year

Now, suppose we have available information shown in Table 2.5, then for each type of technology we can obtain the following expressions, which are plotted in Figure 2.3.

$$C_T^{nuclear} = 65.7 + 0.002\, t$$

$$C_T^{coal} = 37.4 + 0.0072\, t$$

$$C_T^{ct} = 22.4 + 0.014\, t$$

Table 2.5 Data for screening curve analysis

Technology	cg	ct	f	kg	kt	H	cf	v
Nuclear BWR	400	40	3.5	14	15.5	10 500	2E-7	1.2E-4
Coal	220	20	3.5	14	15.5	9 200	7.5E-7	2.7E-4
Combustion Turbine	120	10	0.5	14	15.5	14 000	9E-7	15E-4

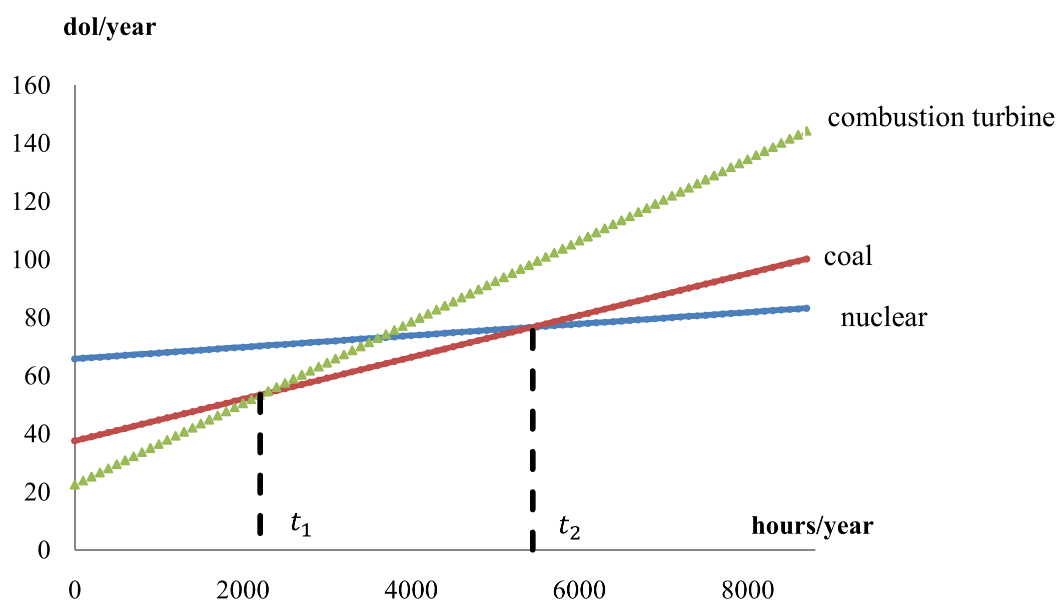

Figure 2.3 Screening curve analysis

Then, projecting the intercepts t_1 and t_2 of the screening curves onto the load duration curve in Figure 2.4, the optimal megawatt amount of each type of capacity can be evaluated. This analysis shows that nuclear power plants should represent 50% of generation capacity, coal power plants 14% of capacity, and combustion turbines 36% of capacity.

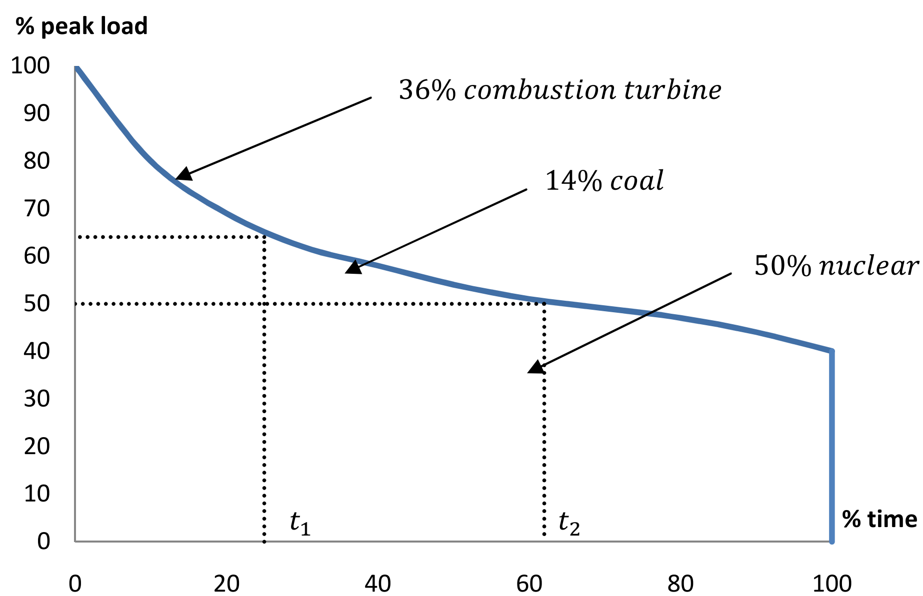

Figure 2.4 Load duration curve

While this simplified analysis is very useful in understanding the concept of an optimal mix, it neglects some very important factors. The operating characteristics of the existing plants are not taken into account, and therefore a more detailed economic analysis must consider the operating characteristics of power plants already in the system. Moreover, the capacity factors for the new plants may change in the future and the analysis conducted thus far assumes that the capacity factors will remain fixed over the lifetime of the plant. This is not an unreasonable assumption, but capacity factors of units do change through time as new and more efficient equipment is added and old equipment is retired.

2.2.3 Reliability, production costing and investment analysis

For detailed planning studies, a widely used procedure combines the concept of reliability, system production simulation and investment costing [8]. Figure 2.5 shows the optimization of generation additions from this perspective.

First, a proposed candidate set of additions is prescribed for each year. This proposed schedule of unit additions is analyzed with a power system reliability evaluation using the loss of load probability (LOLP[1]) index over the planning horizon. The reliability evaluation provides a LOLP calculation in days per year for each year within the planning period. If the LOLP is less than the desired goal (e.g., one day per year), then this proposed set of additions meets the reliability target, and the subsequent steps are then followed. If the LOLP from this proposed set of additions is not adequate or exceeds the target in any study year, then this proposed set needs to be modified to meet reliability criteria. For example, if the LOLP is inadequate in 2017, the 300 MW wind farm that would have been installed in 2018 may have to be advanced one year and installed in 2017, or the plan may need to be modified by increasing the capacity of one or several of these generation units.

[1] The loss of load probability (LOLP) is defined as the probability that the load exceeds the available capacity of the generation system.

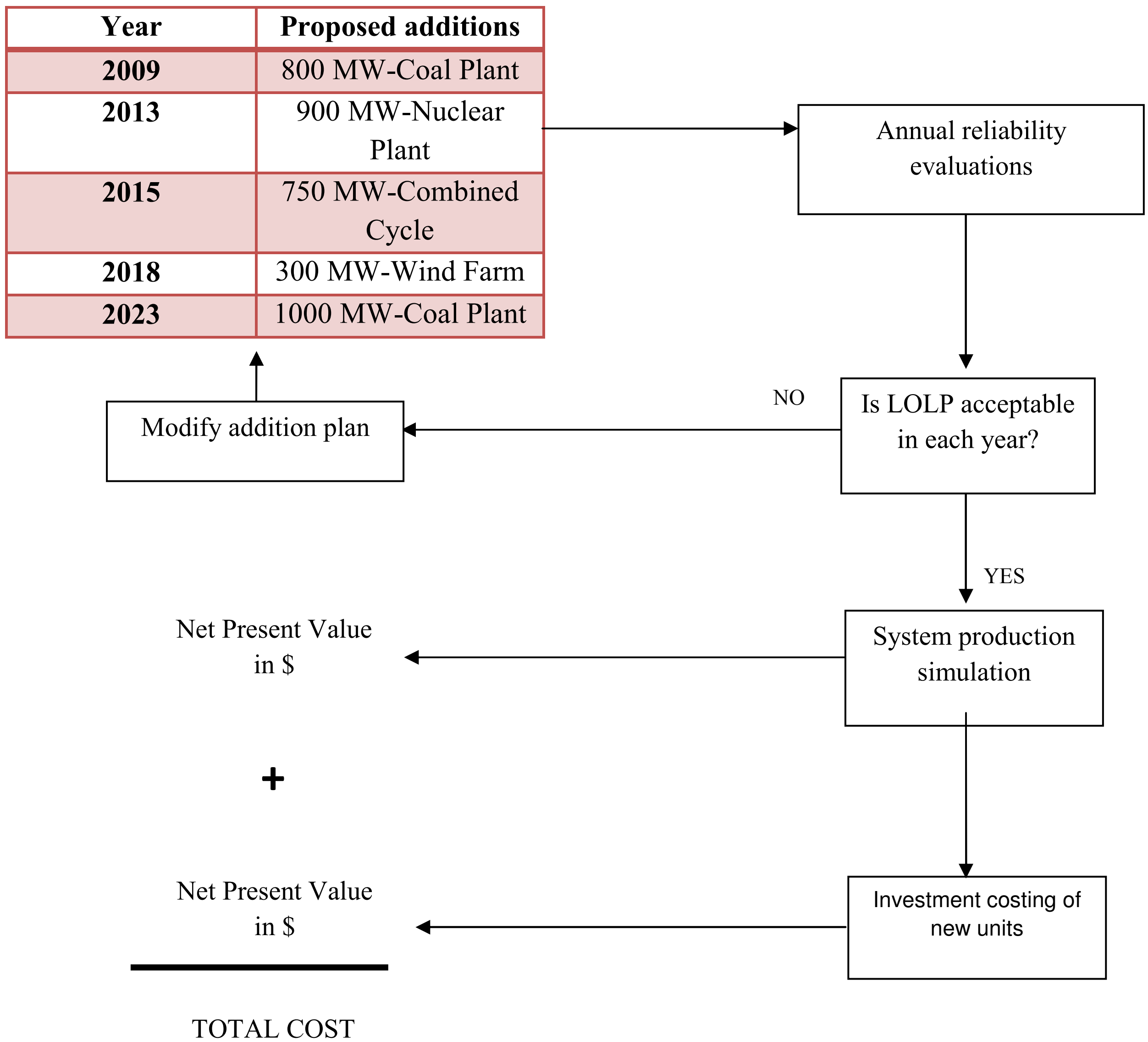

Figure 2.5 Optimization in power system planning

After the proposed addition strategy is modified in order to have an acceptable LOLP, then production simulation and investment costing procedures can be performed. A system production simulation is performed each year for the planning period. The fuel costs and operations costs are computed using the net present value methodology. The investment costs of unit additions to be installed are also computed for the same years; then the sum of these two costs, the production and investment costs, are accumulated and yield the 20 year cumulative present worth cost for the proposed addition plan.

Other plans need to be evaluated with the same methodology; alternative sets of addition may have different capacity additions, timing of power plants additions or modified sizes of the units. Whatever the source of variation, the objective is to find an alternative plan having the lowest cumulative present worth cost.

CHAPTER 3: MODERN PORTFOLIO THEORY

3.1 Introduction to Modern Portfolio Theory

Modern portfolio theory (MPT) is a widely used financial technique for investors to manage risk and maximize portfolio performance working under a variety of uncertainties and unpredictable economic outcomes. MPT was introduced by the Nobel Prize winner Harry Markowitz in 1952 in a paper titled "Portfolio Selection" published in the *Journal of Finance*. MPT proposes the idea that diversification can reduce risk within a portfolio compounded by many securities. According to MPT, a portfolio can achieve lower risk with securities considered in combination than that with securities considered individually [9].

MPT is based on the trade-off analysis between return and risk to obtain efficient portfolios. In essence, an efficient (optimal) portfolio takes no unnecessary risk relative to its expected return [10]. In other words, efficient portfolios are defined by the following properties: for any given level of risk, they maximize the expected return, or they minimize risk for any given level of expected return. The important message of MPT is that portfolios should not be selected by just considering the characteristics of individual securities; instead, portfolios have to be selected by considering how correlation between securities affects the overall risk of a proposed portfolio.

3.2 Modern Portfolio Theory Basics

Markowitz explained the process of selecting an efficient portfolio. First we have to consider a portfolio (Ω) compounded by different securities. Assuming that historical securities returns conform to a normal distribution, every security can be characterized by its expected return (μ_i) and its variance (σ_i^2) or standard deviation (σ_i) [9]. Consider a portfolio that contains *N* securities with fractional weights (ω_i), and define (σ_{ij}) as the covariance of the securities i and j. Then, the expected return of the portfolio is the weighted sum of the expected returns of the individual securities.

$$\mu_\Omega = \sum_{i=1}^{N} \omega_i \, \mu_i \qquad (3.1)$$

The variance of the portfolio is

$$\sigma_\Omega^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} \omega_i \omega_j \sigma_{ij} \qquad (3.2)$$

The correlation factor (ρ_{ij}) between securities i and j is

$$\rho_{ij} = \frac{\sigma_{ij}}{\sigma_i \sigma_j} \qquad (3.3)$$

The risk of a portfolio is defined as the standard deviation (σ_Ω) of previous relative expected returns changes, and its variance (σ_Ω^2) is always less than a simple weighted sum of the variances of the individual securities [10]. This means that the investor obtains an improved trade-off between expected return and variance of the individual securities. This implies that the investor obtains improved trade-offs between expected returns and variance if he constructs efficient portfolios. Most of the benefits of diversification are achieved when constructing a portfolio that holds a great number of securities whose expected returns are not highly correlated [11]. The problem addressed by MPT can be formulated as follows:

Assume that (μ_i) and (σ_i^2) are known or can be estimated for every security i contained in a portfolio (Ω) with $i = 1,2, \dots, N$. What are the expected return μ_Ω and variance σ_Ω^2 of a portfolio that contains a specified relative weighting ω_i of each asset? What choices of ω_i will result in an efficient portfolio? To answer these questions, we can state the next investment optimization problem:

For a given σ_Ω

$$\max \quad \mu_\Omega = \max \quad \sum_{i=1}^{N} \omega_i \, \mu_i$$

s.t.

$$\sum_{i=1}^{N} \omega_i = 1$$

$$\omega_i \geq 0 \quad \text{for } i = 1,2,\dots,N$$

For any portfolio with *N* securities, it is not possible to conclude that we can obtain just a single efficient portfolio combination. Rather, we can select a collection of portfolios by maximizing expected return for any given level of risk based on the preferences and risk aversion of decision makers. To illustrate the MPT analysis, consider a portfolio (Ω) containing two securities A and B characterized by parameters shown in Table 3.1.

Table 3.1 Expected returns and standard deviation for securities A and B

Securities	μ	σ	ρ_{AB}
A	10%	15%	-0.8
B	18%	30%	

The expected return of the portfolio is a simple weighted average of the expected returns of the individual components.

$$\mu_\Omega = \sum_{i=1}^{N} \omega_i \mu_i = \omega_1\mu_1 + \omega_2\mu_2 = \omega_1\mu_1 + (1-\omega_1)\mu_2$$

$$\mu_\Omega = 0.1\omega_1 + 0.18(1-\omega_1)$$

$$\mu_\Omega = -0.08\omega_1 + 0.18$$

The expected returns fluctuations are not perfectly correlated. As a result, the variance of the portfolio (σ_Ω^2) is not a simple weighted sum of the variances of the individual securities [10].

$$\sigma_\Omega^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} \omega_i \omega_j \sigma_{ij} \quad = \omega_1^2\sigma_1^2 + \omega_2^2\sigma_2^2 + 2\omega_1\omega_2\rho_{12}\sigma_1\sigma_2$$

$$\sigma_\Omega^2 = 0.1845\omega_1^2 - 0.252\omega_1 + 0.09$$

For given values of $\mu_1, \mu_2, \sigma_1, \sigma_2,\ \rho_{12}$, the values of μ_Ω and σ_Ω^2 will vary as functions of ω_1 and ω_2. Results are presented in Table 3.2 and Figure 3.1 plots the locus of μ_Ω and σ_Ω as ω_1 varies between 0 and 1. The end-points of the curve correspond to portfolios constructed with only one security. The interior points of the line represent alternative trade-offs between risk and expected return that are available as the result of constructing a portfolio that contains both securities.

Table 3.2 Results from MPT analysis

$\boldsymbol{\omega_1}$	$\boldsymbol{\sigma_\Omega^2}$	$\boldsymbol{\sigma_\Omega}$	$\boldsymbol{\mu_\Omega}$
0	0.09	0.3	0.18
0.1	0.067	0.258	0.172
0.2	0.047	0.217	0.164
0.3	0.031	0.176	0.156
0.4	0.019	0.137	0.148
0.5	0.010	0.101	0.14
0.6	0.005	0.072	0.132
0.7	0.004	0.063	0.124
0.8	0.006	0.080	0.116
0.9	0.013	0.112	0.108
1	0.0225	0.15	0.1

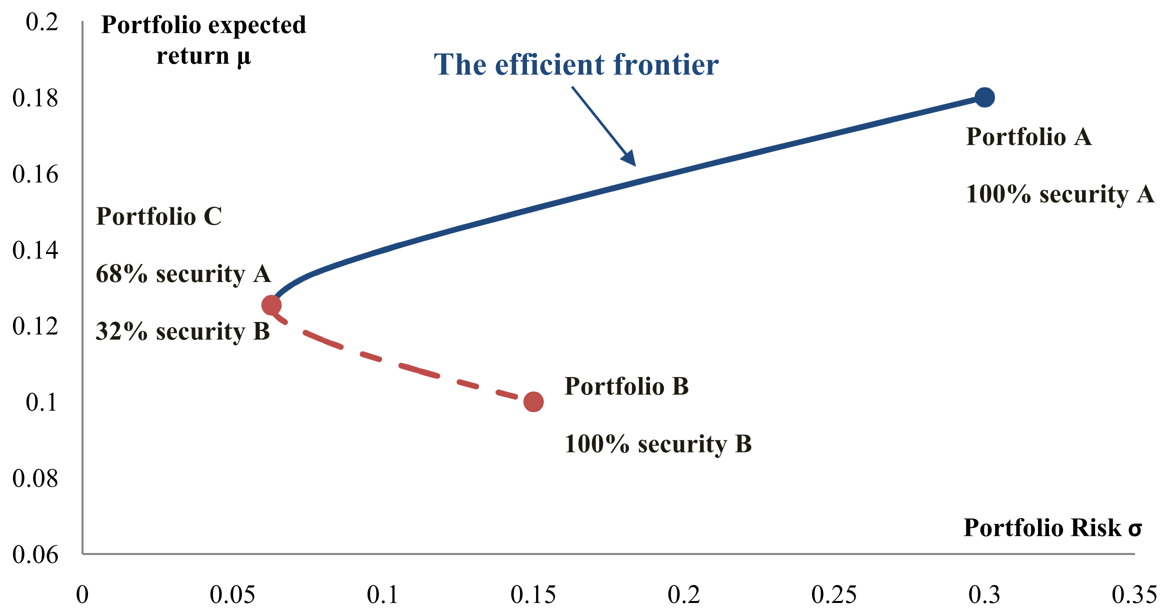

Figure 3.1 Expected return and risk for a two-securities portfolio

An investor may choose any point along the curve, but which point is optimal? The answer depends on the definition of optimal, but it must lie in the upper part of the curve between points illustrating portfolio C (minimum risk portfolio) and portfolio A. The rest of the points that lie between points C and B cannot be optimal portfolios because, for each value of risk σ_Ω along this portion of the curve, a higher expected return μ_Ω can be obtained by choosing a point between C and A. The portion of the curve between points C and A is referred as the *efficient frontier* [12].

Efficient portfolios will involve diversification whenever the expected returns of the securities are not highly correlated. Nevertheless, the diversification effect is not as significant if correlation between securities is highly positive. Figure 3.2 illustrates the trade-off between expected return and risk for different values of correlation factors. The portfolio effect strengthens as the correlation factor approaches to -1.

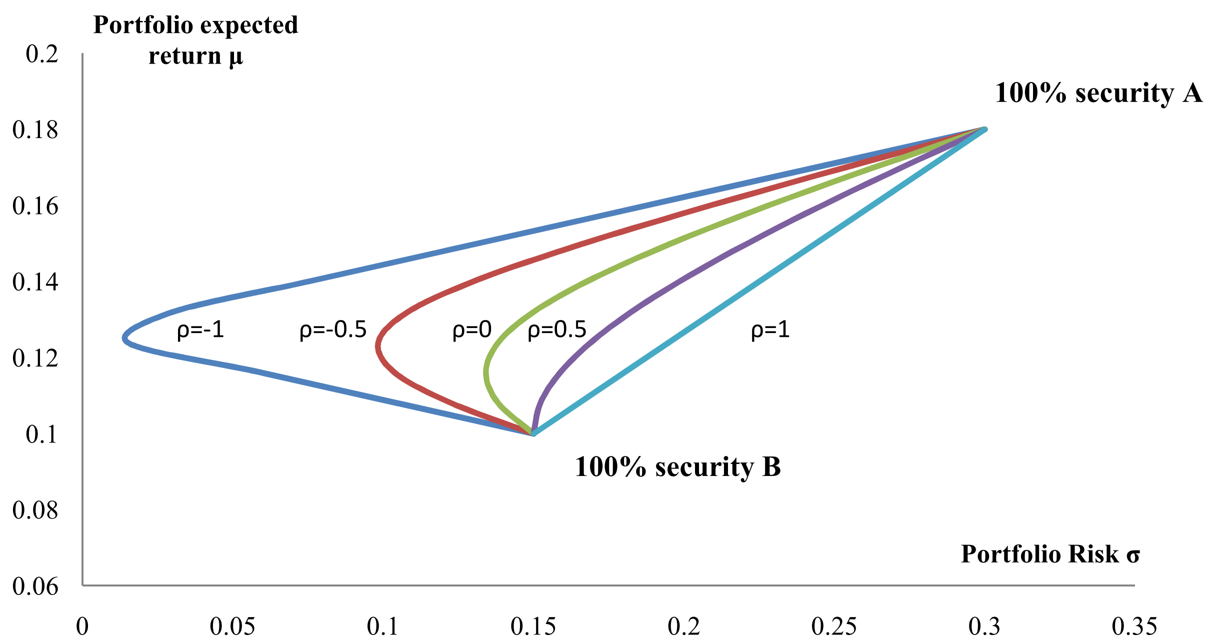

Figure 3.2 Expected return and risk for a two-securities portfolio

The example with two securities can be easily extended to *N* securities following the same procedure described previously.

3.3 MPT Framework for Power Systems Planning

The main idea is the following: Consider two technologies A and B. Suppose that technology A represents renewable generation (solar, wind, geothermal, etc.)

which has a relatively high generation cost and low risk. Now suppose that technology B represents fossil fuel generation (coal, natural gas, oil, etc.) with lower generation cost but higher risk than technology A. At this moment, and just trying to simplify the main idea, consider the correlation factor between these two technologies to be exactly equal to zero.

When applying MPT, the total risk of the portfolio decreases when the riskier technology B is added to a portfolio consisting of 100% of technology A. This is counterintuitive since technology B is riskier than technology A. In Figure 3.3 we find portfolio H (the minimum risk portfolio), illustrating the idea of MPT analysis that we can combine technologies to decrease risk, rather than just consider them individually.

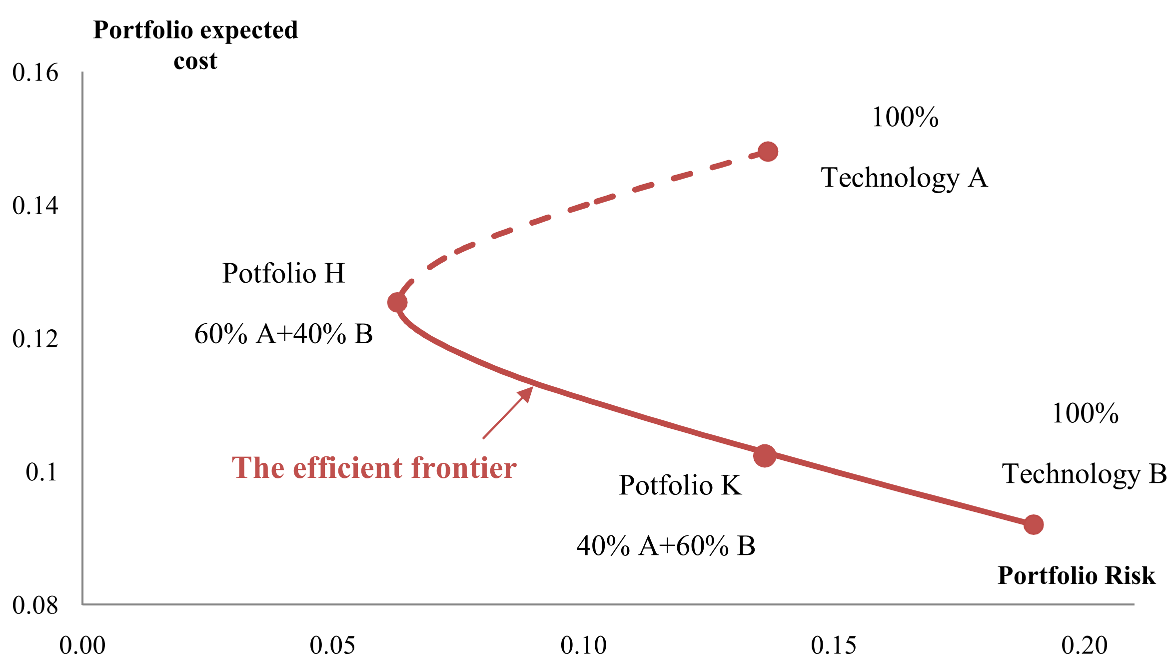

Figure 3.3 MPT analysis for generation technologies

Decision makers surely will not hold any portfolio above portfolio H because, for the same level of risk, they can obtain lower generation costs with any other portfolio lying in the lower part of the curve; in this case, the part of the curve that connects portfolio H with portfolio of 100% of technology B is the efficient frontier. On the other hand, portfolio K illustrates a combination of diversified alternatives producing efficient results because, for the same level of risk as portfolio of 100% A, it can obtain a lower generation cost. These effects cannot be considered in the least-cost methodology. The answer for an optimal planning using MPT is not a portfolio; rather, it is an efficient frontier showing where to find efficient portfolios.

In order to apply MPT to power systems planning, the following analogies have to be considered: generation technologies are securities in a portfolio, and the weighting factors represent the percentages of generated energy by different types of technologies compounding a portfolio. Instead of considering the expected return, expected generation cost [2] $E(C)$ will be considered, and technology risk (σ_i) is defined as the weighted average of individual components. In this way we define the overall expected generation cost of the portfolio (Ω) compounded by N technologies $\Omega = \{1,2,\dots,N\}$ as follows:

[2] Expected generation cost is considered the same as the expected levelized generation cost (LGC) for all technologies.

$$E(C_\Omega) = \sum_{i=1}^{N} \omega_i \, E(C_i) \tag{3.4}$$

where ω_i is the fractional weight of the energy generated by the i_{th} technology and $E(C_i)$ is its expected levelized generation cost. The variance of the portfolio (σ_Ω^2) is defined as

$$(\sigma_\Omega^2) = \sum_{i=1}^{N} \sum_{j=1}^{N} \omega_i \omega_j \rho_{ij} \, \sigma_i \sigma_j \tag{3.5}$$

where ρ_{ij} is the correlation factor between the cost of technologies i and j. At this moment is convenient to recall that generation cost of each technology is mainly integrated by three components: investment cost, fuel cost and operation and maintenance cost. Therefore, to calculate technology variance[3] (σ_i^2) we have to apply equation (3.2) obtaining the next expression:

$$\sigma_i^2 = \left(\omega_i^I \sigma_i^I + \omega_i^F \sigma_i^F + \omega_i^{O\&M} \sigma_i^{O\&M}\right)^2 \tag{3.6}$$

where:

ω_i^I = is the proportion of investment cost in the total technology cost of technology i

ω_i^F = is the proportion of fuel cost in the total technology cost of technology i

$\omega_i^{O\&M}$ = is the proportion of O&M cost in the total technology cost of technology i

σ_i^I= is the standard deviation of the historical investment costs of technology i

[3] For MPT model, technology variance σ_i^2 is calculated assuming a perfect positive correlation ($\rho = 1$) between investment, fuel and O&M costs.

σ_i^F= is the standard deviation of the historical fuel costs of technology i

$\sigma_i^{O\&M}$= is the standard deviation of the historical O&M costs of technology i

3.4 Application of MPT: An Illustration

Suppose we want to propose new generation portfolios for the next horizon up to year 2018 for some region or country. We will only consider the following power plant types: nuclear, thermal oil, combined cycle and wind.

According to [13], nuclear power plants are characterized for a high capacity factor and high investment cost; they are used as base load generation units to serve the demand. Their levelized cost is mainly compounded by the investment cost. On the other hand, combined cycle power plants are increasing their percentage generation in many countries as a consequence of their low investment costs, relatively short construction periods and high electric efficiency values; however, their levelized cost is mainly compounded by fuel cost, so it is highly volatile as a consequence of the fluctuations in the price of natural gas. Thermal oil power plants use a very well-known and mature technology, and similarly to combined cycle power plants, their levelized generation cost is mainly compounded by fuel cost. Wind power plants use a renewable source of energy; they have the great advantage of not being affected by the volatility in the fossil fuels prices, but have the disadvantage to generate energy in an intermittent way. Similarly to nuclear power plants, their levelized generation cost is mainly compounded by the investment cost [14].

It is intuitive to think of combined cycle and thermal oil power plants as riskier technologies than nuclear and wind due to large historical fluctuations in fossil fuel prices.[4] Within the MPT framework we take into account that renewable technologies are capital-intensive; however, they have a relatively fixed cost structure over time and these fixed costs have little fluctuation over time, or are uncorrelated with major risk drivers such as fossil fuels costs [15]. So when applying MPT to assess the inclusion of renewable technologies, we obtain a more profound insight into diversification than using least-cost methodologies.

To illustrate the application of MPT, we refer to our planning problem taking into account only four technologies. Assuming we are able to get or compute all the input data such as expected levelized generation costs, technology risks and the correlation matrix between the generation costs of the different technologies, we can provide an efficient frontier to decision maker so that, based on their risk aversion, an optimal portfolio can be selected.

Start with a portfolio $\Omega = \{Nuclear, Thermal\ oil, Combined\ cycle, Wind\}$. Assume we have obtained or computed the expected generation cost taking into account future fuel prices forecasting, technological trends, information provided from equipment manufacturers, etc. And from historical records we can compute the variance and

[4] Due to different generation cost compositions, fluctuations affect different technologies in different ways. For instance, a fluctuation in the fuel cost has a bigger impact in combined cycle power plants than in nuclear power plants, whereas a fluctuation in investment cost will affect nuclear power plants more than combined cycle power plants.

standard deviation for each technology in the portfolio. Parameters are presented in Table 3.3 and a correlation matrix is presented in Table 3.4.

Table 3.3 Expected generation costs and their variance

Technology	Expected generation cost ($/MWh)	Variance σ^2	Standard Deviation σ
Nuclear	81.2	0.00866	0.0931
Combined Cycle	72.3	0.0302	0.1739
Thermal Oil	87.5	0.0245	0.1567
Wind	105.97	0.0005	0.0239

Table 3.4 Correlation Matrix for expected generation cost

	Nuclear	**Thermal Oil**	**Combined Cycle**	**Wind**
Nuclear	1	-0.15	0.2	0
Thermal Oil	-0.15	1	0.8	0
Combined Cycle	0.2	0.8	1	0
Wind	0	0	0	1

With MPT analysis we can obtain the set of all possible combinations as shown in Figure 3.5 and we can observe the locus of four portfolios integrated by 100% of each technology and portfolio H, which is the minimum risk portfolio. There are many possible combinations for constructing a portfolio; however, decision makers should be interested in those portfolios located on the efficient frontier only, so the next step in the analysis is to obtain the curve representing the efficient frontier.

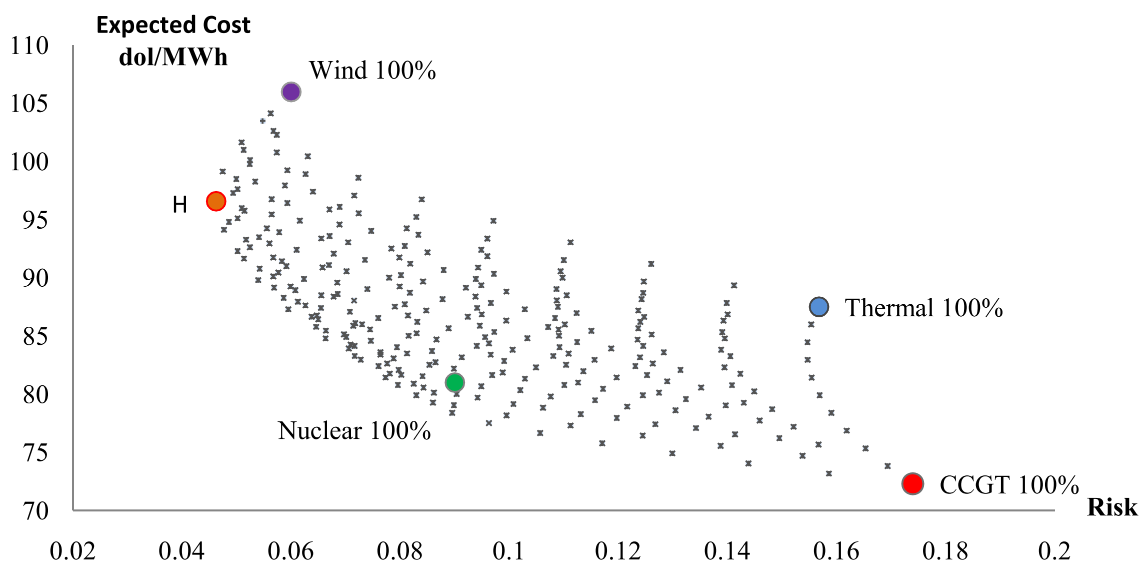

Figure 3.5 Feasible combinations for generation portfolios

The efficient frontier is, as explained before, the curve where we can find all the efficient portfolios. In the context of power systems planning, we obtain the efficient frontier by solving the next optimization problem:

For all possible σ_Ω

$$\min \quad E(C_\Omega) = \min \quad \sum_{i=1}^{N} \omega_i E(C_i)$$

s.t.

$$\sum_{i=1}^{N} \omega_i = 1$$

$$\omega_i \geq 0 \quad \text{for } i = 1,2,3,4$$

Now, instead of solving a problem to maximize expected return as in the finance context, we have to solve the optimization problem by minimizing the expected generation cost $E(C_{\Omega})$. The efficient frontier in Figure 3.6 is the curve starting from point H (minimum risk portfolio) and ends with the point Z representing a portfolio compounded exclusively by combined cycle technology. The minimum risk portfolio is compounded by 29.35% nuclear, 11.23% thermal and 59.42% of wind technology.

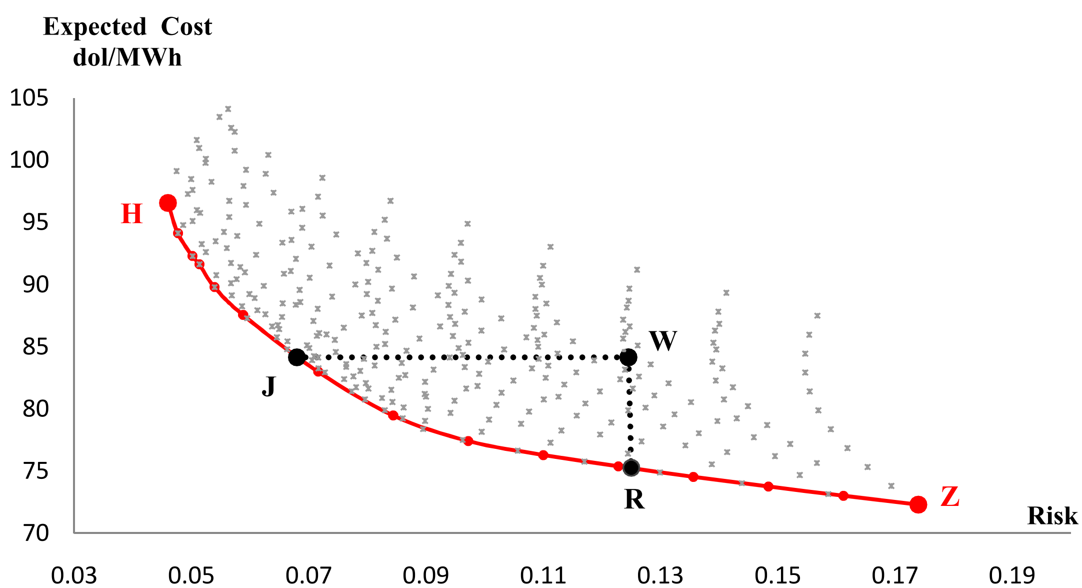

Figure 3.6 Efficient frontier for a four-technology portfolio

Suppose we select point W, which represents a portfolio strongly based on fossil fuels (10% nuclear, 40% thermal and 50% combined cycle) and excluding renewable technology, as a target for some electric utility. Then MPT analysis demonstrates that this portfolio is not efficient because for the same level of risk, a lower generation cost can be achieved by selecting a portfolio that includes more nuclear technology represented by point R (34.05% nuclear, 28.32% thermal and 37.63% combined cycle). On the other hand, point J (65.97% nuclear, 7.87% thermal, 18.35% combined cycle and 7.81% of wind technology) represents an efficient portfolio with the same expected generation cost as target portfolio W; however, portfolio J achieves lower risk by the inclusion of more nuclear and renewable technology.

It is important to notice that in order to obtain optimal portfolios we can include more renewable technologies, reducing the risk of the portfolio having the same expected cost as portfolios that depend highly on fossil fuels; this outcome could not have been pointed out with least-cost methodologies. Another important outcome is that, starting from point H and all the way over the efficient frontier up to point Z, the expected generation cost is decreasing and portfolio risk is increasing. This illustrates precisely the trade-off between cost and risk: the lower the cost the higher the risk, meaning that we cannot achieve a lower expected generation cost without taking more and more risk.

CHAPTER 4: MEXICAN CASE ANALYSIS

4.1 Current Status of the Mexican Power Sector

The electricity service in Mexico is vertically integrated and currently dominated by two state-owned enterprises: the Comisión Federal de Electricidad (CFE), which is in charge of generation, transmission and distribution nationwide, and Luz y Fuerza del Centro (LFC), which is responsible for the distribution service in Mexico City and surrounding areas. Since 1992, independent power producers (IPPs), self-generators, cogenerators, and power exporters have been allowed to participate in the electric power sector by selling the power they generate to CFE. Power may also be generated or imported by large users and transported through the public transmission grid to meet their own requirements.

Both CFE and LFC are directly involved in most of the activities in the power sector; they are in charge of organizing, administering, operating and planning the generation, transmission and distribution systems. At this time there is no competitive activity in the sector, except for build-own-operate (BOO) and build-own-transfer (BOT) projects.

At the end of the year 2007, the total installed generation capacity was 59 008 MW [16]. Together CFE, LFC and IPPs had a total installed capacity of 51 029 MW whereas power exporters, self-generators, cogenerators and own users had a generation capacity of 7 979 MW. Figure 4.1 displays the total installed generation capacity in the entire Mexican electric power sector.

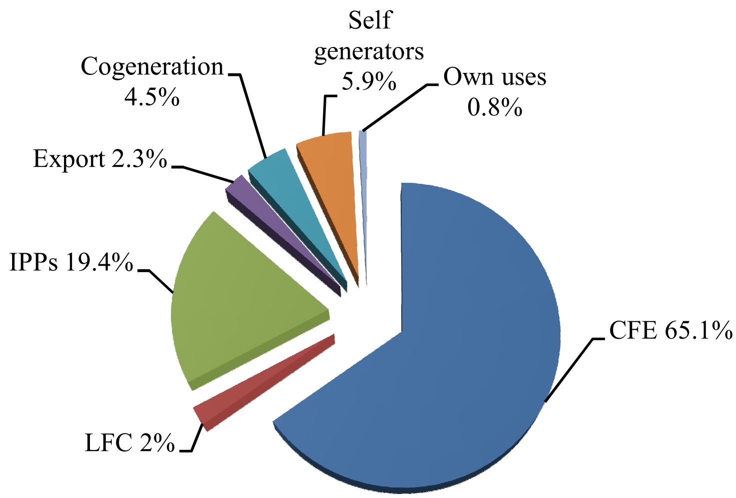

Figure 4.1 Total installed generation capacity by sector

Considering exclusively the public service (integrated by CFE, LFC and IPPs), the power generation capacity in Mexico is strongly reliant on fossil fuels such as oil, coal and natural gas. Thermal oil power plants represent 25.2% of power generation capacity, whereas combined cycle gas turbine (CCGT) power plants represent 32.7% and coal power plants 5.1%. Although exploitation of solar and biomass resources has great potential, geothermal and wind energies are the only renewable sources (excluding hydropower) with a significant contribution to the energy generation mix. Geothermal power plants represent 1.9% and wind power plants represent 0.2% of the generation capacity. Figure 4.2 shows the total installed capacity of the public service divided by type of technology.

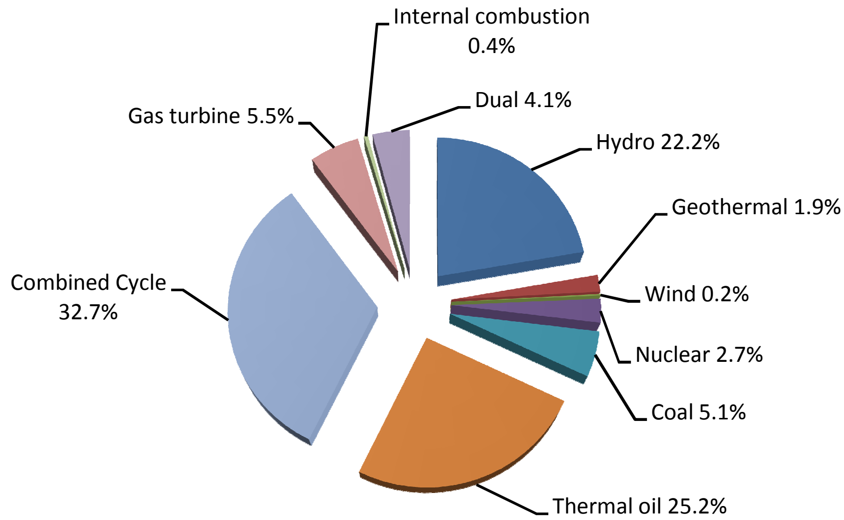

Figure 4.2 Installed generation capacity in the public sector

The expansion of the generation system will be based mainly on the construction of CCGT power plants fueled by natural gas. These plants were chosen over other technologies because of their low investment and operation and maintenance costs, for their short construction periods, as well as the environmental advantages that natural gas has over some other fossil fuels such as coal or fuel oil. According to the Electric Sector Outlook published annually for the Ministry of Energy, the expansion of the Mexican power generation system for the year 2017 will require the addition of 14 315 MW. This capacity is divided into two types. The first is called committed capacity, meaning that the project is in the construction stage or is already committed. The second is noncommitted capacity, and it consists of two classes: that in which the technology has already been decided, and that for which the technology needs to be selected (called free technology).

Table 4.1 shows how the additional capacity will be covered by the different technologies. As seen in that table, the main contribution is through CCGT power plants. However, because of the high volatility in natural gas prices or limited gas supply, other generation alternatives need to be considered. Fewer CCGT power plants would create an important opportunity to consider the viability of some other technologies such as nuclear, coal gasification, and renewable. Figures 4.3 and 4.4 display the geographical distribution of both committed and noncommitted new power plants that will be added to the generation system.[5]

Table 4.1 Additional generation capacity by technologies (MW)

Technology	Committed	Noncommitted	Total
Hydro	750	474	1224
CCGT	1436	7500	8936
GT	284	175	459
Coal	678	700	1378
CT	11	212	223
Nuclear	0	0	0
Geothermal	158	75	233
Wind	203	304	507
Thermal oil	0	0	0
Free	0	1355	1355
TOTAL	3520	10795	14315

[5] Figures 4.3 and 4.4 were taken from [16].

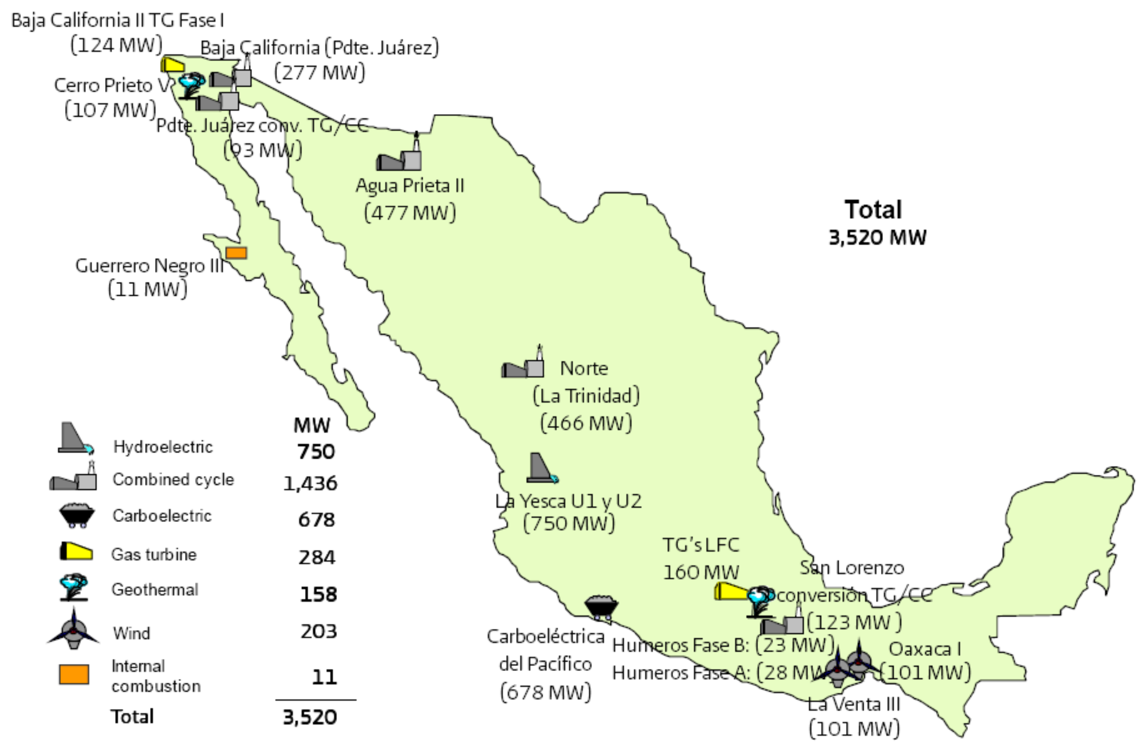

Figure 4.3 Committed generation capacity 2009-2012

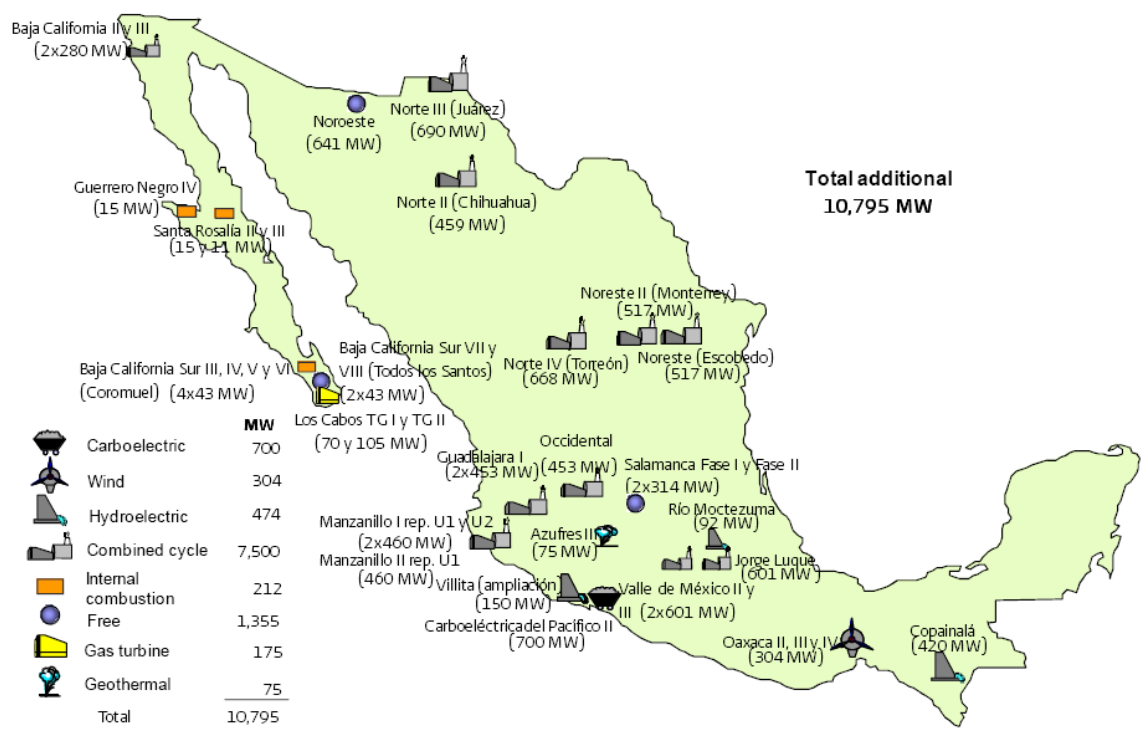

Figure 4.4 Non-committed capacity 2011-2017

4.2 Expansion Strategy for Year 2017

Planning strategy of additional capacity is obtained from technical and economical assessment of the different alternatives using the methods described in second chapter and selecting the one which achieved the least overall generation cost. Table 4.2 shows the electricity generation in 2008 and the expected generation by 2017 divided by type of technology.

Table 4.2 Actual and projected electricity generation

Power plant type	2008		2017	
	GWh	%	GWh	%
Hydro	39 880	16.8	31 863	10
CCGT	106 822	45	192 134	60.3
GT	1 662	0.7	637	0.2
Coal	26 587	11.2	42 378	13.3
CT	1 424	0.6	25 49	0.8
Nuclear	8 071	3.4	13 383	4.2
Geoth + Wind	11 869	5	10 196	3.2
Thermal Oil	41 067	17.3	25 490	8
TOTAL GENERATION	**237 382**	**100**	**318 631**	**100**

4.3 MPT Analysis for the Mexican Portfolio

We will analyze the Mexican generation system expansion within the MPT framework to identify the set of optimal portfolios that could be able to meet energy demand for the same planning horizon up to year 2017. For the purpose of pure analysis we will consider that the new 14 315 MW to be added to the actual generation system consists entirely of free technology and it is still possible to decide the type of technology that will be used. For the model we have to compute all necessary input data: expected generation costs, technology cost risks and technology cost correlation factors.

4.3.1 Technology generation costs

In Chapter 2 we introduced the concept of levelized generation cost used in bus-bar methodology for a direct economic comparison. This same concept will be used to calculate the expected generation costs for year 2017 for the nine technologies considered in this analysis. Technical and economic information as well as all assumptions made for each technology are listed in Appendix A and shown from Table A.1 to Table A.9. Results of computations for expected generation costs are shown in Table 4.3.

Table 4.3 Expected generation costs

	Expected Generation Cost ($/MWh)
Hydro	91.35
CCGT	70.04
GT	137.72
CT	117.5
Coal	76.29
Nuclear	74.48
Geothermal	80.24
Thermal oil	87.5
Wind	93.06

In order to compute technology risk values and correlation coefficients, it was necessary to obtain as much historical data as possible. The results presented in this thesis are based on the information extracted from a collection of documents titled COPAR[6] [17]-[42]. Each document is published annually by CFE with the main objective to consolidate a strong database based on reliable information for power generation projects. All the information included in such documents is based on equipment purchases by CFE, contracts for new power plant construction, specialized information from abroad, technical studies by manufacturers about new generation technologies, and forecasts about economic growth and fuel prices. All necessary information has been collected from COPAR documents since its third edition in 1983 until the most recent available version in 2008; this certainly assures the statistical robustness of the input data for the MPT model.

4.3.2 Technology cost risks

Technology cost risk is the year-to-year variability of the generation cost for a certain technology, measured as the standard deviation of historical records on a yearly basis. As described in Chapter 3, if we can characterize historical distributions of risk parameters with a normal distribution, averages and standard deviations are representative and reveal enough information for the risk assessment used in MPT framework. This thesis uses the Jarque-Bera test for normality to verify that historical records of generation costs can be fitted with a normal distribution. Results are shown in Appendix B. To estimate technology risks, we have to take into account that the cost of different technologies is

[6] COPAR is the Spanish acronym for Costs and Parameters for the Investment Projects Formulation in the Electric Power Sector.

compounded in different ways for investment, fuel and operation and maintenance costs as shown in Table 4.4.

Table 4.4 Fractional weights components of generation costs

%	Investment	Fuel	O&M	Total
Hydro	96.9	0.8[7]	2.4	100
CCGT	18.8	75.2	6.0	100
GT	3.71	58.4	4.5	100
CT	3.82	39.4	22.4	100
Coal	5.03	37.9	11.8	100
Nuclear	7.21	14.3	13.6	100
Geothermal	89.7[8]	0.0	10.3	100
Thermal oil	27.5	65.0	7.5	100
Wind	89.6	0.0	10.4	100

All the technologies considered in this study are existing technologies and so the investment risk for such plants is set to zero. We could expect that technologies based on fossil fuels are riskier than those technologies using renewable sources of energy, mainly as a consequence of the well-known high volatility of fossil fuel prices. Indeed, this expectation is confirmed by the results presented in Table 4.5 showing the technology risk values computed according Equation (3.6) where the total value of risk is a weighted average of the risk stream components.

[7] The fuel cost for a hydroelectric power plant refers to the cost of all necessary permits.

[8] Investment cost for a geothermal power plant includes all necessary investment and operation and maintenance costs of the geothermal field to extract and use the underground steam.

Table 4.5 Technology risks components

	Investment	Fuel	O&M	Total
Themal oil	0	0.250	0.668	0.212
GT	0	0.419	0.315	0.259
CCGT	0	0.376	0.376	0.306
CT	0	0.286	0.674	0.264
Coal	0	0.327	0.499	0.183
Nuclear	0	0.252	0.183	0.061
Geothermal	0	0	0.656	0.068
Hydro	0	0	0.733	0.017
Wind	0	0	0.044	0.005

4.3.3 Technology costs correlation coefficients

In probability theory and statistics, the correlation coefficient is a dimensionless measure between -1 and 1 of the strength and direction of a linear relationship between two random variables [43]. If the values of two random variables move together in the same direction, the correlation coefficient will be positive and random variables that move in opposite directions will have negative correlation coefficients, while values of random variables without observed relationship will have a correlation coefficient value equal to zero (in this case the random variables are said to be independent of each other).

For MPT analysis is intuitive to expect that generation costs of technologies based on fossil fuels like combined cycle, thermal oil and coal power plants are positively correlated because their levelized cost are mainly compounded by fuel costs and these costs usually move together in the fossil fuel international price variations. On the other hand, it is assumed that correlation factors between renewable-based technologies and fossil fuel-based technologies are zero. Then after computing all correlation factors, we obtain the 9 x 9 correlation square matrix shown in Table 4.6.

Table 4.6 Correlation factors matrix

	GT	CT	Thermal	CCGT	Coal	Nuclear	Geo	Hydro	Wind
GT	1	0.802	0.884	0.968	0.818	-0.189	0	0	0
CT	0.802	1	0.924	0.880	0.647	0.276	0	0	0
Thermal	0.884	0.924	1	0.899	0.722	0.260	0	0	0
CCGT	0.968	0.880	0.899	1	0.852	-0.245	0	0	0
Coal	0.818	0.647	0.722	0.852	1	0.143	0	0	0
Nuclear	-0.189	0.276	0.260	-0.245	0.143	1	0	0	0
Geo	0	0	0	0	0	0	1	0	0
Hydro	0	0	0	0	0	0	0	1	0
Wind	0	0	0	0	0	0	0	0	1

4.3.4 Identifying feasible portfolios

In theory, each technology could potentially replace the entire current energy mix, but in real life there exist technical and economical limitations that we have to consider in our MPT model as new constraints for our optimization problem statement. For instance, we have to consider a nonzero minimum for combustion and gas turbines because they are needed to serve peaking loads. In the case of renewable technologies their availability is limited by supplies of both natural resources and equipment, while for the remaining technologies there are neither practical nor policy restrictions on their deployment. Therefore, in this work we maintain the generation level as planned for year 2017 for combustion turbines in 0.8% and gas turbines in 0.2%. For renewable technologies we set new boundaries that will be considered as upper limits: for wind[9] the upper limit is 8.75%, for geothermal power plants it is11.38%, and for hydro power plants it is19.69% [44].

4.3.5 Optimization problem statement

For a portfolio (Ω) compounded by nine different generation technologies $\Omega = \{Thermal\ oil, CCGT, Coal, GT, CT, Nuclear, Hydro, Geothermics, Wind\}$. Compute the efficient frontier by solving the following optimization problem:

For all possible σ_Ω

$$\min \quad E(C_\Omega) = \min \quad \sum_{i=1}^{9} \omega_i E(C_i)$$

s.t.

$$\sum_{i=1}^{N} \omega_i = 1$$

$$\omega_i \geq 0 \text{ for } i = 1,2,\dots,9$$

$$\omega^{CT} = 0.008$$

$$\omega^{GT} = 0.002$$

$$\omega^{Wind} \leq 0.0875$$

$$\omega^{Geo} \leq 0.1138$$

$$\omega^{Hydro} \leq 0.1969$$

Results and graphics are obtained using an Excel workbook containing all historical records from COPAR collection, the model inputs assumed in this chapter, and an optimization routine implemented with macros and Excel's

[9] We consider wind power class 7, with average wind speed between 8.8 and 11.9 m/s at 50 m height.

internal solver to compute the minimum cost portfolio for each possible value of portfolio risk subject to the specified constraints.

4.3.6 Portfolio analysis: interpreting the efficient frontier

As previously described, MPT analysis proposes the change from a risk-return to a cost-risk efficient frontier for creating an appropriate framework for electricity generation planning. There exist an infinite number of portfolio choices and the model only focus on finding the optimal ones to construct the efficient frontier. Figure 4.5 displays the efficient frontier for power system expansion, starting with portfolio H with the minimum-risk portfolio; the model minimizes cost while moving forward and taking more risk until it reaches point Z, representing the minimum-cost optimal portfolio.

The target portfolio represents the business-as-usual strategy for generation expansion based on least-cost methodology without taking MPT analysis into account. In this case it represents the Mexican forecasted generation technologies mix for year 2017. At this point the generation system will be 60% dependent on combined cycle power plants fueled by natural gas to meet electricity requirements. Intuitively, such a high dependence on any one fuel source has a high risk level attached. Moreover, the cost of such a portfolio could be expected to increase if forecasted gas prices increase in the future. According to MPT results, the model indicates that such a target portfolio has an overall expected generation cost of 76.66 \$/MWh and a portfolio risk of 0.22.

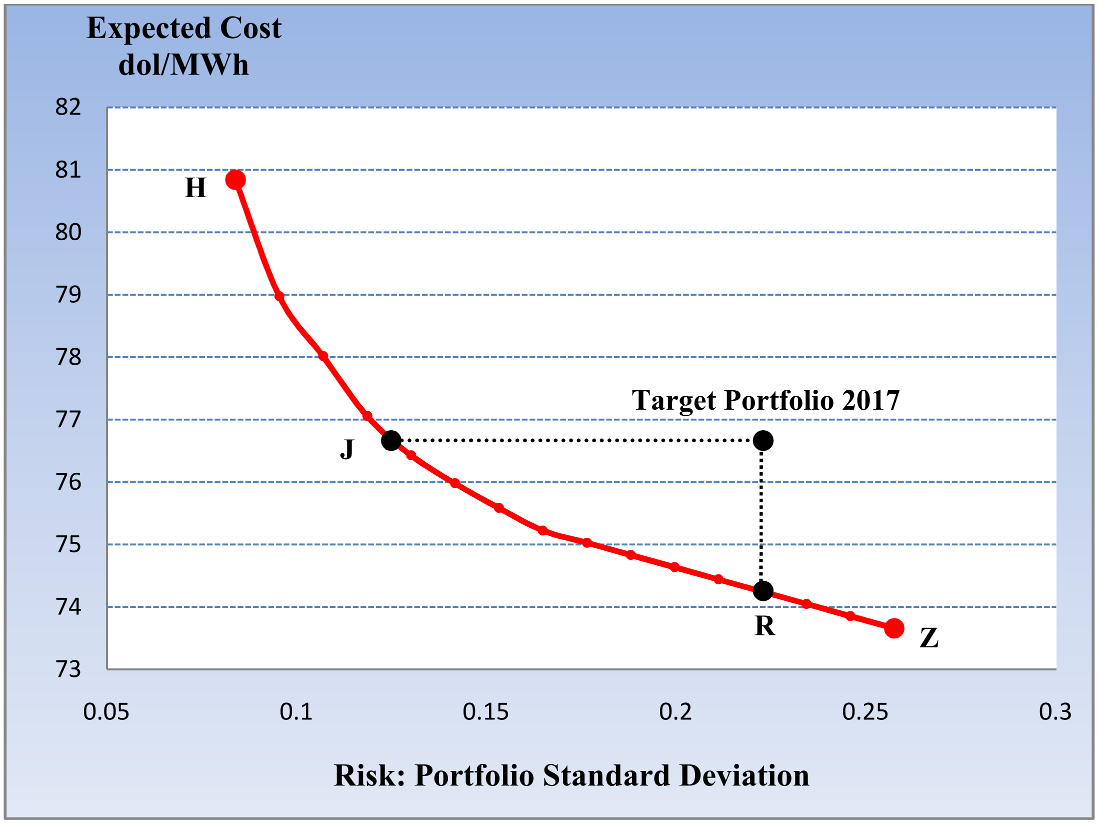

Figure 4.5 Efficient frontier for the Mexican generation system

Point H represents the portfolio with the lowest possible risk level taking into account technology data and feasible boundaries. Such a portfolio would generally consist of a diversity of fuel sources in order to mitigate the dependence on any one type of generation. In this case renewable energies like hydro, geothermal and wind would be used to generate 35.82% of the total energy, whereas nuclear power plants would generate 15.11% and coal power plants 8.34%. One interesting aspect of this portfolio is that it does not consider the inclusion of more combined cycle power plants achieving an overall expected cost of 80.84 $/MWh and a minimum level of risk of 0.0834.

Point J represents the optimal portfolio with a cost level equal to that of the target portfolio. It demonstrates the possibility to have the same cost profile as the target portfolio but achieve a lower level of risk exposure. In this case the risk factor is reduced from 0.22 to 0.124. Again, more nuclear and coal power plants as well as deeper penetration of renewable technologies can be used to meet electricity demand and displace some natural gas needs from the generation system. Indeed, the deployment of renewables such as hydro, geothermal and wind does not increase the generation cost while reducing the risk exposure. Portfolio J has a level of risk of 0.124 for the same cost as the target portfolio.

Point R represents the optimal portfolio with the same level of risk as the target portfolio. This portfolio demonstrates that the same risk profile can be achieved at a lower cost. This is achieved by the inclusion of technologies that offer the same risk profile but are more cost effective. With this portfolio we notice that in order to reduce cost we should include more nuclear power plants with a generation of 24.38% and combined cycle power plant with a generation of 43.31%. In this case we have obtained a reduction in the cost to accomplish an overall generation cost of 74.56 $/MWh.

Point Z represents the efficient portfolio with the lowest possible generation cost. This portfolio considers that the vast majority of the new capacity addition will be based on CCGT power plants; MPT analysis shows that the cost of electricity in this instance would be 73.66 $/MWh. This portfolio is integrated by combined cycle power plants with 66.32% of the total generation and has a level of risk of 0.257, which is the highest possible among the collection of efficient portfolios.

Figure 4.6 and Table 4.7 summarize the results of MPT analysis describing relevant efficient portfolios and illustrating their composition.

Table 4.7 Portfolios composition for the Mexican case

%	Portfolios				
	H	**Target**	**J**	**R**	**Z**
GT	0.2	0.2	0.2	0.2	0.2
CT	0.8	0.8	0.8	0.8	0.8
Thermal	8	8	8.4	9.06	9.78
CCGT	31.73	60.3	35.58	43.31	66.32
Coal	8.34	13.3	9.38	10.32	11.52
Nuclear	15.11	4.2	19.76	24.38	2.53
Geo	11.38	2	6.54	2.63	2.3
Hydro	15.69	10	11.5	7.95	6.13
Wind	8.75	1.2	7.84	1.35	0.7
TOTAL	100	100	100	100	100

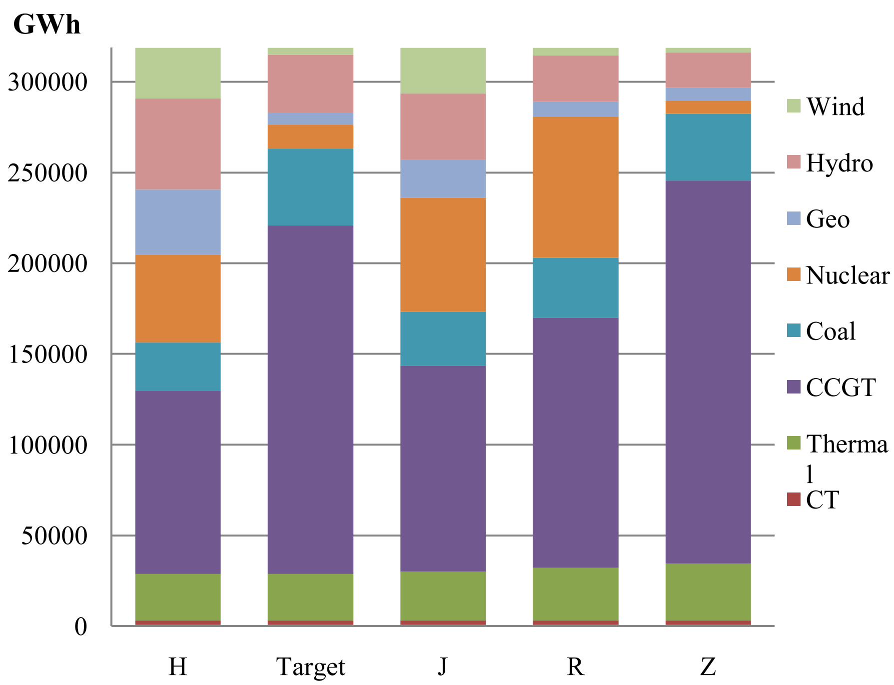

Figure 4.6 Portfolios composition for the Mexican case

CHAPTER 5: CONCLUSIONS

In view of the world's scarcity of primary fuels, there is a strong need to consider the diversification of electric generation sources. This thesis has introduced MPT framework as a new approach in the assessment of power generation system expansion strategies. The results provided by this thesis have revealed only potential expected generation cost and risk level reduction through diversification.

Mexico, like many other countries, has been growing mainly through the use of combined cycle power plants that burn natural gas. Recent gas price volatility prompts one to wonder about better options to fulfill energy requirements. For the Mexican case we can make the following points:

1) Nuclear power plants are the best option to obtain lower expected generation cost while maintaining the same risk profile as the target portfolio using business-as-usual strategies.
2) High penetration of renewable energies such as wind, geothermal and hydro can reduce significantly the level of risk without accepting higher expected generation cost compared to that of the target portfolio.
3) Target portfolio is suboptimal in the MPT framework proposed in this thesis, meaning that we could achieve lower generation cost for the same risk profile or have lower risk for the same cost profile.

4) High dependence on combined cycle power plants indeed leads to a lower generation cost; however, it also exposes generation portfolios to unnecessary risk.

Further work can be done in the Mexican case considering the inclusion of new technologies for future planning horizons such as integrated gasification combined cycle (IGCC), fluidized bed coal power plants (FBCPP), new thermal power plants working at hypercritical temperatures, power plants operating under cogeneration schemes, environmental constraints regarding CO_2 emissions, or even with new policies or legislative commitments.

It is also important to point out that, like all models, MPT is an abstraction from reality. Thus, it can be used to inform decisions, but in no way can it predict outcomes with any certainty. MPT is well suited for vertically integrated electricity markets (like the Mexican case) where there exists a main company devoted to develop the expansion strategies for the power generation system. In this case decision makers could have available more detailed information about technology trends and how they are going to impact the system; therefore, decision makers could be able to more precisely identify expected generation costs and all possible constraints to perform the optimization procedure when applying MPT. On the other hand, in liberalized electricity markets, the MPT model is harder to apply due to all the possible actions of market actors. Nevertheless, the results obtained should be useful and representative.

It has to be recognized that there exist some important aspects of power generation planning that could be improved using MPT, especially in the risk assessment of proposed portfolios. Thus, least-cost methodologies are not enough to obtain a good insight into how renewable energies have a positive portfolio effect by reducing risk.

Although there are many different theoretical approaches to measure diversification (e.g., Shannon-Weiner or Herfindahl-Hirschman indexes), MPT is a well-suited approach to assess this concept within power systems planning. The strength of MPT analysis relies on the assumptions that past events are the best available guide to the future. This is not to claim that unexpected events will not happen, only that the effect of those events is already known from past experience. The main objective of this thesis has been to provide a new tool for risk assessment in electricity resource planning; its purpose is to complement the existing methodologies and serve as starting point to set up the basis and guidelines to develop an integrated least-cost-variance methodology for power systems planning.

APPENDIX A: INPUT DATA FOR MPT ANALYSIS

Tables A.1 – A.9 provide all the necessary input data to compute the expected levelized generation cost for each technology.

Table A.1 Input data for thermal power plants

Thermal power plant				
Capacity	700	[MW]	Investment Schedule	
Electric Efficiency	37.58	%	year	%
Capacity Factor	75	%	-4	1.7
Discount rate	12	%	-3	25.5
Project Lifetime	30	years	-2	55.3
Construction Time	4	years	-1	17.5
Investment Cost	1387	[$/kW]		
Fuel Cost	0.0065	[$/MJ]		
O&M Cost	5.11	[$/MWh]		

Table A.2 Input data for gas turbine power plants

Gas Turbine power plant				
Capacity	189.6	[MW]	Investment Schedule	
Electric Efficiency	33.68	%	year	%
Capacity Factor	12.5	%	-1	100
Discount rate	12	%		
Project Lifetime	30	years		
Construction Time	1	years		
Investment Cost	602	[$/kW]		
Fuel Cost	7.68	[$/MMBTU]		
O&M Cost	9.21	[$/MWh]		

Table A.3 Input data for CCGT power plants

Combined Cycle Gas Turbine power plant				
Capacity	815.3	[MW]	Investment Schedule	
Electric Efficiency	53.11	%	year	%
Capacity Factor	80	%	-3	2.2
Discount rate	12	%	-2	79
Project Lifetime	30	years	-1	18.8
Construction Time	3	years		
Investment Cost	834	[$/kW]		
Fuel Cost	8.3	[$/MMBTU]		
O&M Cost	3.8	[$/MWh]		

Table A.4 Input data for combustion turbine power plants

Combustion Turbine power plant				
Capacity	42.2	[MW]	Investment Schedule	
Electric Efficiency	45.07	%	year	%
Capacity Factor	65	%	-3	4.3
Discount rate	12	%	-2	85.6
Project Lifetime	25	years	-1	10.1
Construction Time	3	years		
Investment Cost	1943	[$/kW]		
Fuel Cost	0.0076	[$/MJ]		
O&M Cost	30.81	[$/MWh]		

Table A.5 Input data for coal power plants

Coal power plant				
Capacity	700	[MW]	Investment Schedule	
Electric Efficiency	37.87	%	year	%
Capacity Factor	80	%	-4	11
Discount rate	12	%	-3	60.1
Project Lifetime	30	years	-2	24.3
Construction Time	4	years	-1	4.6
Investment Cost	1470	[$/kW]		
Fuel Cost	0.0056	[$/MJ]		
O&M Cost	4.57	[$/MWh]		

Table A.6 Input data for nuclear power plants

Nuclear power plant				
Capacity	1356	[MW]	Investment Schedule	
Electric Efficiency	34.54	%	year	%
Capacity Factor	85	%	-5	3.5
Discount rate	12	%	-4	16.1
Project Lifetime	40	years	-3	41.7
Construction Time	5	years	-2	30.7
Investment Cost	2700	[$/kW]	-1	8
Fuel Cost	0.00125	[$/MJ]		
O&M Cost	8.54	[$/MWh]		

Table A.7 Input data for geothermal power plants

Geothermal power plant				
Capacity	107.8	[MW]	Investment Schedule	
Electric Efficiency		%	year	%
Capacity Factor	85	%	-3	2.5
Discount rate	12	%	-2	60
Project Lifetime	30	years	-1	37.5
Construction Time	3	years		
Investment Cost	1432	[$/kW]		
Fuel Cost		[$/MJ]		
O&M Cost	4.57	[$/MWh]		

Table A.8 Input data for hydro power plants

Hydro power plant				
Capacity	1500	[MW]	Investment Schedule	
Electric Efficiency		%	year	%
Capacity Factor	42	%	-6	11.4
Discount rate	12	%	-5	18.7
Project Lifetime	50	years	-4	14.7
Construction Time	6	years	-3	21.3
Investment Cost	1987	[$/kW]	-2	24.9
Fuel Cost		[$/MJ]	-1	9
O&M Cost	8.96	[$/MWh]		

Table A.9 Input data for hydro power plants

Wind power plant				
Capacity	100.5	[MW]	Investment Schedule	
Electric Efficiency		%	year	%
Capacity Factor	75	%	-12	1.4
Discount rate	12	%	-11	3
Project Lifetime	30	years	-10	5.8
Construction Time	12	years	-9	9.8
Investment Cost	2023	[$/kW]	-8	14
Fuel Cost		[$/MJ]	-7	16.6
O&M Cost	8.93	[$/MWh]	-6	16.1
			-5	13
			-4	9.1
			-3	5.8
			-2	3.5
			-1	2.1

APPENDIX B: JARQUE-BERA NORMALITY RESULTS

In statistics, the Jarque-Bera test is a goodness-of-fit measure of departure from normality, based on the sample kurtosis and skewness. The test is named after Carlos Jarque and Anil Bera. The test statistic JB is defined as follows:

$$\mathrm{JB} = \frac{n}{6}\left(S^2 + \frac{(K-3)^2}{4}\right)$$

where n is the number of observations, S is the sample skewness and K is the sample kurtosis, defined as

$$S = \frac{\mu_3}{\sigma^3} = \frac{\mu_3}{(\sigma^2)^{\frac{3}{2}}} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{\frac{3}{2}}}$$

$$K = \frac{\mu_4}{\sigma^4} = \frac{\mu_3}{(\sigma^2)^2} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{2}}$$

where μ_3 and μ_4 are the third and fourth central moments, respectively, $\bar{x}$ is the sample mean, and σ^2 is the sample variance. The JB statistic follows a chi-squared (χ^2) distribution with two degrees of freedom. If the statistics exceed the limits given in Table B.1, the assumption that the analyzed variable can be fitted into a normal distribution must be rejected.

Table B.1 Upper limits for Jarque-Bera test

Significance level (%)	**χ^2 distribution yields**
10	4.605
5	5.991
1	9.21

Table B.2 displays the Jarque-Bera results for the generation costs for each technology considered in this thesis.

Table B.2. Jarque-Bera test results

Historical Generation Costs (1983-2008)	
Thermo	4.12
GT	2.32
CCGT	0.253
CT	3.01
Coal	1.08
Nuclear	0.876
Geothermal	3.82
Hydro	4.36
Wind	0.92

REFERENCES

[1] A.J. Covarrubias, "Expansion planning for electric power systems," *IAEA Bulletin*, vol. 21, no. 2/3, pp. 55-64, 1979.

[2] K. Costello, "Diversity of generation technologies: Implications for decision-making and public policy," *The Electricity Journal*, vol. 20, no. 5, pp. 10-21, June 2007.

[3] K. Costello, "A perspective on fuel diversity," *The Electricity Journal*, vol. 18, no. 4, pp. 28-47, May 2005.

[4] J. Joode and M.G. Boots, "Concepts of investment risks and strategies in electricity generation," Energy Research Centre of Netherlands, ECN-061, June 2005.

[5] A. De Almeida, "A least-cost planning strategy for the European Community," presented at European Council for an Energy Efficient Economy (ECEEE), Conference Proceedings, Portugal, Panel 1, 1993.

[6] R. Sedano and R. Cowart, "Power system planning and investment," New England Demand Response Initiative (NEDRI) Report, March 2003.

[7] H. Stoll, *Least-Cost Electric Utility Planning*. New York, NY: John Wiley, 1989.

[8] F. Schweppe, H. Merrill, and W. Burke, "Leas-cost planning: Issues and Methods," *Proceedings of the IEEE*, vol. 77, no. 6, pp. 899-907, June 1989.

[9] G. Bernstein, "Fundamental principles of modern portfolio theory & option pricing," presented at the General Insurance Convention, United Kingdom, June 1987.

[10] S. Awerbuch and M. Berger, "Applying portfolio theory to EU electricity planning and policy-making," International Energy Agency, report number EET/2003/03, Paris, February 2003.

[11] R. Campbell, R. Huisman, and K. Koedijk, "Optimal portfolio selection in a value-at-risk framework," *Journal of Banking & Finance*, vol. 25, pp. 1789-1804, 2001.

[12] F. Kienzle, G. Koeppel, P. Stricker and G. Anderson, "Efficient electricity production portfolios taking into account physical boundaries," presented at

the 27th USAEE/IAEE North American Conference, Houston, TX, September 17, 2007.

[13] M. Chupka and G. Basheda, "Rising utility construction costs: Sources and impacts," The Edison Foundation, Washington, DC, September 2007.

[14] R. Doherty, H. Outhred, and M. O'Malley, "Establishing the role that wind generation may have in future generation portfolios," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1415-1422, August 2006.

[15] M. Liu and F. Wu, "Risk management in a competitive electricity market," *Electrical Power & Energy Systems*, vol. 29, pp. 690-697, 2007.

[16] Dirección General de Planeación Energética, "Prospectiva del sector eléctrico 2008-2017," Secretaría de Energía, México, D.F., 2009

[17] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 3ª edición, 1983.

[18] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 4ª edición, 1984.

[19] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 5ª edición, 1985.

[20] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 6ª edición, 1986.

[21] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 7ª edición, 1987.

[22] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 8ª edición, 1988.

[23] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 9ª edición, 1989.

[24] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 10ª edición, 1990.

[25] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 11ª edición, 1991.

[26] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 12ª edición, 1992.

[27] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 13ª edición, 1993.

[28] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 14ª edición, 1994.

[29] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 15ª edición, 1995.

[30] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 16ª edición, 1996.

[31] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 17ª edición, 1997.

[32] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 18ª edición, 1998.

[33] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 19ª edición, 1999.

[34] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 20ª edición, 2000.

[35] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 21ª edición, 2001.

[36] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 22ª edición, 2002.

[37] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 23ª edición, 2003.

[38] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 24ª edición, 2004.

[39] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 25ª edición, 2005.

[40] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 26ª edición, 2006.

[41] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 27ª edición, 2007.

[42] Gerencia de Evaluación y Programación de Inversiones, "Costos y parámetros de referencia para la formulación de proyectos de inversión del sector eléctrico; Generación," Subdirección de Programación, Comisión Federal de Electricidad, México, D.F., 28ª edición, 2008.

[43] S. Ross, *A First Course in Probability*, 7th ed. Upper Saddle River, NJ: Prentice Hall, 2006.

[44] B. Ruiz, V. Rodríguez-Padilla, and J. Martínez, "Renewable energy sources in the Mexican electricity sector," *Renewable Energy Journal*, vol. 33, pp. 1346-1353, 2008.