FLEXIBILITY VALUE IN ELECTRIC TRANSMISSION EXPANSION PLANNING

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January 29, 2016

A dissertation submitted in partial fulfillment of the requirements for the degree of:
Doctor en Ingeniería Industrial
División de Ingeniería
Universidad del Norte, Área Metropolitana de Barranquilla.
2016

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To my mother, wife and children

ACKNOWLEDGMENTS

I want to express special thanks to my advisors Dr. Enzo Sauma and Dr. Angel Gonzalez, because they guided me through this research process and helped me when I had difficulties without their direction this research would not have been possible. To Professor David Pozo who provided me data about the Colombian System and cleared my doubts about optimization as well as Prof. Tomás Reyes who helped me to increase my understanding about real options during my stay in Santiago. Also, to Universidad del Norte who provided time and resources to my formation.

Thanks to my mother who planted on me the seed of perseverance and sacrifice through her example.

To my beloved wife, thanks for joining me and be my support when I wanted to give up. Also, thanks to my children because of their patience.

Abstract

Electric Transmission Expansion Planning (TEP) is a complex task exposed to multiple sources of uncertainties when the electricity market has been restructured. Approaches like those based on scenarios and robustness have been proposed and used by planners[1] to deal with uncertainties. Alternatives of solution for expansion are identified and economically evaluated by planners through methodologies based on Discounted Cash Flow (DCF). In general, these approaches have the risk to produce undersized or oversized designs of transmission lines because of uncertainties in demand growth rates and economies of scale. In addition, DCF helps to make a decision only with the information available today and it does not consider managerial flexibility (i.e. manager's ability to adjust its initial decision when uncertainty is resolved). In consequence, transmission expansion projects are auctioned and the winner investor is forced to execute the project under bidding terms without the possibility to adapt the project to unpredictable events. This research introduces flexibility in TEP process and estimates its value as an approach to cope with uncertainties. To do that, a methodology based on Real Options is used and the value of flexibility is estimated in terms of social welfare. In particular, an option to defer a transmission expansion is applied and its value is estimated by using a binomial tree technique. Volatility for building a binomial tree is estimated by using a MonteCarlo simulation. Two cases are modeled: the first is a binodal case to develop the methodology and the second one is a reduced version of Colombian transmission networks used with two purposes 1) to estimate the flexibility value and 2) to compare the solution given by the approach proposed against the solution given by the approach commonly used by majority of planners. Results suggest flexibility is a valid approach to be introduced in TEP in order to handle uncertainties.

The flexibility in TEP represents a potential change of paradigm that enables planners to adapt, change or adjust their initial decisions according to new information in an economical manner. This change of paradigm increases social welfare in comparison to traditional approaches; in addition, it allows deferring investments until they are required, so smaller commitments are made at the beginning. Flexibility allows using traditional strategies for expansion but also strategies different to those based only in transmission lines, so new possibilities of research about a mix of them are open to take advantage of this approach.

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[1] The role of planners in transmission system expansion includes planning, directing or arranging transmission expansions to ensure efficient, reliable and nondiscriminatory service in restructured markets. Their purpose is to enhance competition and reduce market power of generators (Hirst & Kirby, 2001; Wu et al., 2006).

Our main contributions are highlighted:

- Flexibility is intentional, that means, flexibility is not an improvised decision, it must be included from the outset of the decision making process, and implies creation of options or alternatives in response to unpredictable future scenarios.
- A penalty term is included in the formula to represent the evolution of the underlying asset value because this was defined as the influence on social welfare produced by an expansion; so, if this expansion is not executed at specific period, the benefit will not be received.
- To build the binomial tree is necessary to estimate a volatility factor; this represents the uncertainties that affect the underlying asset value. A common approach is using MonteCarlo simulation to estimate volatility. Our contribution is to use this technique to estimate volatility for each node of the binomial tree when it is supposed changes in the number of uncertainties that affect the process.
- Flexibility has a cost so option value to defer is an upper limit to that cost. This is the meaning of the option value and this is one of the main contributions of this research.

Keywords: Flexibility, Real Options, Robustness, Multistage Stochastic Programming, Adapting Costs, Power System Expansion Planning, Transmission Expansion Planning, Option to Defer, Binomial Tree, Transmission Expansion Planning in Colombia, Montecarlo simulation.

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CHAPTER 1

1. Introduction

Economic growth of a country is closely linked to their electricity consumption (Apergis & Payne, 2010a, 2010b; Yoo & Lee, 2010) and therefore to the strength of its electrical infrastructure. Transmission systems are one of its main components[2] because they allow transporting electricity, under large voltage to reduce costs, from the generator to the end user by using transmission lines, transformers, and protection equipment, among others. Hence, Transmission Expansion Planning (TEP) is of interest to any government. Today, most of countries have separated transmission, generation and distribution activities so they are managed as independent business units by different agents. This scheme (called decentralized, restructured or deregulated) seeks to promote competition in generation and free access to transmission networks. In this model, the State, directly or indirectly, has assumed the role of a system designer, executor of rules for compensation and expansion of the transmission system as well as operation coordinator. New challenges and uncertainties appear under this model so an alternative approach based on flexibility is analyzed in this research as a strategy to cope with uncertainties.

In restructured markets, transmission expansion planning (TEP) assesses both technical impact on system reliability, and economic and environmental impact on society. The process must consider alternatives for transmission expansions such as generation planning and demand side management; TEP also takes into account uncertainties, for example: generation expansion and demand growth, among others

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[2] Generation and distribution systems are the other components

The transmission planning authority is responsible of this task but the investment is assigned to a private investor via a public tender.

The resulting transmission system has (i) to enable generators to supply requirements of growing electricity demand, (ii) to promote competition among generators, (iii) to reduce the exercise of market power of generators, (iv) to increase reliability of the system, and (v) to provide a nondiscriminatory transmission service to all market participants (Hirst & Kirby, 2001; Wu, Zheng, & Wen, 2006).

However, the model poses new challenges and uncertainties such as more market participants, creation of institutions for control and operation of transmission networks to ensure non-discriminatory access to them, and creation of incentives to attract investors in the long term, among others. Open access to networks increases the number of transactions and their use differently as planned and designed. In consequence, line congestion appears preventing covering of loads at low cost. As a result, competition diminishes, power market increases and system reliability reduces (Cedeño & Arora, 2011; Molina & Rudnick, 2010; Rosellon, 2003; Wu et al., 2006). On the other hand, transmission is a capital intensive business, i.e. investments are expensive; also, transmission assets have a long lifetime (20 – 40 years) and during this lifetime many changes can occur, i.e. technological changes in generation may produce generators exit, or load may have a growth different from planned due to unexpected economic development. In consequence, if a transmission line is built under a wrong forecasting, it may be partially used with the aggravating circumstance that the line cannot be relocated because such investment are partially irreversible (D. Kirschen & Strbac, 2010). In summary, making decisions right in TEP is a key issue.

1.1. Present State of Knowledge

Evidently, TEP process is complex and subject to high uncertainties in restructured markets. Complexity of TEP process can be seen through the multiple perspectives that the problem can be analyzed; for example, solutions alternatives for TEP problems can be found by mathematical optimization, heuristic, and meta-heuristic models; the process involves the analysis of planning horizon using either a deterministic or dynamic point of view; in the optimization problem, restructured markets open the possibility of working with objective functions different to cost minimization, and different tools are possible to apply, e.g. program languages and system modeling (Latorre, Cruz, Areiza, & Villegas, 2003). In addition, the problem can be analyzed from an economic perspective that involves remuneration and incentives for transmission expansion (Molina & Rudnick, 2010). Recently, issues such as renewable distributed generation, environmental impacts, and non-conventional alternatives for expansion have increased the complexity of TEP process (Hemmati, Hooshmand, & Khodabakhshian, 2013).

On the other hand, restructured markets increase uncertainties in TEP; as a result, approaches to cope with uncertainties like probabilistic load flow, probabilistic reliability criteria, scenario technique, decision analysis and fuzzy decisions have been proposed (M Oloomi Buygi, Shanechi, Balzer, & Shahidehpour, 2003). However, robustness is more frequently applied (Andrews, 1995). Flexibility, or ability to adjust a system in accordance with future conditions, is another useful approach to deal with uncertainties (Andrews, 1995) that is gaining interest in recent time (Francisco D. Munoz, Watson, & Hobbs, 2015). In restructured markets, TEP procedure interacts with generation planning and demand side management to produce transmission alternatives. However, complete information is not available for transmission planners; as a result, it is frequent using simulation for evaluation of alternatives. Evaluation comprises financial analysis, economic assessment and reliability assessment. Accordingly, a final plan is made for approval (Xu, Dong, & Wong, 2006).

1.1.1. Power system expansion planning process in Colombia

Under this framework, Colombia makes TEP centrally**.** UPME is the responsible to prepare generation and transmission expansion plans using mandatory information provided by producers, transporters, distributors and marketers; such information is specified by regulation (CREG, 2001).

Generation plan is indicative. Its purpose is to identify country requirements of new generation plants based on the behavior of National Interconnected System, SIN, and a set of variables such as energy and power demand, hydrology, fuel prices and their availability, energetic resources, and launch of new generation, among others. A number of scenarios are analyzed to evaluate power system performance and to identify expansion requirements, so a scenario methodology is used by UPME. System performance is analyzed in short term (5 years), medium term (10 years) and long term (15 years). Under these terms reliability indexes must be satisfied. This plan has as purpose to provide information and signals in short, medium and long term to market participants about investment in generation plants (UPME, 2014).

In contrast, transmission plans identifies projects that must be executed by investors selected by auctions. To prepare the Transmission Expansion Plan, UPME also follows a methodology based on scenarios. A diagnostic of National Transmission System, STN, and Regional Transmission System, STR, is prepared taking into account a planning horizon for short, medium, and long term. Solution alternatives are proposed for the identified needs. Performance of solution alternatives is evaluated through the planning horizon from a technical point of view. Building time is estimated for the viable alternatives; if it is reasonable, solutions are evaluated from an economical point of view (UPME, 2014).

These solutions constitute an initial Transmission Expansion Plan which is prepared minimizing investment and operation costs and losses of STN. This plan is public and evaluated by CAPT. Recommendations can be followed by UPME who finally elaborates a final and public version of Transmission Expansion Plan for approval of Ministry of Mines and Energy. Authorized final version is the base to prepare public tenders. Bidders have to present an expected annual income for the next 25 years of the auctioned project. Present value of expected annual income is one of the criteria to select a successful bidder, using a discount rate available in public tenders (CREG, 2001).

1.2. Literature Review and Issues

Most countries have deregulated their electric power sector by imposing restrictions to vertically integrated utilities, but with the disadvantage of increasing uncertainties in the expansion planning process to attend the continuing increase in energy demand over time.
To handle these uncertainties, several techniques have been employed in expansion process in both generation (Gorenstin, Campodónico, Costa, & Pereira, 1993; Zhu & Chow, 1997) and transmission (M Oloomi Buygi et al., 2003; Latorre et al., 2003). Two techniques are highlighted: probabilistic choice and risk analysis. They are defined and compared in (Miranda & Proenca, 1997)**.**

Probabilistic choice aims to seek an optimal solution using the expected value of some criterion. Then, it requires the definition of future scenarios with their respective probability. Under this long-term average, bad future results are compensated by good future result; so, it is an appropriate strategy when there are enough repetitions and decisions made over time. Meanwhile, risk analysis focuses on an optimization based on variability of the selected criterion for the future scenarios. Maximum regret is often used as a criterion under this paradigm. This technique estimates an optimal solution and its cost under a specific scenario. In addition, cost deviations are calculated for non-optimal solutions under the same scenario. First, the maximum deviation is identified for each alternative; and second, the solution with the minimum maximum regret through the scenarios is selected among all solutions previously identified. This solution is called robust when it is appropriate for a wide subset of future scenarios or when its regret is zero in all scenarios (Merrill & Wood, 1991). If a plan is not robust, mechanisms to hedge decisions against adverse results are required.

Historically robustness has been applied most frequently in power system planning (M O Buygi, Balzer, Shanechi, & Shahidehpour, 2004; De la Torre, Feltes, Gomez San Roman, & Merrill, 1999; Fang & Hill, 2003; Merrill & Wood, 1991) because robust approach selects the best plan in a number of scenarios simultaneously. However, it has as limitation that capability of adaptation of the transmission plan to unpredictable events is not evaluated at the time of decision; this shortcoming is extended to scenario analysis (Francisco D. Munoz et al., 2015) .

Flexible systems have been proposed, also, especially in generation expansion (Gardner, 1996; Gorenstin et al., 1993; Hirst, 1990; Hobbs, Honious, & Bluestein, 1994; Tanabe, Yasuda, Yokoyama, & Sasaki, 1993), even though there are applications in TEP (Hedman, Gao, & Sheble, 2005; Ramanathan & Varadan, 2006). Recently, some authors have emphasized the importance of flexibility as an approach that can increase benefits and reduce cost with respect to current methodologies (Francisco D. Munoz et al., 2015), so the number of published work applying flexibility to cope with uncertainties in TEP has increased (Konstantelos & Strbac, 2015; Loureiro, Claro, & Pereira, 2015; F D Munoz, Hobbs, Ho, & Kasina, 2014; Qiu et al., 2015; Wang et al., 2015).

In the following is shown a literature review about flexibility incorporated in power system expansion planning. First, generation expansion is presented and after that transmission expansion is showed.

1.2.1. Generation

Most of historical applications of flexibility in generation have been focused on the flexibility obtained by the use of a combination of technological alternatives using conventional sources of energy (De la Torre et al., 1999; Hobbs et al., 1994; D. S. Kirschen, Ma, Silva, & Belhomme, 2011; Tanabe et al., 1993), others researchers have emphasized in mathematical schemes to model flexibility as for example (Gorenstin et al., 1993) who argue it is better an adaptable expansion strategy rather than a unique schedule at the beginning of the decision making process. Other approaches intend to capture flexibility value by comparison of costs of alternatives (De la Torre et al., 1999; Hirst, 1990; Qiu et al., 2015). From (Hirst, 1990) it can be inferred that flexibility value depends on the alternatives established as options. This finding reinforces that adaptation implies extra-costs.

In recent years, the extent of the flexibility to decisions involving the use of renewable energy sources has gained interest as a mechanism to increase the value of projects (Fernandes, Cunha, & Ferreira, 2011; Martínez Ceseña, Mutale, & Rivas-Dávalos, 2013). The reason for this is because traditional techniques for project evaluation (Discounted Cash Flow – DCF) has a static nature based on an initial decision to do or not do with the information available at the beginning, so its application in renewable energy projects results in unfeasible projects due to uncertainties from intermittent nature of renewable energy sources and their stochastic fluctuations (D. S. Kirschen et al., 2011).

In other words, DCF approach fails to recognize the value of the decision maker's ability to make adjustments to the decisions as uncertainties are resolved; so, the investor can select the best strategies to implement depending on the current condition. This paradigm shift has allowed the application of Real Option (RO) theories that recognize that the value of flexibility can be significant in many projects and disregarding its value may underestimate investments.

Flexibility is incorporated explicitly through the use of RO (Eduardo Schwartz, 2001). The RO's are understood as the various strategies employed by the decision maker to suit his/her decision to the several scenarios that may occur. Options are not mandatory, hence they are called options. Common examples of RO are: the option to abandon, the options to wait and see, the option to expand, the option to contract, the option to choose, the option of changing resources and the option to make sequential investments or compound options (Mun, 2012).

An important underlying characteristic in all these applications of flexibility in energy generation is the decision maker's freedom to adjust the projects to the evolution of uncertainty in order to protect his/her profit. Naturally, flexibility has a cost; therefore, a cost-benefits analysis should be done from a decision maker perspective.

1.2.2. Transmission

Power transmission is one of the main components of the electrical infrastructure of a country. In consequence, TEP process plays a key role. TEP is a complex process, so it has been analyzed from diverse perspectives summarized in (Hemmati et al., 2013; Latorre et al., 2003; Lee, Ng, Zhong, & Wu, n.d.; Molina & Rudnick, 2010). TEP has been modeled using linear programming (Villasana, Garver, & Salon, 1985), mixed integer linear programming (Alguacil, Motto, & Conejo, 2003; Romero & Monticelli, 1994), Benders decomposition (Binato, Pereira, & Granville, 2001), and game theory (Pozo, Contreras, & Sauma, 2013; E E Sauma & Oren, 2007; Enzo E Sauma & Oren, 2006), among others.

Several uncertainties affect the results of the TEP process. For example: 1) availability of lands; 2) duration of the process to obtain all necessary environmental authorizations; 3) building costs; 4) load growth rate; 5) the entry and exit of new generators, their occurrence time, location, and characteristics; 6) the development of alternatives for a transmission system such as distributed generation and FACTS; and 7) the exploitation of renewable energy sources that are frequently distant from load centers, among others. These uncertainties motivate exploring the introduction of flexibility on TEP. Moreover, some of these uncertainties have gained importance over the last years because of global and local governmental goals in terms of replacing conventional sources of energy and the growing importance of environmental conservation. However, historically there is relatively scarce literature about of flexibility applications on TEP (M Oloomi Buygi et al., 2003; Latorre et al., 2003; Maboke & Kachienga, 2008).

In general, flexibility application on TEP shows a stream measuring the flexibility of a plan (Bresesti, Capasso, Falvo, & Lauria, 2003; Cheng, Zhu, Crow, & Sheble, 2004; Lu, Dong, & Saha, 2005) and another stream seeking for applying flexibility on TEP. In this latter, three methodologies are identified: Adapting Costs (CA), Multistage Stochastic Optimization (MSO), and Real Options (RO).

A flexible solution modeled through CA selects the plan that can be adapted to any scenario with the least adaptation cost (Zhao, Dong, Lindsay, & Wong, 2009). Specifically, addition of transmission lines to an optimal plan, from an investment perspective, to satisfy reliability and security objectives under other scenarios requires extra costs, namely adaptation costs. Uncertainties like load level and new generation capacity (Zhao et al., 2009), or distributed generation, DG (Zhao, Foster, Dong, & Wong, 2011), have been handled with this method which can be combined with a robust approach in a multiobjective model to identify robust and flexible solutions (Maghouli, Hosseini, Buygi, & Shahidehpour, 2011). Recent applications extend the models to a co-planning process that involve expansion of gas power plants, gas pipes, and electricity transmission lines as a mechanism to improve the interaction between gas and electricity system (Qiu et al., 2015). These applications recognize that flexibility implies extra costs that can be measured.

On the other hand, MSO, when is used to model flexibility, takes into account uncertainty is cleared over time so new information obtained in previous stages is considered to make adjustment over initial investment decisions (“here and now”) in a subsequent phase (“wait and see”). This approach has been used for generation expansion planning (Gorenstin et al., 1993), and recent applications have been extended to TEP (F D Munoz et al., 2014). MSO recognizes not all investment decisions must be made at a given stage, but some of them can be delayed until more information is available. This focus is valid when expansion is based on conventional transmission assets, or alternatively by using non-conventional assets, or non-network solutions such as phase shifter, storage devices (Konstantelos & Strbac, 2015), or demand side management (Göransson, Goop, Unger, Odenberger, & Johnsson, 2014). Under this context, TEP is considered as a set of sequential investments that are triggered according to some “signals”. The initial investment decisions have to support this capability of adjustment so this implies an extra cost that is not included in the ordinary investments; consequently, it has to be quantified.

Evidently, TEP implies irreversible investments, i.e., they are not recoverable. From the point of view of Dixit & Pindyck (1994), an opportunity to invest can be viewed as a right not an obligation to buy an asset at the future. If an irreversible investment is made today, the option to invest is exercised. However, waiting for new information might change the initial decision. According to those authors, this flexibility has value, and consequently, it has to be included in the project worth. RO theory recognizes that managerial flexibility value might be substantial in many projects and if it is not considered, project worth may be underestimated (Eduardo Schwartz, 2001). In other words, RO allows estimating flexibility value (Neufville, n.d.).

Under this paradigm, flexibility, in particular RO, can be viewed as a source of value so can increase the Net Present Value of transmission plans alternatives (Boyle, Guthrie, & Meade, 2006). Applications of RO analysis in TEP require estimation of components of a project cash flow and its construction, identification of volatility and options, and solution of a real option problem (Hedman et al., 2005). The solution can be obtained by using techniques based on continuous time stochastic models (Dixit & Pindyck, 1994), or discrete time stochastic models like binomial tree (Cox, Ross, & Rubinstein, 1979). Both techniques have been applied on TEP (G Blanco, Waniek, Olsina, Garcés, & Rehtanz, 2011; Ramanathan & Varadan, 2006). Other applications of RO on TEP can be found on literature; some of them are focus on determining the optimal time to invest in transmission lines (Fleten, Heggedal, & Siddiqui, 2011), or the value added due to flexibility (Loureiro et al., 2015; Maboke & Kachienga, 2008). However, the implications of this value have not been explained yet. In addition, most of these researches have been focused on the value of flexibility from a private profit perspective, but in some electricity markets, for example Colombia, electricity transporters have their revenues regulated so it is better to focus the flexibility value from a social welfare perspective. Some authors have employed this view (Gerardo Blanco & Olsina, 2011; Lopez, Aguilera, & Blanco, 2013), but using saved costs as a simile of social welfare; however, total surplus is a proper economic measure to represent social welfare. Total surplus has not been used yet.

These approaches differ in the way they incorporate flexibility, RO is the only approach allowing estimating the increase in the Net Present Value that comes from the value of flexibility, but the other two approaches give no information about that value.

In Colombia, TEP has been analyzed as a stochastic problem of two stages using a linear mixed binary problem (Vinasco, Tejada, Da Silva, & Rider, 2014). Other researchers have contributed on Colombian TEP, but their scope is different from flexibility. Although electric regulations in Colombia requires flexible plans in medium and long term (CREG, 2001), studies applying flexibility are not abundant in recognized scientific literature.

Finally, another important issue is the difference between transmission investment and its planning in the context of restructured markets. The planner has the responsibility to identify the most appropriate plan in terms of reliability and social welfare (Wu et al., 2006). In consequence, investors are restricted to make changes to the optimal plan, autonomously, when the decision to execute that plan was made. In our opinion, this fact can be a barrier to include flexibility in transmission investments. In other words, the assumption made in most papers applying flexibility on TEP is that the investor has leeway to make changes. This assumption could not be a reflection of what really happens in these markets.

1.3. Problem Relevant to the Study

Colombia makes TEP centrally taking into account the uncertainties above mentioned. Transmission plans are prepared using a methodology based on minimum cost and cost/benefit analysis. Several scenarios are analyzed so transmission projects are evaluated to satisfy reliability requirements. For each scenario, a plan that meets all requirements of the network with the minimum cost is chosen. Then, the planner prepares an auction ensuring to private investors recovering their investment costs, e.g. throughout a regulated tariff. The winning bidder commits to execute the expansion according to bidding terms. Two problems arise from this methodology:

The first is minimum cost planning is used at the first stage when they choose one project for each scenario. Even though the planner performs a cost/benefit analysis on the subset of projects, there is no assurance that the one project that was initially chosen for each scenario is better than the ones that were disregarded based on cost only. This reflects back on traditional methods that do not evaluate how much a project is worth because the planner just considers whether or not it meets the requirements and if it is the cheapest (Hedman et al., 2005).

The second is there is no possibility to adapt the selected project to unpredictable events.

In general, these methods tend to produce oversized transmission lines because of the economies of scale, or to select lines that improve social benefit but they are suboptimal. In addition, these methods do not consider managerial flexibility and its value.

1.4. Research Objectives

The purpose of this dissertation is to estimate the value of flexibility in TEP from a social welfare perspective using total surplus; a strategy based on two sequential expansions of transmission lines in the same place of an electrical system is proposed to introduce flexibility. The first expansion solves congestion problems that may arise under expected demand growth rate and the second expansion is deferred until external conditions are appropriate. The second expansion project is analyzed as a real defer-option and its value is estimated by using a binomial tree technique in terms of social welfare. The results are compared against a robust approach. This procedure attends the specific objectives of this research: (i) to define a methodology to estimate flexibility value; (ii) to apply the defined methodology in a reduced model of Colombian transmission network; (iii) to compare results from a model that involves flexibility against traditional models used in TEP, and (iv) to describe current TEP process in Colombia to identify barriers to apply flexibility.

Our hypothesis states flexibility has value in TEP, but what is this value? And how cans this value is estimated?

1.5. Organization of this Thesis

The document is organized as follows: this first chapter introduces the importance of TEP, describes the problem, presents the current state of knowledge, reviews the state of the art of flexibility, shows the research objectives and significant contributions of this research, and describes how this doctoral thesis is organized.

The second chapter contains a characterization of flexibility as an approach to deal with uncertainties. This part is similar in content to a paper co-authored by Alvin Henao, Enzo Sauma and Angel Gonzalez, which was sent to the Renewable and Sustainable Energy Reviews journal. In chapter three, we build a case of a two nodes electric system in order to develop a methodology of introducing flexibility in TEP and estimate flexibility value by using a Real Option approach (RO). This chapter is similar in content to a paper co-authored by Alvin Henao, Enzo Sauma, Tomás Reyes and Angel González, which was sent to the Energy Economics Journal. Chapter four contains a description of the Colombian electric system, its expansion process, and a reduced version of the real system. The goal of this chapter is to apply the methodology developed in the previous chapter on a reduced representation of Colombian transmission network in order to estimate flexibility value, as well as, to identify barriers to apply the methodology in the Colombian TEP process. The content of this chapter is identical in content to a paper co-authored by Alvin Henao, Enzo Sauma and Angel Gonzalez, which was sent to the Energy Journal. Finally, Chapter V presents conclusions of this research. Chapters 2 - 4 have a self-contained structure, so it is possible to read each chapter without reading the other ones.

1.6. Significant contributions of the Research

Each chapter of this dissertation contains important contributions to the state of the art of flexibility when it is applied on TEP: The next paragraphs describe the content of each chapter and the contribution associated.

1.6.1. Overview of Incorporating Flexibility in Power System Expansion Planning

The pretension of this part is to characterize flexibility as an approach to deal with uncertainties because the meaning of the term is very wide and it is necessary to understand its scope in the field of decision making. A chronological revision is made in order to analyze the evolution of this concept in decision making process. Special emphasis is put in literature related to power system expansion. As a result, a comprehensive characterization of flexibility is made, which is the base to develop a methodology in subsequent chapters. A particular characteristic emerges as a contribution of this research: flexibility is intentional, that means, flexibility is not an improvised decision, and it must be included from the outset of the decision making process, and implies creation of options or alternatives in response to unpredictable future scenarios, but it has a cost.

1.6.2. Estimating the value of the option to defer an investment in Transmission Expansion Planning by using Real Options

This chapter is focused in the development of a strategy to introduce flexibility. To do that, a binodal electricity system is built. The flexible strategy consists of two sequential expansions of transmission lines. The first expansion is proposed to solve congestion problems that may arise under expected demand growth rate and the second expansion is deferred until external conditions are appropriate. We use the theory of real option to evaluate the execution of the second expansion project, so an option to defer is evaluated and its value is estimated by using a binomial tree technique in terms of social welfare. The underlying asset is defined as the present value of the incremental benefit that produces the second expansion in terms of social welfare. This value may change through the time in virtue of uncertainties; this evolution is represented by a binomial tree. If this expansion is not executed at specific period, the benefit will not be received, so it is necessary to introduce a penalty term in the evolution of the underlying asset through the time. This is one of the contributions of this research. To build the binomial tree is necessary to estimate a volatility factor; this represents the uncertainties affect the underlying asset value. A common approach is using MonteCarlo simulation to estimate volatility. Our contribution is to use this technique to estimate volatility for each node of the binomial tree when it is supposed changes in the number of uncertainties that affect the process.

1.6.3. Estimating the value of the option to defer an investment in Transmission Expansion Planning in Colombia using Real Options

The strategy and methodology defined in the previous chapter is applied in this chapter on a reduced version of Colombian electricity system. Our purpose is to identify the value of flexibility in a representation of a real system and compare the results with robustness, a traditional approach commonly used in TEP. Although solutions given by the two approaches may converge, an interesting interpretation arises when both approaches are compared: Under a robust approach the system is built minimizing all costs, this produces a rigid system that cannot be expanded in the future if conditions are different from planned, whereas the same solution obtained by a flexible approach allows the system to be expanded in the future because the option is open from the outset. This ability implies an extra cost that is not included in the robust investment, so the limit for this extra cost is provided by the option value to defer this flexible expansion. This is the meaning of the option value and this is one of the main contributions of this research.

1.7. Summary and Conclusions

It has been shown the importance of electric transmission system planning and the complexities surrounding this process. It is a hot topic around the world because TEP has a strong economic impact for the development of countries. Approaches like robustness have been traditionally applied in TEP to handle uncertainties, but recent research has shown that flexibility approach may reflect better the attitude of planners and investors when uncertainties are revealed. Unfortunately, those researches have been applied in context different from Colombia.

This dissertation will apply pertinent and previously available techniques in the current state of knowledge in order to analyze implications of flexibility approach on Colombian TEP from a perspective of social welfare.

Our main contribution is to explore this approach in Colombia; however, other contributions of worldwide interest arise.

In consequence, this dissertation seeks to identify flexibility value in the Colombian TEP using a simplification of the National Interconnected System (SIN). The flexibility value is estimated using a methodology based on Real Options; in particular, a binomial tree technique is applied because of its simplicity, intuitive understanding, and because it is appropriate to determine flexibility value (Copeland & Tufano, 2004). In addition, in order to understand the meaning of flexibility value a comparison between a flexible approach and a robust approach is shown.

CHAPTER 2

2. Overview of Incorporating Flexibility in Power System Expansion Planning

Abstract

This chapter presents a characterization of flexibility as a tool for risk analysis in power system expansion planning. It reviews several applications of the flexibility concept on both generation and transmission expansion planning as a mechanism to cope with uncertainty. From literature review is possible to infer the following characteristics of flexibility: 1) Flexibility implies adaptability; 2) adaptability is associated with the ability to adjust a system inexpensively in response to uncertainty evolution over time; 3) the response seeks to take advantage of favorable conditions or to hedge against unfavorable condition, so it is risk reduction approach; 4) flexibility is intentional, it means flexibility is included from the beginning in the decision making process; 5) at the beginning in the decision making process, options are identified to cope uncertainties; 6) the more open options are from the beginning, the more flexible is the investment plan; 7) waiting to make a decision when more information is available is always an option; 8) flexibility is an alternative for robustness, they can coexist and complement, but they can be mutually exclusive so they can be in conflict; 9) flexibility in an investment plan is different from its value; 10) flexibility value can be captured by real options.

2.1. Introduction to the chapter

Power system expansion planning is crucial to obtain economic development in the long term. It is the search of the best alternatives in generation, transmission and distribution systems in order to keep satisfied the growing demand for energy, taking into account multiple technical, economic, political and environmental constraints. The general steps to make a power system expansion planning can be consulted in (Wu et al., 2006).

Two general models describe electricity sectors of countries around the world; so, they are the context in which decisions are taken about power system expansion planning (Cedeño & Arora, 2011; Molina & Rudnick, 2010; Rosellon, 2003; Wu et al., 2006):

- Centralized or Integrated: There is a vertically integrated chain of generation – transmission – distribution. Electrical assets are mostly owned by state utilities. Their objective is to meet current and future demand safely, reliable and affordable. Generation and transmission planning is coordinated and based on load forecasts. Investments are recovered at a rate of return approved by regulation. Expansion planning focuses on alternatives that reduce system total cost under reliability constraints..
- Decentralized or restructured: generation, transmission and distribution are separate business units, managed by different agents. This scheme seeks to promote competition in the generation and free access to the transmission networks. Transmission and distributions are considered natural monopolies. The State, directly or indirectly, has assumed the role of design and application of rules for compensation and expansion of the transmission system as well as operation coordinator. Under this context the paradigm of maximizing profits is not obvious and it appears conflict of interest between social welfare and private interests.

The following strategies are useful to cope with uncertainty in investments (Andrews, 1995):

- To invest in robust projects.
- To invest with flexibility in order to make changes easily and economically.
- To ignore risks.

Under this perspective, risk analysis acquires a new dimension, flexibility. Most research in power systems, in particular in Transmission Expansion Planning (TEP), have focused on reliability and optimality (Enzo E Sauma & Oren, 2006), but flexibility has become important in recent years

(Francisco D. Munoz et al., 2015). Under this framework this chapter aims to review those research works applying risk analysis strategies in power system expansion, with special emphasis on flexibility.

In the following section, it is explained the differences among robustness, adaptability and flexibility and after conclusions are presented.

2.2. Robustness, flexibility and adaptability

In order to differentiate we review these concepts under the investment planning point of view. First, historical approaches are reviewed to build a complete vision, after that an analysis of main findings is registered.

Flexibility is a portfolio of adaptable resources to uncertain conditions, easily and inexpensively (Hirst, 1990). Hirst (1990) highlights results of the California Energy Commission in which flexibility acts as an insurance premium paid to mitigate possible effects of higher costs scenarios. In consequence, flexibility is an inclusive alternative to robustness, since it is possible to work with results that are not quite robust, but that would be the best solutions. These solutions require hedging strategies against adverse scenarios. So flexibility might be a substitute for these hedging mechanisms.

Flexibility is defined as the ability to adapt the design of a system or its operation to changing conditions (Hobbs et al., 1994). Flexibility is improved when options are left open when a decision is made.

There is a subtle difference between robustness and flexibility in (De la Torre et al., 1999), where the authors select a solution for a transmission expansion plan in Central America. The solution is flexible because there would be a future expansion if conditions are appropriate after an initial expansion is made. But the solution is not robust because its regret is not zero in all scenarios analyzed.

(Lu et al., 2005) defines flexibility as the system ability to allow reconfigurations with minimum penalties. This approach is similar to the adaptability concept proposed by (Stigler, 1939), who defines adaptability as the ability of a same technology to be adjusted to a wide rank of requirements inexpensively. According to Stigler adaptability and flexibility are different because the latter is wider since it may imply to use a different technology to achieve the desired goal (for example minimization of production cost). Stigler highlights the greater adaptability is, the lesser flexibility need. Note that this is one of the first articles about flexibility but in the context of production. In (Andrews, 1995) there is not difference between flexibility and adaptability, rather these terms are interrelated because a flexible investment is adaptable to changes in future conditions. According to Andrews, flexibility allows to defer decisions until more information is available, so decision quality is improved. In consequence, flexibility reduces risk because less investment is required at the beginning.

Electrical expansion plans are plagued of uncertainties, so those plans should be reviewed periodically and to be adjusted according to new information (Vasquez & Olsina, 2007). Plans can be done with flexibility, so planner can adjust them easily and inexpensively under unfavorable conditions. However, plans can be designed robustly to withstand such events unchanged. This means flexibility is an alternative to robustness, but both arise to cope with uncertainties by a planner.

An approach to define flexibility based on cost can be found in (Maghouli et al., 2011; Tanabe et al., 1993; Zhao et al., 2009, 2011), those plans with lower difference in cost relative to a base case are considered flexible.

Flexibility is analyzed from diverse perspectives in (Saleh, Mark, & Jordan, 2009). From a decision theory point of view, a measure of flexibility in a plan is the number of open alternatives after a first commitment is made. Under real options perspective, managerial flexibility is a mechanism of planning and resource allocating under uncertainty. This approach recognizes the managerial ability to adjust the course of a project by actions that arise because market uncertainty is cleared over time. Options are not focused in flexibility but in its financial value. According to Saleh et al. (2009), projects or investment plans are flexible if they contain contingent decisions for: 1) to hedge against negative future market conditions and 2) to grow if there are favorable market's conditions. A plan is rigid if it has few options and it is flexible if it has many options. Therefore, flexibility denotes not having restrictions to maneuver against unforeseen events. In contrast, robustness does not allow this adaptability since it takes a unique solution, which in principle would have the best behavior in all scenarios. However, it is possible that flexible solutions differ from a robust solution under favorable or unfavorable scenarios.

In summary, according to reviewed literature, the following aspects are relevant for flexibility under the context of decision making: 1) Flexibility implies adaptability; 2) adaptability is associated with the ability to adjust a system inexpensively in response to uncertainty evolution over time; 3) the response seek to take advantage of favorable condition or to avoid unfavorable conditions, so it is a risk reduction approach; 4) flexibility is intentional, which means flexibility is included from the beginning in the decision making process; 5) at the beginning in the decision making process, options are identified to cope uncertainties; 6) the more open options are from the beginning, the more flexible is the investment plan; 7) waiting to make a decision when more information is available is always an option; 8) flexibility is an alternative for robustness, they can coexist and complement (Gorenstin et al., 1993), but they can be mutually exclusive so they can be in conflict (Maghouli et al., 2011); 9) flexibility in an investment plan is different from its value; 10) flexibility value can be captured by real options.

Besides the above, it also follows that there are investment environments where flexibility has value. In addition, there are investment plans that are more flexible than others by virtue of the number of options they contain; these options can be exercised if it has been identified that flexibility has value. Recognizing the difference between the existence of flexibility and the value of flexibility is important to define a framework for implementing flexibility. In consequence, we can formulate these questions: Is flexibility valuable in the context of power system expansion planning? How to measure its worth? And finally, how to develop flexible expansion plans? Answers to these questions are explored in the next chapters.

2.3. Chapter Conclusions

This chapter discusses the concept of flexibility in terms of definitions and methodologies used by various researchers who have analyzed flexibility in power system expansion planning. Given the uncertainties that are involved in this context, the inclusion of flexibility provides a valuable approach from a conceptual point of view to cope with them.

However, introducing flexibility in TEP is not a standard procedure; in consequence, an appropriate methodology that takes into account the characteristics of flexibility above mentioned must be developed.

CHAPTER 3

3. Estimating the value of the option to defer an investment in Transmission Expansion Planning by using Real Options

Abstract

Several countries centrally perform Transmission Expansion Planning (TEP) seeking to maximize social welfare, but there are uncertainties affecting investment success. Additional to reliability considerations, the traditional project valuation method, discounted cash flow (DCF), determines the execution of investment projects. If a transmission project has a positive Net Present Value (NPV), the planner auctions the line and it must be executed in inflexible terms of bidding. However, if future scenarios are different from what was forecasted, such project could be inappropriate because of overinvestment or underinvestment. DCF does not take into account the responses of the planner when uncertainties are resolved because DCF evaluates the project with the information available today. Under TEP, managerial flexibility could be useful because decisions may change over time by the emergence of new information. Investors can defer or expand according to such information. The aim of this chapter is to determine the value of adding flexibility to TEP through real options, in particular binomial trees. Our analysis includes two components: a fixed expansion as a response of our best knowledge about the future and a flexible expansion to endow planner with flexibility. Results suggest flexibility increases project value.

3.1. Introduction to the chapter

Centerpiece in Transmission Expansion Planning (TEP) is the identification of appropriate transmission lines to ensure reliability, interconnect new generators and support future demand growth. Under deregulated environments, TEP comprises a set of processes mutually interrelated that involve generation planning, demand side management, power system operation, and the evaluation of transmission line alternatives from a financial and economic perspective (Xu et al., 2006).

Uncertainties such as demand growth and new generation entrance, among others, affect the aforementioned process. Such uncertainties create risks in TEP and can be handled through robustness and flexibility (Andrews, 1995). Additional to reliability considerations, from an economic perspective, the traditional project valuation method of discounted cash flows (DCF), is usually used to determine the Net Present Value (NPV) of the project and whether the project should be executed or not. In other words, if a transmission project has a positive social NPV, the planner auctions the project and the winning bidder commits to execute the project under the predetermined terms.

The DCF approach assumes that the manager is passive once committed to execute the project. In real life managers have the flexibility to alter their strategy to react better to different realizations of initially forecasted variables. Under TEP, managerial flexibility should be very useful because decisions may change over time with the diffusion of new information. The aim of this chapter is to determine the value of adding flexibility to the process of transmission expansion through real options. We decide this approach because an investor has an option not the obligation to "buy" the transmission assets according to available information. Also, such investment is partially irreversible, it is subject to uncertainty, and it may be delayed, so conditions to apply RO are given (Dixit & Pindyck, 1994).

This chapter values the flexibility of a transmission planner who designs for long term, maximizing social welfare through total surplus, and taking into account oligopolistic behavior of electricity generators[3], in order to reflect some characteristics of real markets. More importantly, in order to shelter investment against risk, the planner has the possibility to make a flexible expansion over a fixed one.

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[3] The source of energy to be transformed in electricity by generators is not considered in this research.

Real options have been widely used to incorporate flexibility in investment projects (Eduardo Schwartz, 2001; Mun, 2006). In our specific setup, we value the flexibility using a binomial options pricing model (Cox, Ross and Rubinstein 1979). This discrete-time binomial tree model allows us to explicitly compute the value of flexibility over time.

The rest of the chapter is organized as follows: next subsections describe TEP modeling and outlines real options approach, in particular binomial trees. Section 2 defines the methodology that integrates TEP modeling with real options and presents an application case. Section 3 contains results, sensitivity analysis and conclusions.

3.1.1. TEP Modeling

Electric transmission expansion planning (TEP) is a complex task. The process has been analyzed from an economic, regulatory, planning, design, modeling, technical and operational perspective by a number of researchers through time. For summarized findings see (Hemmati et al., 2013), (Molina & Rudnick, 2010), (Lee et al., n.d.), and (Latorre et al., 2003).

TEP has been modeled using linear programming (Villasana et al., 1985), mixed integer linear programming (Romero & Monticelli, 1994). TEP has multiple objectives in conflict with each other (Enzo E Sauma & Oren, 2009) so the use of multicriteria solution techniques is frequent. Other models use game theory which consider strategic behavior of competitors (Downward, 2010; Pozo et al., 2013; E E Sauma & Oren, 2007; Enzo E Sauma & Oren, 2006).

TEP has some characteristics that justify flexible decisions:

- High investment cost and benefits.
- Partly irreversible investment.
- Benefits coming from investment are under high uncertainty in the future.

In consequence, some authors have included managerial flexibility in TEP to cope with uncertainties but using several approaches such as multi-stage stochastic programming, adapting cost and real options. Multi-stage stochastic programming is used to identify some investments that can be delayed by waiting until new information arrives (F D Munoz et al., 2014) or using different alternatives to traditional transmission until it is unavoidable (Konstantelos & Strbac, 2015) but in any case a solution is identified a priori according to scenarios previously defined and without considering the ability of the investor to adapt its reaction as determined by uncertainty evolution.

Adapting cost is similar to a robust plan in their philosophy because it analyzes the performance of alternative plans under several scenarios and those that present least adapting cost in worst case scenario is selected as the most flexible plan (Zhao et al., 2009). Real options has been applied using Montecarlo simulation (Gerardo Blanco, Olsina, Garcés, & Rehtanz, 2011) or binomial trees (Ramanathan & Varadan, 2006); the first focused in social welfare through saving cost and the second focused in private interests. We introduce flexibility by using a sequential expansion of transmission lines. The first expansion solves congestion problems that may arise under expected demand growth rate and the second expansion is deferred until external conditions are appropriate. The latter expansion is an underlying asset to build an option to defer. The option value is estimated by using real options and it is measured in terms of social welfare, i.e. the total surplus.

3.1.2. Real Options

There are good reference books describing limitations of methodologies based on discounted cash flow (DCF) and showing the goodness of RO theory, its application, conceptual base, and methods and techniques to apply it (Dixit & Pindyck, 1994; Eduardo Schwartz, 2001; Mun, 2012). In particular, a comprehensive comparison among different methodologies to make decisions, included RO, can be consulted in (Kodukula & Papudesu, 2006). Accordingly we emphasize in RO.

Options theory evolved from proposed models from Cohen, Black and Scholes (Cohen, Black, & Scholes, 1972) and Merton (Merton, 1973). In general, there are two approaches to value real options: the first one uses a continuous time random walk model for the underlying asset price evolution (Cohen et al., 1972; Dixit & Pindyck, 1994; Merton, 1973) and the second one is based on a discrete time binomial model for the evolution of the price (Cox et al., 1979; Eduardo Schwartz, 2001; Mun, 2006). A comparison between these two approaches can be consulted in (Chvalkovská & Hrubý, 2010). The binomial model is widely used to capture the value of flexibility (Eduardo Schwartz, 2001) by allowing the agent to react to different realizations of initially forecasted variables. According to (Copeland & Tufano, 2004), binomial model uses a math less exigent than calculus-based models. It can be easily adapted to introduce changes in volatility, early and multiple decisions. These advantages allow the investor using spreadsheet programs to build a decision model. In consequence, it is an important advantage that demystifies RO and it helps to spread its use outside academia. We are conscious about the importance of flexibility to deal with uncertainty so our interest is to make easier the application of flexibility approach in real sector.

3.2. Methodology

The block diagram in Figure *3-1* describes in general form our methodology. We start from an electric system without congestion.

The next assumptions are followed:

- Initial conditions such as generated power at each electrical node, loads, and flows among nodes are known or can be calculated. This is not a critical assumption considering the focus of the research what is to develop a methodology to introduce flexibility.
- We suppose new transmission assets are available one year after it was decided to expand. This is an unrealistic assumption but we take advantage of the methodology of binomial tree, which allows adapting periods larger than one year. However we propose more future research about this topic.
- Only one an individual transmission investment is made to support flexibility. This assumption is not critical and is only done for simplicity.
- Capacity of flexible investment is known from the beginning. This is not a critical assumption considering the focus of the research what is to develop a methodology to introduce flexibility.
- Underlying asset follows a path described by a binomial tree. More future research is necessary in order to identify the best model that describes the variable.
- The energy dispatch model uses a DC approximation of Kirchhoff's laws. This is not a critical assumption considering the focus of the research what is to develop a methodology to introduce flexibility.
- A reliable electric system is assumed. During transmission expansion planning, first the expansion is assessed from a technical point of view, after it is assessed from an economic point of view, so it is not a critical assumption, taking into account the focus of this research.
- Total surplus is estimated using fixed load at maximum level during each year of planning horizon. Load has a strong impact on the system, so fluctuations may affect line congestion. As a result, estimation of total surplus is affected. More research is needed in this topic, so is a limitation of this dissertation. The proposed methodology produces a cash flow of total surplus and the future values are discounted using a discount rate that depends of the investor. This is not a critical assumption because RO application starts from the project

present value without options; in consequence, any effect produced by discounted rate was already evaluated.

- Load growth rate is uncertain from one year to the next. There is uncertainty in generation costs at year 8. This is a common assumption made for simplicity in order to produce variability in the cash flow. Other sources of uncertainty may be explored in future research.

Initially, a set of rigid expansion alternatives over the base case is proposed. Although multiple methodologies can be used in order to identify which alternative is more appropriate, we do not emphasize in them because they are not the focus of this research[4]. For this case, we use the maximum Expected Incremental Total Surplus Present Value ($EITSPV$) to select the most appropriate fixed expansion. Under each scenario, the difference at each year between the forecasted total surplus from a proposed expansion and the forecasted total surplus from a base case produces incremental total surplus values. After, those values are brought to present under each scenario and the maximum is selected as $EITSPV$.

In second place, we evaluate a flexible expansion over the fixed one. This flexible expansion allows the system to be better prepared to handle unpredictable future scenarios of, for example, higher demand. We value the flexible expansion as a real option. In similar fashion that $EITSPV$, a new Incremental Total Surplus Present Value has to be estimated, $ITSPV$, but now this is obtained using forecasted values of total surplus from flexible expansion and fixed expansion. $ITSPV$ due to the flexible expansion and before investment costs is the underlying asset value, S_0. If investment costs are subtracted from S_0, we obtain the value of the project without flexibilities, $PVWF$.

To evaluate flexibility through real options, it is important to consider the following definitions (Kodukula & Papudesu, 2006):

- Underlying asset initial value, S_0: the expected Present Value (PV) of the project at time 0 computed from DCF valuation.
- Volatility of the underlying asset, σ_t: the variability of the return on the PV of the project from period 0 to t.

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[4] For a summarized review of approaches and methodologies of transmission expansion see (Hemmati et al., 2013; Latorre et al., 2003; Molina & Rudnick, 2010)

- Exercise price or strike price, X_t: the investment needed to obtain the PV of the project at period t.
- Time left to exercise the option – maturity time, T: in some real option applications it is not clear how much time is available to exercise an option because of the nature of real assets and investment projects (Kodukula & Papudesu, 2006). We propose to use a planning horizon for TEP because during that time the evolution of an electric system is analyzed.
- A binomial tree is a representation of the evolution of the underlying asset through time.

Other concepts from Financial Options Theory such as option price, intrinsic value, time value .

In the rest of this section, we divide our explanation in two parts: first we explain how to estimate flexibility value and secondly how to estimate S_0.

To estimate flexibility value, it is useful to use Monte Carlo simulation to produce multiple paths of the underlying asset evolution through the lifetime of the transmission asset. Multiple paths are caused by the uncertainties modelled. Results from Monte Carlo simulation are useful to estimate a volatility that will be used to build a binomial tree (Copeland & Antikarov, 2001). The following expressions are needed to estimate volatility:

$$Z_t^i = ln\left(\frac{PV_t^i}{PV_0}\right) \tag{3-1}$$

$$\sigma_t = std\ dev.(Z_t^i) \tag{3-2}$$

$$\sigma_1 = \sigma_t/\sqrt{t} \tag{3-3}$$

Where PV_t^i represents the present value of the project at period t and obtained from Monte Carlo simulation i. Sub-index t may be any discrete time at the future, so σ_t corresponds to the variability through time step t. Z_t^i is a logarithmic cash flow return for t years, estimated from Monte Carlo simulation i. σ_1 is the volatility for one time step.

Figure 3-1. General block diagram

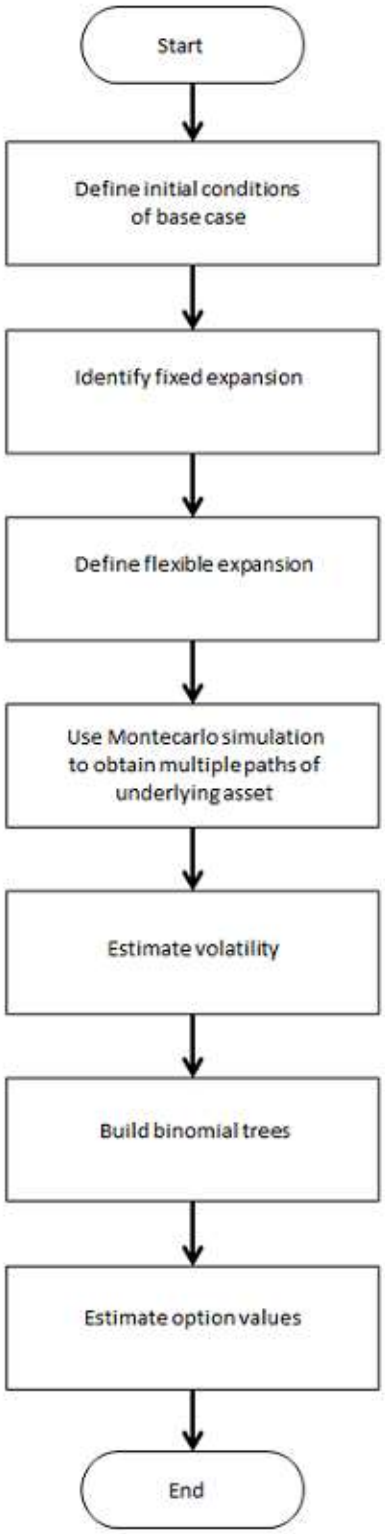
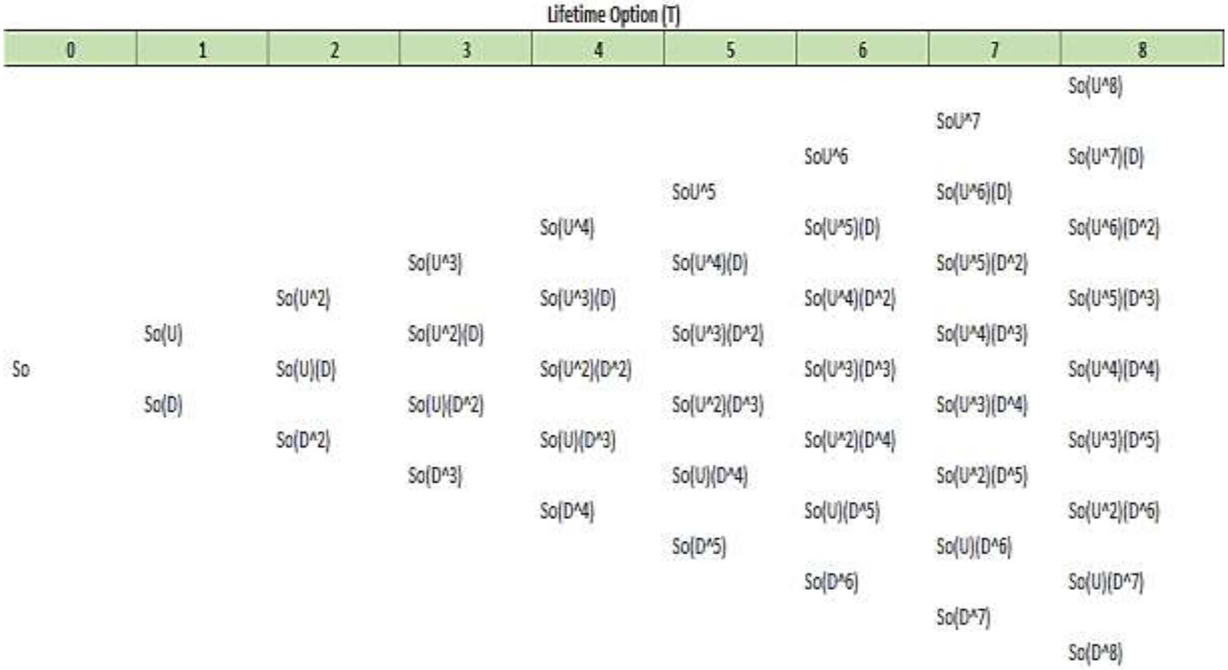


Figure 3-1. General block diagram

A binomial tree has the appearance described by Figure *3-2*:



Lifetime Option (T)

0	1	2	3	4	5	6	7	8
								So(U^8)
							SoU^7	
						SoU^6		So(U^7)(D)
					SoU^5		So(U^6)(D)	
				So(U^4)		So(U^5)(D)		So(U^6)(D^2)
			So(U^3)		So(U^4)(D)		So(U^5)(D^2)	
		So(U^2)		So(U^3)(D)		So(U^4)(D^2)		So(U^5)(D^3)
	So(U)		So(U^2)(D)		So(U^3)(D^2)		So(U^4)(D^3)	
So		So(U)(D)		So(U^2)(D^2)		So(U^3)(D^3)		So(U^4)(D^4)
	So(D)		So(U)(D^2)		So(U^2)(D^3)		So(U^3)(D^4)	
		So(D^2)		So(U)(D^3)		So(U^2)(D^4)		So(U^3)(D^5)
			So(D^3)		So(U)(D^4)		So(U^2)(D^5)	
				So(D^4)		So(U)(D^5)		So(U^2)(D^6)
					So(D^5)		So(U)(D^6)	
						So(D^6)		So(U)(D^7)
							So(D^7)	
								So(D^8)

Figure 3-2. Binomial tree appearance with δt =1 year

At any time, the underlying asset value, S_0, can go up or down due to the realization of the uncertainties in the model. S_0 is multiplied by a factor *U* larger than 1 to represent upward movement. On the other hand, when the value goes down, it is multiplied by a factor *D* smaller than 1. Under the binomial tree technique *U* and *D* are calculated as follows:

$$\mathrm{U} = \exp(\sigma_1\sqrt{\delta \mathrm{t}})$$

$$\mathrm{D} = {}^{1}\!/_{\mathrm{U}}$$

Maturity time of the Option defines when ultimate decision can be made (to invest or not), this is 8 years for the example of *Figure 3-2*. The last nodes of the binomial tree (8th period at *Figure 3-2*) contain the range of possible values that the underlying asset can take (from SoU^8 to SoD^8) when the option expires. Indeed, these values indicate present values estimated at period 8, $PV_{8,j}$, where sub-index 8 indicates period of the time and sub-index j indicates the selected node being $j = 1$ the upper node.

Maturity time is divided in multiple stages. At each stage, option value must be estimated and its value defines to invest at that time or to defer until conditions are better, so it is possible to invest before maturity time expires. The more divisions or stages in maturity time, the more accuracy in option value estimation.

To value the option, we start from the last nodes at maturity time. Transmission expansion can be compared with a call option so its value at each node of 8th period, $OV_{8,j}$, is estimated as follows:

$$\mathrm{OV_{8,j}} = \max\{\mathrm{PV_{8,j}} - \mathrm{X_8}, 0\} \tag{3-4}$$

Decision to invest will occur if $OV_{8,j} > 0$.

For earlier periods, option value ($OV_{t,j}$) is obtained applying the following maximization criterion:

$$\mathrm{OV_{t,j}} = \max\{\mathrm{PV_{t,j}} - \mathrm{X_t}, \mathrm{DV_{t,j}}\}, \qquad t < 8 \tag{3-5}$$

Where $DV_{t,j}$ is the expected discounted value of not exercising the option in period *t* and waiting until next period to decide:

$$\mathrm{DV_{t,j}} = [\mathrm{p} * \mathrm{OV_{t+\delta t,j}} + (1-\mathrm{p}) * \mathrm{OV_{t+\delta t,j+1}}]\mathrm{e}^{-\mathrm{Rf}*\delta \mathrm{t}} \tag{3-6}$$

In this last equation the probability, p, used to compute the expected value is calculated under a risk assumption neutral (Mun, 2006) with the following formula:

$$\mathrm{p} = \frac{\mathrm{e^{Rf}} - \mathrm{D}}{\mathrm{U} - \mathrm{D}}$$

Where R_f is a parameter that represents the risk free rate of return.

It is possible to invest a stage t if $PV_{t,j} - X_t > DV_{t,j}$

At the end of this recursive procedure, the initial node will contain the option value, $OV_{0,1}$, we call this PVO. To estimate the option value, $PVWF$ should subtract from PVO.

The procedure described above is a general algorithm to estimate option value by using a binomial tree technique. In our case, we assume a maturity time of 14 years because some countries use this period as planning horizon[5]. Additionally, we model two kinds of uncertainties that affect the $ITSPV$ of the project: demand growth rates and generation costs. Uncertainty in demand growth rates comes from unpredictable future scenarios, such as, an unexpected special load entrance or an under-perform behavior of economy. Similarly, generation costs may rise or fall according to new installed technologies that come to the generation market.

We suppose that uncertainty about demand growth is present during lifetime of the option, but after the year 8 the system might change generation costs because new generation units can enter at that time. This assumption implies two estimations of volatilities. One of them is for the first 8 years of maturity time and the second one is for the last 6 years. This fact changes U and D factors for the last 6 years of maturity time so a non-recombining binomial tree is produced (*Figure 3-3*). At the end of year 8 we have multiple starting nodes for binomial trees, so the second volatility can be estimated following two approaches: calculate a single volatility for the rest of the trees (case A) or calculate one volatility for each tree that born in each node of 8th period (case B). Figure *3-3* illustrates the appearance of a non-recombining binomial tree. In such figure, years from 2 to 6 were omitted for saving space. For the same reason, some intermediate branches are not shown. From year 8th each node produces a new binomial tree because of changes in volatility described above.

To estimate the option value at each stage, we assume there is equivalence between financial and economic costs, so investment costs can be subtracted from social welfare without any correction to obtain net total surplus. In addition, we subtract a penalty to indicate the lost opportunity cost because of not expanding. This penalty will be different to zero if there is congestion in the electric system at that time. The idea behind this penalty is that congestion reduces social welfare not only in electric markets but also in the rest of economy. The penalty magnitude is estimated as incremental total surplus produced by the flexible expansion if such expansion is made in the period of analysis.

To calculate the probability to exercise the option at the end of the binomial tree, first we calculate the number of paths arriving to a specific node, second the number of paths belonging to nodes where the option is exercised is summed, and finally, its sum is divided by the total sum of paths arriving at the end of the maturity time.

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[5] E.g., Colombia in South America

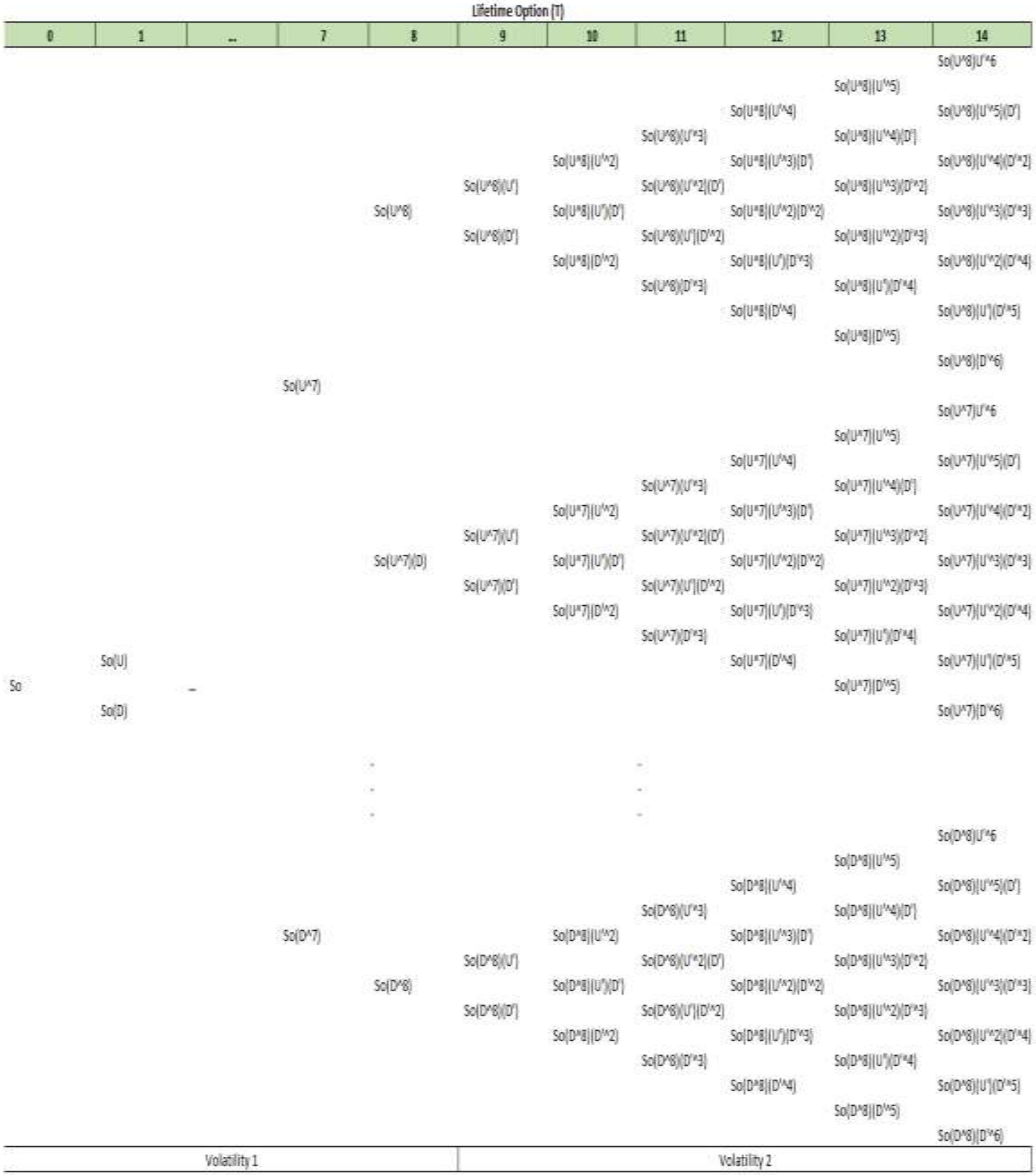

Figure 3-3. Non-recombining binomial tree for options with changing volatilities

Finally, we obtain an option value in terms of total surplus as representation of social welfare. To estimate the option value, $PVWF$ should subtract from PVO, at the start of the binomial tree.

Before estimating our underlying asset value, S_0, it is necessary to estimate $ITSPV$ because we suppose they are the same. To do that, we have to estimate the incremental total surplus at each year of useful life asset (25 year) for flexible expansion project and after those values are brought to present. Those estimations are obtained from the base case illustrated in Figure *3-4*. This is a system of two electrical nodes interconnected by a congested transmission line. Each node has unlimited generation capacity described by a curve of marginal cost and load described by a demand curve, both curves are assumed linear. In addition, node 1 produces energy at lower cost than node 2.

The flow through the line is determined by an Independent System Operator, ISO, according to the producer's bids and line capacity. We assume total surplus is the same through the year but it may change annually due to different demand growth rates. In addition, we assume that there is a probability that a new generation unit will enter in period 8. If this happen generation cost in node 2 will change. This base case evolves through an asset useful life of 25 years.

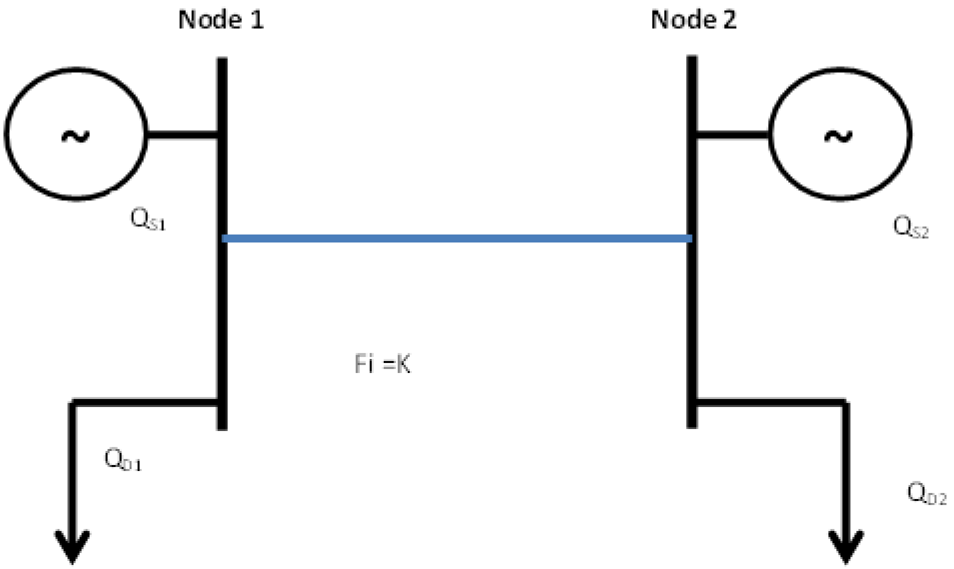

Figure 3-4. Two nodes electric transmission system.

Symbols:

P_{Ni}: Node i price, with parameters $a_i,\ b_i \epsilon \mathbb{R}$ [$\$/MWh$]

Q_{Di}: Node i power demand [MW]

Q_{Si}: Node i power supply [MW]

$\mp F_i$: Power flow from/to node i (it will be negative if flow is exiting from node i) $[MW]$

CT_i: Node i generation total cost, with parameters $c_i,\ d_i,\ e_i \epsilon \mathbb{R}$ $[\frac{\$}{MWh}]$

K: Maximum capacity of transmission line $[MW]$

U: Generator's profit $[\frac{\$}{year}]$

ΔBS: Social Welfare measured as total surplus $[\frac{\$}{year}]$

Generators have the following structure for their marginal costs:

$$\mathrm{CM_i = d_i + 2e_iQ_{Si}} \tag{3-7}$$

Node loads have the following structure:

$$\mathrm{P_{Ni} = a_i - b_iQ_{Di}} \tag{3-8}$$

At each time during planning horizon, operating conditions of the system must be identified; such conditions are defined by generator's behavior and ISO decision. We follow the approach proposed by (Enzo E Sauma & Oren, 2006) in which ISO determines the flow through the transmission line according to the producers bids. ISO wants to maximize incremental social welfare (ΔBS). Producers want to maximize their profit (U). The market equilibrium is modeled as Nash-Cournot equilibrium. The model is adapted to the system shown in Figure *3-4*, its solution follows the procedure suggested by (Enzo E Sauma & Oren, 2006) in which Karush Kuhn Tucker conditions are used to solve the problem through a linear complementarity problem, LCP. Our adapted model is the following:

Generator’s behavior:

$$\max_{Q_{si}\epsilon R+} U = [a_1 - b_1(Q_{s1} + F_1)]Q_{s1} - (d_1Q_{s1} + e_1Q_{s1}^2) + [a_2 - b_2(Q_{s2} + F_2)]Q_{s2} - (d_2Q_{s2} + e_1Q_{s2}^2) - c_1 - c_2$$

Subject to:

$$Q_{s1} \geq 0$$
$$Q_{s2} \geq 0$$

ISO governs system operation by:

$$\max_{F_i\epsilon R+} \Delta BS = \int_0^{F_1} [a_1 - b_1(Q_{s1} + X_1)]dX_1 + \int_0^{F_2} [a_2 - b_2(Q_{s2} + X_2)]dX_2$$

Subject to:

$$F_1 + F_2 = 0$$
$$F_1 \leq K$$
$$F_1 \geq -K$$
$$F_2 \leq K$$
$$F_2 \geq -K$$
$$Q_{s1} + F_1 \geq 0$$
$$Q_{s2} + F_2 \geq 0$$

Results from the previous problem let us to calculate the following variables:

- Prices at node i:

$$P_{Ni} = a_i - b_i(Q_{si} \pm F) \tag{3-9}$$

- Consumer surplus at node i:

$$EC_i = \frac{1}{2}(a_i - P_{Ni})(Q_{si} \pm F) \tag{3-10}$$

- Producer surplus at node i:

$$\mathrm{EP_i} = \frac{1}{2}(\mathrm{P_{Ni}} - \mathrm{d_i})(\mathrm{Q_{si}} \pm \mathrm{F}) \tag{3-11}$$

- Congestion rent:

$$\mathrm{RC} = |\mathrm{F} * (\mathrm{P_{N1}} - \mathrm{P_{N2}})| \tag{3-12}$$

- Total surplus (Social Welfare):

$$\mathrm{ET} = \sum_{i=1}^{2} \mathrm{EC_i} + \sum_{i=1}^{2} \mathrm{EP_i} + \mathrm{RC} \tag{3-13}$$

Estimations of total surplus by equation (3-13) are made for flexible expansion and fixed expansion, its difference at each year during transmission asset useful life produces incremental total surplus, then $ITSPV$ can be obtained and therefore S_0.

3.3. Results and discussion

The values of the parameters used in equations (3-7) and (3-8) are shown in Table *3-1*[6]. We suppose that generation costs may change or not since the 8th period. Those new parameters are in the lower part of Table *3-1*:

Node	a	b	d	e
Node 1	120	0.04	10	0.0075
Node2	300	0.08	12	0.0090
Parameters for new generation at node 2			11	0.0080

Table 3-1. System parameters

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[6] Generator cost parameters were obtained from (Okada et al., 2000)

Under these conditions a fixed expansion of 2,000 MW is identified as the most appropriate to alleviate congestion during the full period of 25 years, using $EITSPV$ [7].

Unexpected demand growth rates used for flexible expansion are in Table *3-2*:

Demand behavior	Growth rate
High demand	4%
Medium demand	2%
Low demand	1%

Table 3-2. Unexpected demand growth rates

A flexible expansion will be added on fixed expansion only if evolution of uncertainties favors it. Investment costs for possible expansions are shown in Table *3-3*:

Voltage (kV)	Capital cost (Thousands of dollars/km	Capacity (MW)	Cost (Thousands of dollars /MW-km)
230	298	350	0.85
345	559	900	0.62
500	745	2,000	0.37
765	1,118	4,000	0.28

Table 3-3. Transmission investment according line capacity. Adapted from(Hirst & Kirby, 2001)

After a fixed expansion of 2,000 MW, the system shown in Figure *3-4* has the following conditions (Table *3-4*):

---

[7] As it was aforementioned $EITSPV$ is estimated from differences among forecasted total surplus produced by a proposed expansion and forecasted total surplus from a base case, then those differences are expressed in terms of present worth. A 2000 MW expansion produced the maximum $EITSPV$.

Condition	**Node 1**	**Node 2**
Demand (MW)	513.9	2,507
Generation (MW)	2,009	1,011.9
Price ($/MWh)	$99.4	$99.4
Consumer surplus ($ M)	$ 46.3	$2,202.2
Producer surplus ($ M)	$787	$387.6
Congestion rent ($ M)	$0	
Total surplus ($ M)	$3,423.1	
Line capacity (MW)	2,000	
Line length (km)	300	
Flow 1-2 (MW)	1,495.1	

Table 3-4. Starting conditions for flexible expansion analysis

A flexible expansion of 350 MW on fixed expansion of 2,000 MW was evaluated applying real options. Volatilities were calculated using Monte Carlo simulation with 600 iterations[8]. Standard deviation σ_t of logarithmic cash flow return Z_t^i is volatility. Figure *3-5* shows the histogram of Z_t^i for the first 8th years of maturity time when only demand growth is uncertain. The rest of volatilities are estimated from corresponding histograms. Volatility shown in Figure *3-5* was estimated using equations (3-1) and (3-2) with t in numerator equals 8, i.e. volatility is for 8 years. U and D factors convert such volatility to 1 year using equation (3-3).

---

[8] The focus of this research is the development of a methodology. In this case the number of iterations was reduced to diminish the computer time processing. The impact of this decision is reflected in the estimated value of volatility, and consequently in the defer-option value. In consequence, subsequent researches may improve the estimation of the option value by checking the number of iterations.

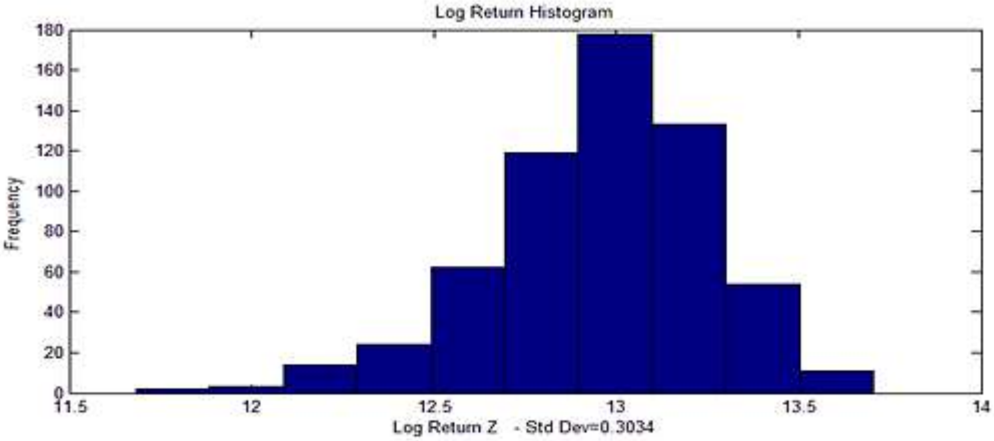

Figure 3-5. Histogram of Z_t^i

Table *3-5* shows input parameters to build binomial trees. Binomial trees are built using $ITSPV$. This is the underlying asset value, S_0, and it is estimated in \$105.5 M for an asset useful life of 25 years. To obtain a value of \$105.4 M of dollars at period zero, first we forecast incremental total surplus between 2350 and 2000 MW through useful transmission asset under scenarios of entrance of new generation and demand growth rate shown in Table *3-1* and Table *3-2*, and after, we bring to present those values using a social discount rate of 10%. Investment in terms of social cost equals \$89.4 M[9].

There are two columns in Table *3-5*, one for estimation of volatility under case A and the other one for case B. Parameters identified with number 1 are referred to the first part of both binomial trees (first 8th years of maturity time of the option) and they are equal to each other. Parameters identified with number 2 are for the rest of lifetime of the option (last 6 years). Second column includes for each parameter its standard deviation because of the way volatility was calculated, i.e. case B requires a Monte Carlo simulation for each terminal node of the first part of binomial tree because conditions in there are different. Each simulation produces volatility, so results are summarized by a mean and standard deviation. For case A, we take a geometric mean of those parameters. Case B volatility is for a period of 6 years (because is the rest of lifetime of the option), so it is converted to volatilities for one year in order to estimate U2 and D2 factors. P2 and P1 are

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[9] This value is obtained multiplying line length from *Table 3-4* and investment value from *Table 3-3*.

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probabilities adjusted by risk to solve binomial tree in the second and first part, respectively. Factor Rf represents risk free rate.

For simplicity, we use results from case A because results of Table *3-5* present a low standard deviation for case B, so it is not necessary to use this second approach. This second approach will be useful when there be multiple uncertainties affecting in different periods.

Description	Estimation of volatility under case A	Estimation of volatility under case B
Total surplus present value ($ Millions of dollars) – Underlying asset value, So	$105.5	$105.5
Investment ($ Millions of dollars)	$89.4	$89.4
Volatility 1	30%	30%
Volatility 2	24.8%	24.8% (geometric mean) 0.006 (standard deviation)
U1	1.11	1.11
U2	1.11	1.11 (mean) 0.003 (std. dev.)
D1	0.89	0.89
D2	0.9	0.9 (mean) 0.002 (std. dev.)
p1	0.61	0.61
P2, mean	0.62	0.62 (mean) 0.004 (std. dev.)
Rf	0.03	0.03

Table 3-5. Input parameters for binomial trees. Expansion to 2350 (350 MW flexible)

A representation of evolution of total surplus, S_0, through the time is shown in *Figure 3-6*. For a better reading, the figure is divided in 4 parts; each of these parts is shown separately for details

(See *Figure 3-7*, *Figure 3-8*, and *Figure 3-9*). Binomial tree is non-recombining because of two values of U and D of Table *3-5*. U and D factors, identified with number 1 in the Table *3-5*, are used for the first part of the binomial tree when only demand growth uncertainty is considered. Those identified with number 2 are used for the second part of binomial tree when changes in generation cost enter as uncertainty, too. The values at the end of maturity time (year 14) represent possible values that the underlying asset can reach because of uncertainties. Numbers in boxes in *Figure 3-7*, *Figure 3-8*, and *Figure 3-9* represent up and down movements of S_0.

Some binomial trees in Figure *3-8* and Figure *3-9* have values under the boxes, they are penalties. The way to obtain such penalties is not shown here but they can be calculated from forecasted incremental total surplus at each period of the planning horizon. Note that penalties appear on upper part of the tree because those places are high demand scenarios where congestion occurs and expansion is required.

In each stage of this non-recombining binomial tree is necessary to subtract penalties and investment, i.e.:

$$\mathrm{NV_{t,j}} = \mathrm{PV_{t,j}} - \mathrm{X_t} - \mathrm{penalties} \qquad (3\text{-}14)$$

The result will be used in equation (3-5) to determine option value ($OV_{t,j}$). Although these net values are not shown here, they will be useful because indicate what would be the net social welfare if investment were made at a given period. It is possible to obtain a number of cases where a lost in social welfare could exist if investment is made at that time.

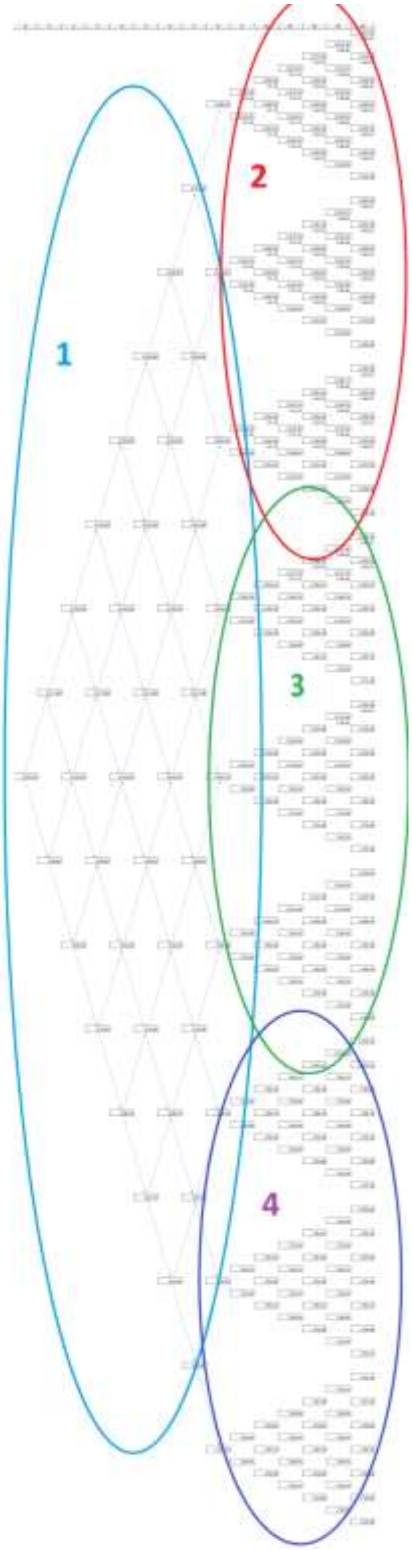
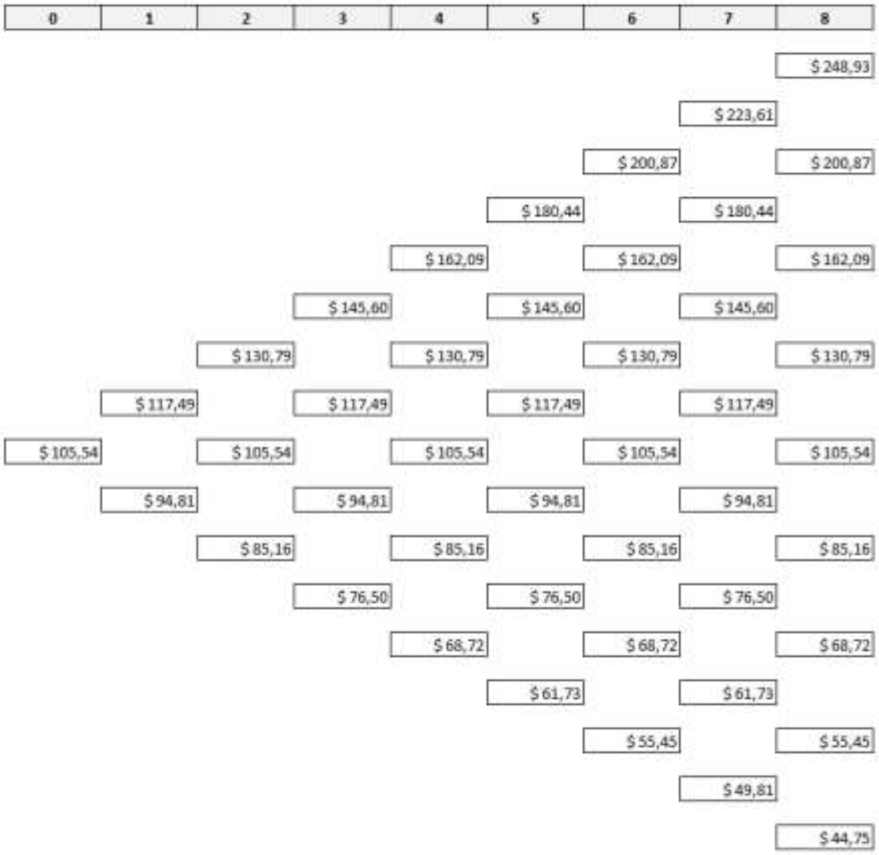


Figure 3-6. Binomial tree for the binodal electric system



0	1	2	3	4	5	6	7	8
								$ 248,93
							$ 223,61	
						$ 200,87		$ 200,87
					$ 180,44		$ 180,44	
				$ 162,09		$ 162,09		$ 162,09
			$ 145,60		$ 145,60		$ 145,60	
		$ 130,79		$ 130,79		$ 130,79		$ 130,79
	$ 117,49		$ 117,49		$ 117,49		$ 117,49	
$ 105,54		$ 105,54		$ 105,54		$ 105,54		$ 105,54
	$ 94,81		$ 94,81		$ 94,81		$ 94,81	
		$ 85,16		$ 85,16		$ 85,16		$ 85,16
			$ 76,50		$ 76,50		$ 76,50	
				$ 68,72		$ 68,72		$ 68,72
					$ 61,73		$ 61,73	
						$ 55,45		$ 55,45
							$ 49,81	
								$ 44,75

Figure 3-7. Section 1 of fig. 3-6 (Values are in millions of dollars)

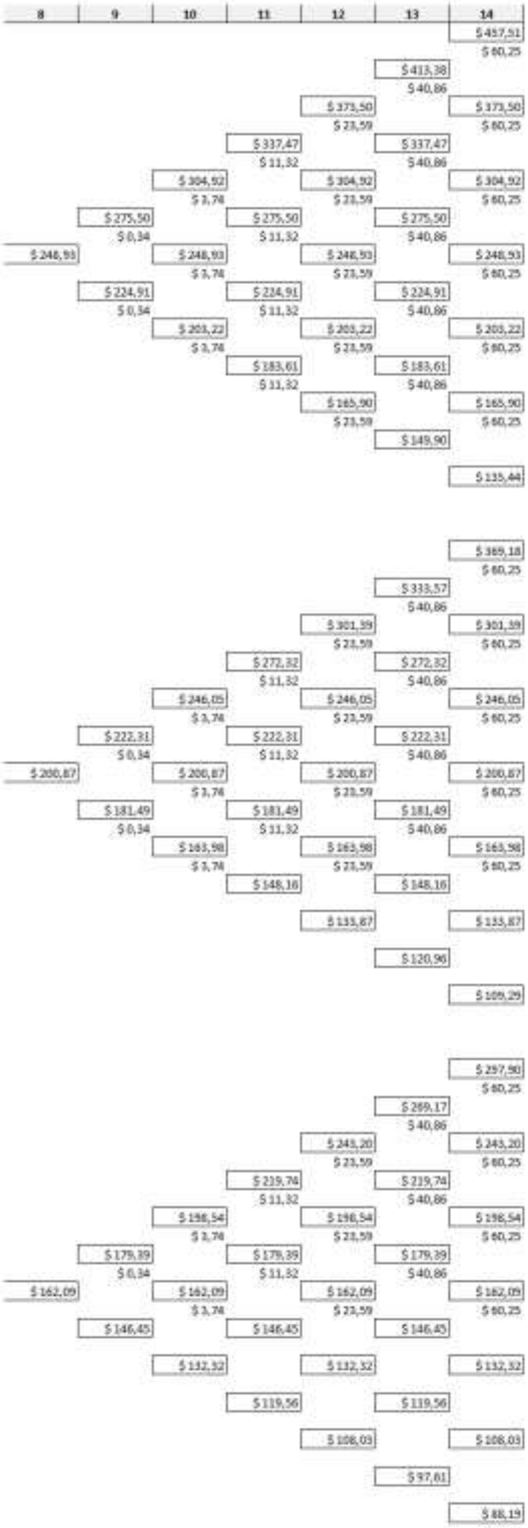


Figure 3-8. Section 2 of fig. 3-6 (Values are in millions of dollars)

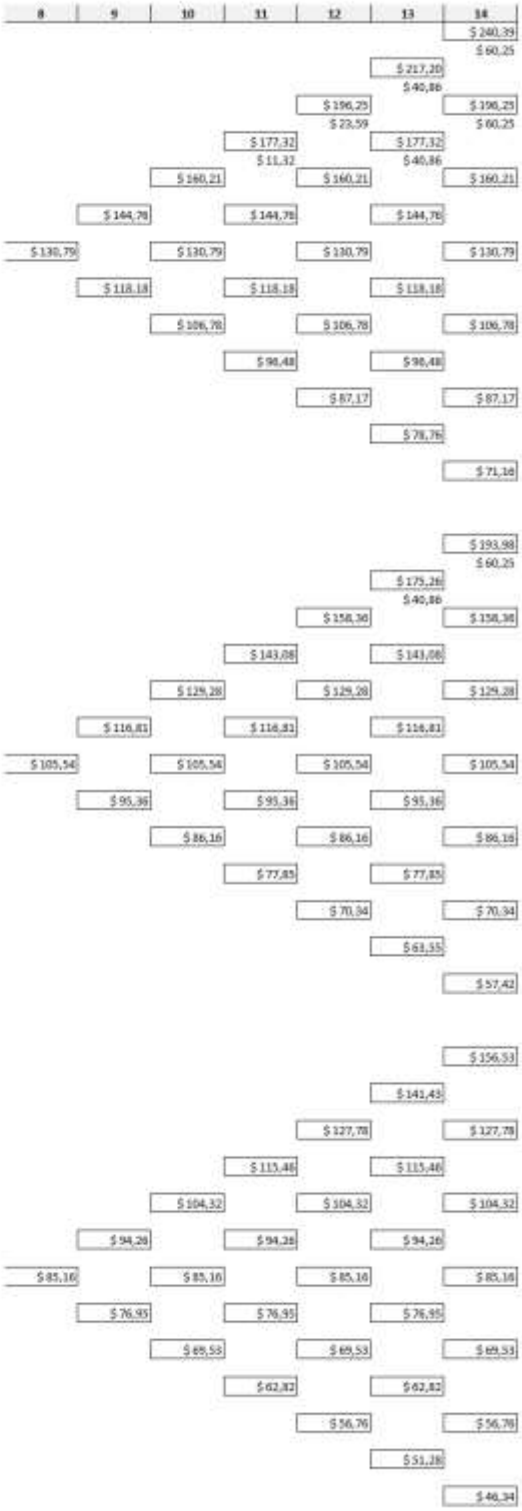


Figure 3-9. Section 3 of fig. 3-6 (Values are in millions of dollars)

8	9	10	11	12	13	14
						$ 126,31
					$ 114,12	
				$ 103,11		$ 103,11
			$ 93,17		$ 93,17	
		$ 84,18		$ 84,18		$ 84,18
	$ 76,06		$ 76,06		$ 76,06	
$ 68,72		$ 68,72		$ 68,72		$ 68,72
	$ 62,09		$ 62,09		$ 62,09	
		$ 56,10		$ 56,10		$ 56,10
			$ 50,69		$ 50,69	
				$ 45,80		$ 45,80
					$ 41,38	
						$ 37,39
						$ 101,92
					$ 92,09	
				$ 83,21		$ 83,21
			$ 75,18		$ 75,18	
		$ 67,93		$ 67,93		$ 67,93
	$ 61,37		$ 61,37		$ 61,37	
$ 55,45		$ 55,45		$ 55,45		$ 55,45
	$ 50,10		$ 50,10		$ 50,10	
		$ 45,27		$ 45,27		$ 45,27
			$ 40,90		$ 40,90	
				$ 36,96		$ 36,96
					$ 33,39	
						$ 30,17
						$ 82,34
					$ 74,31	
				$ 67,14		$ 67,14
			$ 60,66		$ 60,66	
		$ 54,81		$ 54,81		$ 54,81
	$ 49,52		$ 49,52		$ 49,52	
$ 44,75		$ 44,75		$ 44,75		$ 44,75
	$ 40,43		$ 40,43		$ 40,43	
		$ 36,53		$ 36,53		$ 36,53
			$ 33,01		$ 33,01	
				$ 29,82		$ 29,82
					$ 26,95	
						$ 24,35

Figure 3-10. Section 4 of fig. 3-6 (Values are in millions of dollars)

To estimate the value of the option to defer the expansion until conditions be appropriate, it is necessary to build an option value binomial tree. Again non-recombining tree is huge so it is necessary break it to show it. In Figure *3-11* is shown the first 7 years of option value binomial tree while in Figure *3-12* is shown the rest of lifetime of the option. Figure *3-12* presents three parts, the left part contains nodes one to three from up to down, middle part contains nodes 4 to 6, and right part contains the lower nodes 7 to 9. In order, to build a complete representation of the system Figure *3-11* and Figure *3-12* must be read together, that is the purpose of upper cases at the end of nodes of Figure *3-11* and the beginning of Figure *3-12* because they act as bridges between sections of the diagram. For example, third node from up to down in Figure *3-11* has assigned letter C, so binomial trees in Figure *3-12* with that letter at the beginning are linked with that node, i.e. last binomial tree in left part and first binomial tree in middle part.

In those figures, values in boxes represent option values at each stage. Values at the maturity time of the option (year 14) indicate there are scenarios where it is appropriate to make an additional expansion because their values are greater than zero. These values are obtained applying maximization criterion represented by equation (3-4) but using 14th year instead of 8th year. Values compared are over and under boxes. Values over boxes represent asset net values given by equation (3-14). Values under boxes represent at the end of maturity time, option values if they expire without value, and at earlier periods values to defer the investment until next period, $DV_{t,j}$. Option value at each stage is determined by equation (3-5).

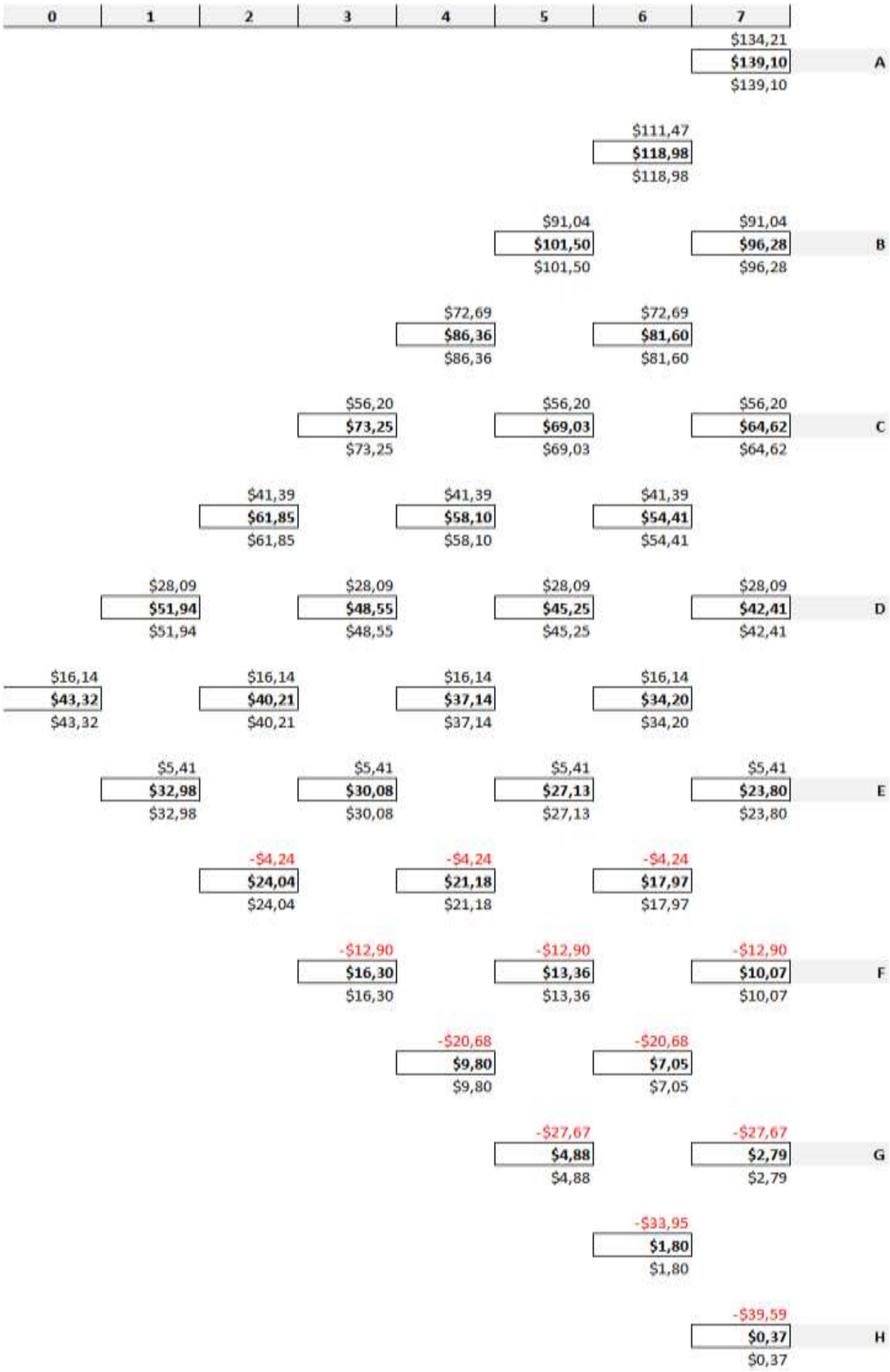


Figure 3-11. Non-recombining binomial tree for option value. First 7 years (Values are in millions of dollars).

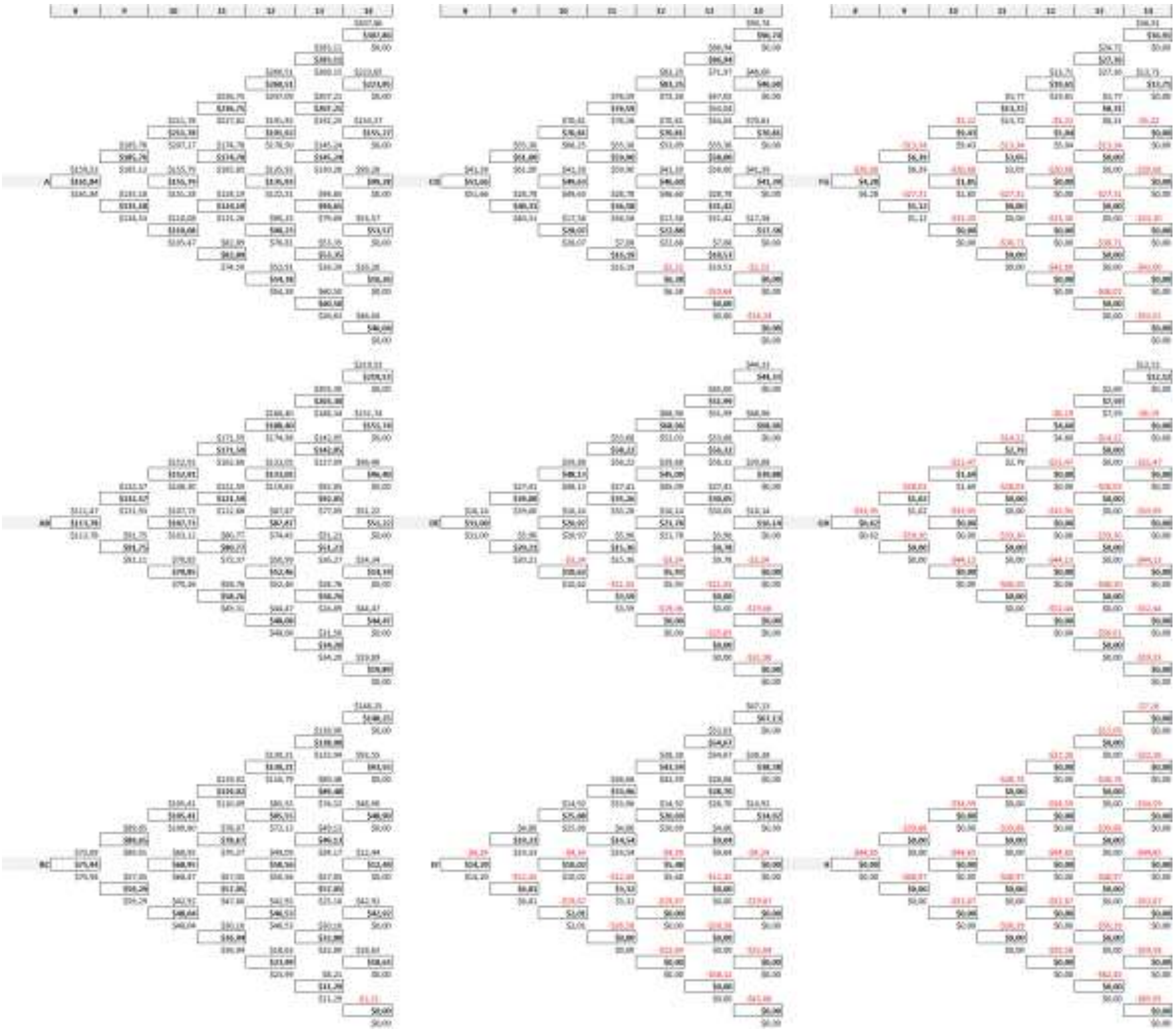


Figure 3-12. Non recombining binomial tree for option value. Years 8 to 14 (Values are in millions of dollars).

Solution of binomial trees produces results in Table *3-6*:

Description	Values
Flexible expansion	350 MW additional to 2000 MW
Project value without flexibility - $PVWF$ ($Millions of dollars)	$16.1

Project value with options - PVO ($Millions of dollars)	$43.3
Option value, $OV_{0,1}$ ($ Millions of dollars)	$27.2
Probability to make flexible expansion, PFE	0.6

Table 3-6. Results flexible expansion

If a planner decides to make an additional expansion of 350 MW at period zero, project net present value will be $16.1 M (in terms of total surplus, this value is located over box at period 0 in Figure *3-11*). In contrast, if a planner decides to defer the expansion, its project value increases to $43.3 millions of dollars (Table *3-6*). This result suggests waiting until conditions would be appropriate to expand. The value of the option to defer additional investment is obtained subtracting row 2 from row 3 in Table *3-6*, so the option value is $27.2 millions of dollars. The planner would find interesting this value if additional initial adaptations over fixed investment cost less than $27.2 millions of dollars. If this were true, the planner would make such additional adaptations in order to make flexible its initial decision. Under scenario of Table *3-2*, probability to exercise an expansion option is 0.6.

Figure 3-13 shows decisions according option value in each stage of binomial tree. Left figure represents upper part of binomial tree and the right one the lower part. We use a color code to represent decision to wait (yellow), to execute (green) or no execute (red).

At period 0 it is better to wait to make a flexible expansion, so this is expressed in the figure. Some boxes present decision with no color to represent that a final decision was made in earlier periods so it is not necessary to extend the analysis after that period.

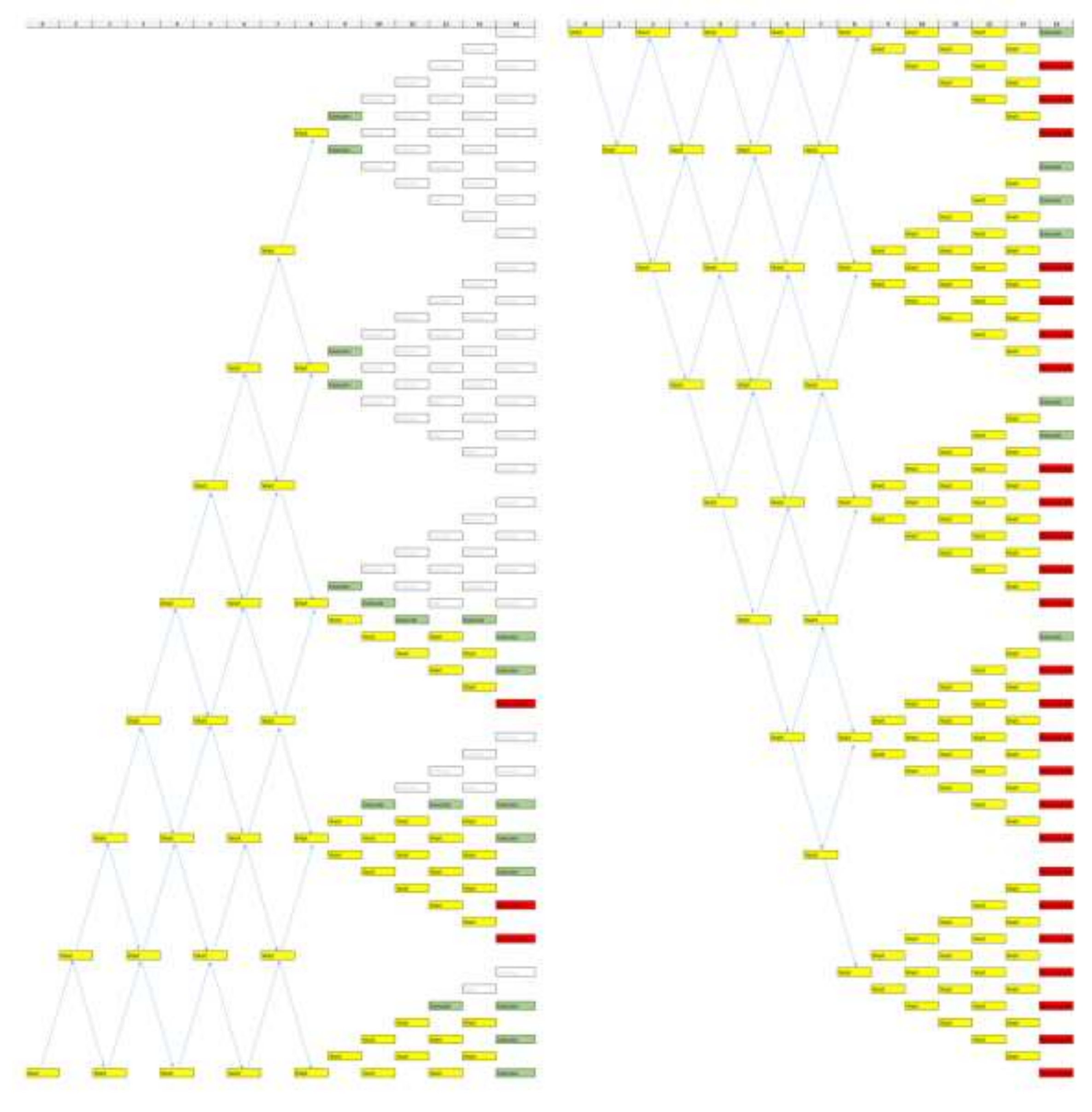


Figure 3-13. Decision according to option value.

3.4. Sensitivity analysis

Different unexpected demand growth rates and flexible expansions were evaluated to estimate how they affect option values.

A first scenario of unexpected low demand considers 1, 2 and 3% demand growth rates for pessimistic, normal and optimistic future demand scenarios, respectively. A second scenario of unexpected high demand considers 1, 2, and 5% demand growth rates for pessimistic, normal and optimistic future demand scenarios, respectively. A base scenario of unexpected normal demand is the same as Table *3-2*. Flexible expansions of 900 MW and 2000 MW are included[10]. For reference 350 MW is included, too.

Sensitivity analysis results are in Table *3-7*:

Flexible expansion **Demand growth rates**	350 MW	900 MW	2000 MW
Scenario 1 (1-2-3% demand growth rates)			
$PVWF$ **($Millions of dollars)**	(-$48.5)	(-$115.6)	(-$171.3)
PVO **($Millions of dollars)**	$1.4	$0.1	$5.5
$OV_{0,1}$ **($Millions of dollars)**	$49.9	$115.7	$171.3
PFE	0	0	0
Volatilities	33% (first part) 27.5% (second part)	32% (first part) 24.8% (second part)	32% (first part) 24.8% (second part)
Base Scenario (1-2-4% demand growth rates)			

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[10] These values are selected considering the available data. See *Table 3-3*.

$PVWF$ ($Millions of dollars)	$16.1	$7.7	(-$29.0)
PVO ($Millions of dollars)	$43.3	$57.4	$43.1
$OV_{0,1}$ ($Millions of dollars)	$27.2	$49.6	$72.1
PFE	0.6	0.4	0.21
Volatilities	30% (first part) 24.8% (second part)	28% (first part) 20.8% (second part)	27% (first part) 20.5% (second part)
Scenario 2 (1-3-5% demand growth rates)			
$PVWF$ ($Millions of dollars)	$151.9	$266.1	$329.8
PVO ($Millions of dollars)	$178.5	$305.9	$383.2
$OV_{0,1}$ ($Millions of dollars)	$26.6	$39.8	$53.4
PFE	1	1	1
Volatilities	27% (first part) 24.8% (second part)	27% (first part) 19.6% (second part)	26% (first part) 18.1% (second part)

Table 3-7. Sensitivity analysis results

From Table *3-7*, it is clear that if unexpected demand growth rates moves among 1 to 3% (Scenario 1), it will not be necessary to make additional expansions over fixed investment because all probabilities are zero, indicating that option to defer and after expand if conditions are convenient it will be difficult to achieve.

Under unexpected demand growth rates moving from 1 to 4% (Base scenario). Option more probable to exercise is an expansion of 350 MW on 2000 MW, it follows an additional expansion of 900 MW on 2000 MW and finally, it is an expansion of another 2000 MW on initial 2000 MW. If this scenario were sure, the best selection would be a flexible expansion of 900 MW over 2000 MW, but there is no certainty about the occurrence of that scenario.

It is possible that scenario 2 (1-3-5% demand growth rate) occurs, so the best flexible expansion would be additional 2000 MW because its PVO is greater than the others, $383.2 millions of dollars (Table *3-7*).

An interesting interpretation of option value is deducted under scenario 1. We see that probabilities of all flexible expansions are zero. Assume there are two planner, planner 1 decides to expand 900 MW at the same time that 2000 MW of fixed expansion, while planner 2 decides to defer such investment until conditions be appropriate. If underlying asset evolves under scenario 1, such flexible expansion will not be necessary, so planner 2 saved $115.7 M but the planner 1 lost $115.6M. According to this option value can be interpreted as an opportunity cost.

Differences in volatility are explained by the following reason:

System under expansion to 2000 MW tends to congest at period 12 if demand grows at high rates permanently. An expansion of additional 350 MW delays congestion until period 17 if demand grows at high rates. If additional expansion is 900 MW, congestion will not appear until period 24 as long as demand grows at high rates permanently. If additional expansion is 2000 MW congestion never occur during asset useful life. Congestion reduces total surplus, so an additional expansion of 350 MW will have lowest expected present value. During Monte Carlo simulation this lowest value will have the chance to achieve more dispersion than the others before congestion occur. This explain why, in most cases, 350 MW has the greatest volatilities

Another sensitivity analysis includes a different change in generation cost. Results shown above were achieved using parameters of Table *3-1*. Those parameters can or cannot change. If they change, they can be those shown below (Table *3-8*), and results under base scenario are shown in Table *3-9*:

Scenario	d	e
Higher cost	11	0.01
Lower cost	11	0.008

Table 3-8. Parameters for sensitivity analysis about generation cost (Okada, Kitamura, Asano, Ishimaru, & Yokoyama, 2000)

Flexible expansion **Change in gen. cost**	350 MW	900 MW	2000 MW
Higher cost			
$PVWF$ ($Millions of dollars)	$24.5	$22.7	(-$10.6)
PVO ($Millions of dollars)	$51.2	$71.1	$57.0
$OV_{0,1}$ ($Millions of dollars)	$26.8	$48.4	$67.6
PFE	0.61	0.61	0.4
Lower cost			
$PVWF$ ($Millions of dollars)	$16.1	$7.7	(-$29.0)
PVO ($Millions of dollars)	$43.2	$57.4	$43.1
$OV_{0,1}$ ($Millions of dollars)	$27.1	$49.6	$72.1
PFE	0.6	0.4	0.21

Table 3-9. Sensitivity analysis results about generation cost

Higher cost in new generation produces rise in equilibrium prices when there is not congestion, it increases differences between nodes when there is congestion, and it accelerates the arrival of congestion to the system. These combined effects are reflected in greater values of $PVWO$ in comparison with lower cost in new generation. Since option value remains approximately equal in all cases, in consequence PVO increases, too.

Greater values in probability for expansions of 900 and 2000 MW are explained by an increase in the number of nodes at the end of binomial tree where the option to expand is convenient.

Finally, we performed an experiment ignoring all penalties due to delaying the investments. Repeating the previous experiments without including penalties we get the results that PVO without penalties are larger than when including penalties because there is an incentive to wait until the end of the maturity time when ignoring penalties (because option value is greater at that time). When including penalties, by the contrary, there more incentives to invest before since the penalties reduce the option value.

3.5. Chapter Conclusions

The existence of uncertainty in power system strategic decisions may induce that initial decisions of transmission investment be inappropriate in the future. Accordingly, a change in the way transmission investment decisions are made, moving from DCF-based approach to a more flexible approach, may increase the investment project value. Real Options (RO) can help us to estimate this value. Social welfare can increase if the initial investment in transmission assets has adaptability in the capacity added, according to the realization of uncertain events. The network planner should assume the cost of implementing a flexible investment scheme if this cost is smaller than the value of the investment-defer option. RO gives us an idea about much to pay in addition to the initial fixed investment to endow the TEP process with the capability of adaptability.

Our analysis is based on four assumptions: first, we suppose new transmission assets are available one year after expansions are decided. Further analysis can be done exploring the uncertainty in the transmission construction time and its effect on the option value. Second, we assume a single transmission investment is made. As future extension, we may analyze an investment portfolio. Third, we assume the capacity of additional flexible investment is known from the beginning. Future research may analyze the optima capacity of the additional flexible investment as the outcome of an optimization formulation. Finally, we assume the binomial tree represents the paths followed by the underlying asset. Future extensions may compare this approach with others.

CHAPTER 4

4. Estimating the value of the option to defer an investment in Transmission Expansion Planning in Colombia using Real Options

Abstract

This chapter seeks for estimating the value of introducing flexibility in the Colombian Transmission Expansion Planning using a Real Options (RO) methodology applied to a reduced version of Colombian Transmission System. To introduce flexibility, the transmission expansion process is divided in two parts: The first one is a fixed expansion that behave well on expected evolution of demand growth rate and the second one is an expansion additional to the first one that acts as an adapting mechanism according to circumstances (i.e., a flexible expansion). An optimal power flow algorithm is applied to evaluate system performance and to establish contributions of transmission expansion in total surplus. We estimate the value of an option to defer the flexible expansion using as underlying asset value the present value of incremental total surplus due to such expansion. The value of the option to defer is determined based on a binomial tree technique, where its volatility is estimated using Montecarlo simulation. Our results show that introducing flexibility in the Colombian Transmission Expansion Planning increases the value of social welfare. This value increment represents an upper bound of the potential investment costs intended to provide adapting ability to the power system.

4.1. Introduction to the chapter

Transmission Expansion Planning, TEP, plays and will continue playing a key role in all countries around the world because of requirements of interconnection between load centers and generation units, especially as a mechanism of renewable energy integration (F D Munoz et al., 2014) and meeting public policy goals (Konstantelos & Strbac, 2015). However, nonstop demand growth and increasing penetration of renewable energies[11] due to a greater demand of regulation pose new challenges to electrical systems aggregating sources of uncertainties (Quintero, Zhang, Chakhchoukh, Vittal, & Heydt, 2014). In consequence, approaches to address uncertainties in TEP are required. Flexibility and robustness are important approaches to address uncertainties in this field (Andrews, 1995).

Flexibility in TEP is defined as the ability to adapt quickly and without greater costs a specific blueprint designed under some assumed future conditions, to any change in such conditions (Latorre et al., 2003).

Flexibility can be achieved from an operational point of view through changes in the configuration of the network (Sener, 1996)[12], and from a strategic perspective when expansion projects let to apply options like delaying investment until more information is available. A flexible plan can be reached by models like adapting cost, multistage stochastic optimization and real options; the latter also allows capturing flexibility value.

This chapter is organized as follows: section 2 describes Colombian electric system, its simplified model, and the process of Colombian power system expansion planning. Section 3 explains the methodology. Section 4 shows results obtained. Finally conclusions are presented in section 5.

4.2. Colombia's Power Sector Description

The Colombian power system is organized as shown in Table *4-1* (UPME, 2013):

Management and Policy	**Ministry of Mines and Energy**
Planning	Mining and Energy Planning Unit (UPME)

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[11] Uncertainties come from type, size, intermittency of renewables and short lead time to build facilities in comparison with conventional plants, then the network planner is not full-informed to make decisions about long term investments (Konstantelos & Strbac, 2015).

[12] According to the author, changes in configuration network comprise: 1) Circuits added or deleted, 2) a phase angle inserted into the network, 3) changes in circuit impedance, 4) changes in network nodes, 5) open or close circuit breakers.

Regulation	Energy and Gas Regulatory Commission (CREG)
Surveillance	Superintendent of Public Utilities
System Operation and Market Administration	XM – Market experts
Technical Consulting	Planning Advisory Committee of Transmission (CAPT). National Operation Council – (CNO). Advisory Committee for Coordination and Follow Country Energy Situation (CACSSE).

Table 4-1. Colombian electric system organization

Next, we list the key agents of the power sector in Colombia and describe their roles (those listed in Table *4-1*):

- Ministry of Mines and Energy defines interconnection network expansion plans according to National Development Plan and Energetic National Plan, and it prepares the document selecting the execution of transmission expansion projects, among others.
- UPME is a national administrative unit of technical nature; it is assigned to Ministry of Mines and Energy. UPME has to make and update a number of plans related with mines and energy in Colombia, among them, the Energetic National Plan and the Electric Expansion Plan; all of them have to be aligned with National Development Plan.
- CREG is a technical entity, its goal is to achieve that most people receive services like electric energy, natural gas and liquid petroleum gas at low cost, but with an appropriate remuneration to suppliers.
- Superintendent of Public Service is a technical institution that exerts control, inspection and surveillance of entities providing public services.
- XM is a subsidiary of the ISA business group, responsible for providing planning services and coordination of the operation of resources of the SIN and management of power trading system in the wholesale market. Settlement and administration charges for using national networks interconnected system is a function of XM, too.
- CAPT is an UPME assessor committee with participation of representatives of large energy intensive consumers, marketers and transmission companies. Its function is to agree on issues dealing with criteria, strategies and methods for National Transmission System - STN expansion. In addition, CAPT selects the supervision firm for transmission projects in execution.

- CNO for electricity sector is an independent entity not assigned to any governmental institution and it has as main function to agree on technical issues for ensuring a secure, reliable and economical operation of SIN.
- CACSSE acts as activities coordinator among governmental entities to cover electric demand, to do that it tracks key variables and expansion plans to proposes policies and actions to diminish electricity rationing probabilities (UPME, 2015).

The SIN is an electric system constituted by generation units, interconnection networks, regional and interregional transmission networks, distribution networks and user's electric loads (CREG, 2001). SIN has been divided into six areas and its corresponding subareas taking into account network constraints, such constraints force generation in such regions or limit trade with the rest of SIN regions. Areas and subareas are shown in Table *4-2* (XM, 2014). These areas are the base for the system simplification we use in this research:

SIN Areas	Subareas
Caribe I	Cordoba-Sucre
	Cerromatoso
Caribe II	Atlántico
	Bolivar
	GCM (Guajira-Cesar-Magdalena)
Northeast	CENS
	Bucaramanga
Antioquia	Antioquia
	San Carlos
Center	Bogotá
	Tolima
	Meta
Southwest	CQR
	Valle
	Cauca - Nariño

Table 4-2. Areas and subareas SIN

Colombia has a total generation capacity of 15 thousands of MW, two thirds of them come from hydroelectric plants (Table *4-3*) (XM, 2015):

Source	MW	%
Hydraulic	10,315	64.0
Thermal	4,402	31.0
Smaller plants (<=20MW)	694.7	4.5
Cogeneration	77.3	0.5
Total generation capacity	15,489	100.0

Table 4-3. Composition of generation capacity in Colombia

SIN has approximately 24 thousands of km of transmission lines, 57% belongs to STN. STN is an interconnected transmission system constituted by a set of transmission lines with their connection modules. Its operation condition is at least 220 kV (CREG, 2001). Those transmission lines below 220 kV that do not belong to Local Distribution System (SDL) are considered a Regional Transmission System, STR.

The following figure shows percentage distribution of STN lines:

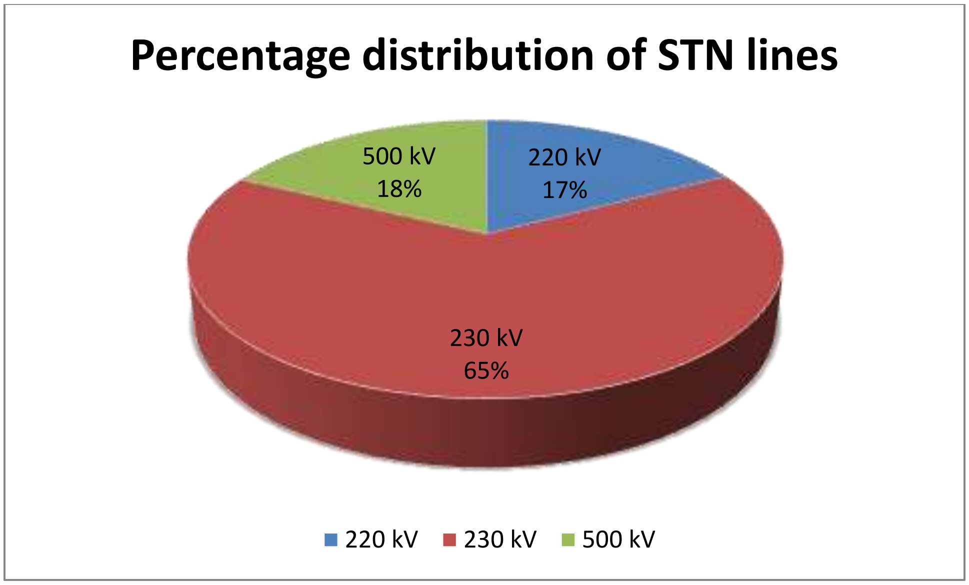

Figure 4-1. STN lines - Source: Adaptation from (XM, 2014)

The last expansion plan for generation and transmission elaborated by UPME (UPME, 2016) states that until year 2021, the Colombian system does not require additional installed capacity in generation taking into account demand forecasting for energy. However, the plan considers penetration of renewable energy from Guajira, in particular, 3,131 MW of eolic energy are projected to enter during 2015-2029 so it is necessary developing of new infrastructure to take advantage of this projection.

4.2.1. Simplification of National Interconnected System – SIN

We use a simplified representation of Colombian SIN modeled by (Pozo & Molina, 2013). SIN was modelled using six nodes, those nodes contains load centers and main generation units. Historical data of energy produced and its price taken from XM web page were considered by cited authors to build the model. We update the original model including generation units 18 and 19 at nodes 2 and 3 because they correspond to generation expansion until 2015. The system is shown in Figure *4-2*.

Localization of generation units and their capacity are shown in Table *4-4*, a minimum difference exists between generation capacity modeled and official data reported in Table *4-3* (less than 1%), which is not relevant for the purpose of this research work. Transmission lines properties and starting and terminal nodes are shown in Table *4-5*. Total system load at the beginning and its distribution by nodes are shown in Table *4-6*.

Generator	**Type**	**Node**	**Marginal Cost (USD$/MWh)**	**Max Power (MW)**
Unit 1	Coal	1	98.6	290
Unit 2	Gas	1	399.4	2,127
Unit 3	Gas	1	465.6	187
Unit 4	Hydro	2	232.5	550
Unit 5	Coal	3	83.5	315
Unit 6	Hydro	4	180.7	2,949.8
Unit 7	Gas	4	636.9	485
Unit 8	Hydro	4	190.9	1,806
Unit 9	Gas	4	392.5	278
Unit 10	Hydro	5	144.8	1,894.6
Unit 11	Coal	5	85.1	225
Unit 12	Hydro	5	207.7	1000
Unit 13	Gas	5	28.6	50.7
Unit 14	Hydro	6	1,230.4	881.9
Unit 15	Gas	6	142	205
Unit 16	Gas	6	621.4	230.9
Unit 17	Hydro	6	239.2	945
Unit 18	Coal	2	89.1	414.0
Unit 19	Hydro	3	369.7	800.0
Total				15,635

Table 4-4. Generation units' properties

Line	Max flow (MW)	Reactance X (p.u.)	Starting Node	Final Node
L1	1200	0.0423	1	3
L2	1300	0.0209	1	2
L3	1300	0.0316	2	4
L4	500	0.1381	3	5
L5	400	0.0602	4	3
L6	200	0.1604	4	3
L7	800	0.033	4	3
L8	700	0.0261	4	5
L9	300	0.0452	4	4
L10	250	0.0648	4	6
L11	250	0.0994	4	6
L12	550	0.027	4	6
L13	215	0.1018	5	6
L14	215	0.2182	5	6

Table 4-5. Transmission lines' properties

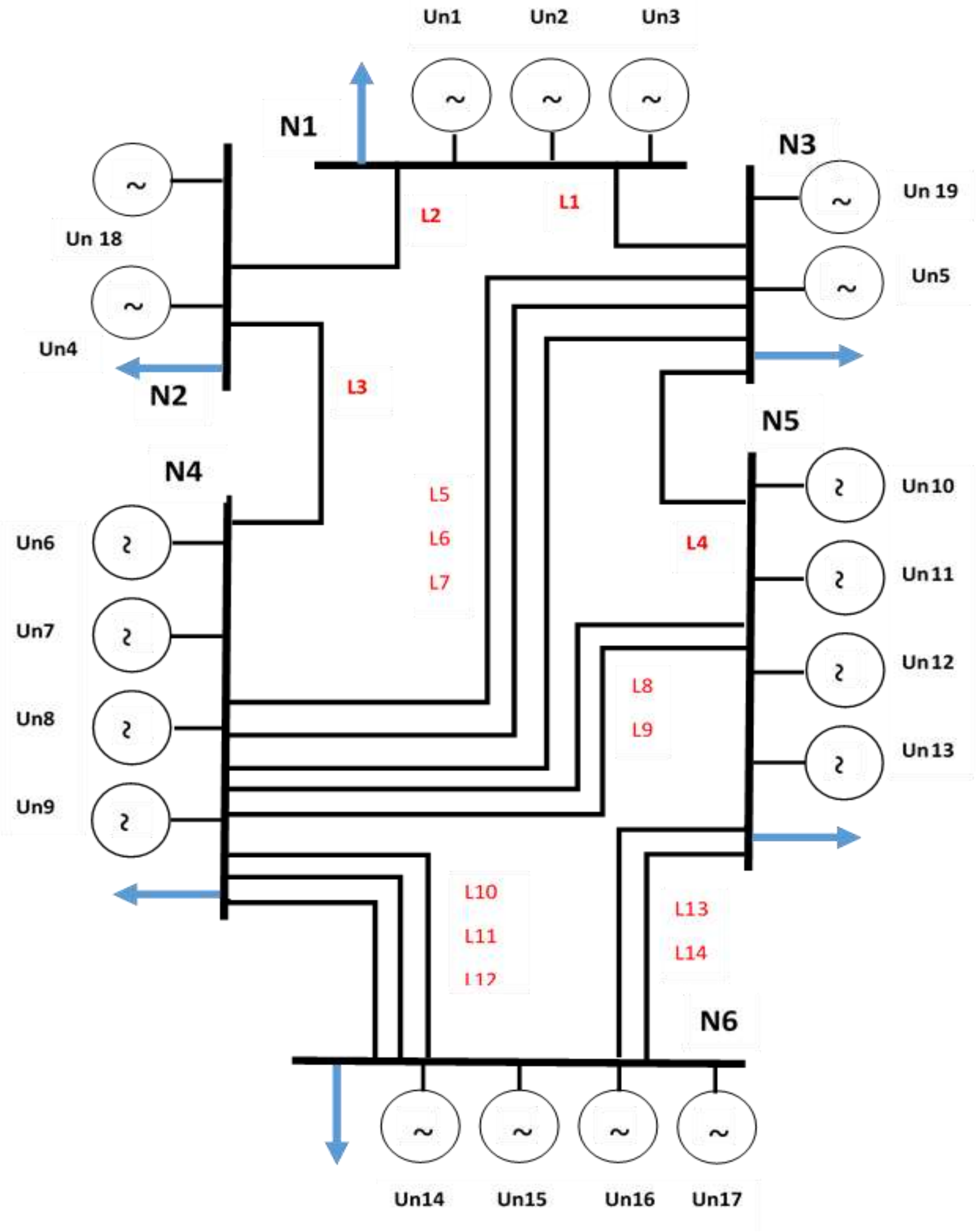

Figure 4-2. Simplified Colombian Interconnection System

Node	Load (MW)
Node 1	1990.3
Node 2	141.8
Node 3	772.4
Node 4	1773.9
Node 5	2821
Node 6	1940.2
Total (MW)	9439.6

Table 4-6. Loads

4.3. Methodology

4.3.1. Real Options

Real Options approach does not assume that managerial decisions are static during the planning horizon, so we apply this approach. To apply this approach our assumptions are below:

- Colombian power system can be represented by 6 load and generation centers as shown in Figure *4-2*.
- Demand growth rate moves from 2.0 to 2.7% because forecasted data utilized by UPME are from 2.4 to 2.5% for a planning horizon, T, from 2014 to 2028[13].
- Planning horizon T, is considered as a maturity time of the option for estimation of flexibility value. Planning horizon is 14 year.
- Demand in Colombia is highly inelastic, elasticity is averaged in 0.22 from 1999 to 2014 (UPME, 2014). In consequence, it implies insensitivity to generation costs and it behaves as price-taker so it cannot influence conditions to build prices. This situation let us to assume demand constant relative to prices at each node of the system.
- Analyses are based assuming a fixed load at maximum level during each year of planning horizon. Load growth rate is uncertain from one year to the next.
- Energy prices are constant over time.
- We consider a discrete set of alternatives for both fixed expansion and flexible expansion.
- There is not load curtailment so demand is covered completely and the system is reliable, neither loss of energy are considered.
- Only uncertainty in demand growth is considered.
- The energy dispatch model uses a DC approximation of Kirchhoff's laws.

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[13] Table 2-2 in (UPME, 2014)

- Only expansions based on conventional transmission assets (e.g. transmission lines) are considered and their lead time is one year, which means a planner must to decide an expansion one year before such expansion is available.
- Generation expansion projected in (UPME, 2014) are included in the Matlab code to be considered in the long term. Characteristics of these expansions and their entry dates are on Table *4-7* (year 2015 is t=0).Those expansions corresponds to Termonorte at node 1 in 2018 and Ituango at node 4 in 2018 and 2022, both are new generation units, but for simplicity we added them to existing units (termonorte to unit 2 and Ituango to unit 6).

Generation units	Capacity added (MW)	Final capacity (MW)	Available from
Unit 2	88	2,215	2018 (t=3 in Matlab code)
Unit 6	352	3,301.8	2018 (t=3 in Matlab code)
Unit 6	2,400	5,701.8	2022 (t=7 in Matlab code)

Table 4-7. Generation expansion projected

In order to build a base line and to diagnose performance of the system described by Figure *4-2*, load at each node (Table *4-6*) is projected over planning horizon. Demand growth rate used to forecast future values of node loads are 2, 2.5 and 2.7%. At each period an Optimal Power Flow (OPF) algorithm is applied to establish quantities produced by generators, flows throughout lines and marginal prices at each node. Equations describing OPF are shown in the following:

$$\min_{q_i, f_l, \delta_n} \sum_{i \in I} C_i * q_i \tag{4-1}$$

S.T:

$$\sum_{i \in I_n} q_i + \sum_{l \in L} \Gamma_{ln} f_l = d_n, \quad \forall n \, \epsilon \, N \tag{4-2}$$

$$f_l = \frac{S_b}{x_l} \sum_{n \in N} \Gamma_{ln} \, \delta_n, \quad \forall l \, \epsilon \, L \tag{4-3}$$

$$-F_l^{max} \leq f_l \leq F_l^{max}, \quad \forall l \, \epsilon \, L \tag{4-4}$$

$$0 \leq q_i \leq Q_i^{max}, \quad \forall \mathrm{i} \tag{4-5}$$

$$-\frac{\pi}{2} \leq \delta_n \leq \frac{\pi}{2}, \quad \forall n \tag{4-6}$$

$$\delta_1 = 0 \tag{4-7}$$

Where:

i: Generator index, $i \in \{1,\ 2, \dots, 19\}$

n: Node index, $n \in N = \{1,2, \dots ,6\}$

I_n: Set of producers in node n.

I: Set of producers.

L: Set of transmission lines.

l: Line index.

C_i: Marginal cost of generator i.

δ: Voltage in node n.

d: Load in node n.

F_l^{max}: Maximum capacity of line l.

Q_i^{max}: Maximum power given by generator i.

Γ_{ln}: Line to node Incidence matrix.

q_i, f_l, δ_n: Decision variables (Quantity to produce by generator i, flow through line l, and voltage in node n, respectively).

Results obtained allow us to identify places where transmission expansion is useful because limits on capacity lines are reached. We estimate characteristics of new lines to add via adjusting a curve from data of the Table *4-5* and estimating their values from curve equation (Pozo et al., 2013), this approach allows us to include lines in concordance with current system.

The transmission expansion process is divided in two parts to incorporate flexibility: The first one is a fixed expansion that behave well on normal evolution of system conditions and the second one is an expansion over the first one that acts as adapting mechanism according to circumstances. We call this second expansion a flexible expansion.

To determine the size of fixed expansion several alternatives are included in places where lines are congested and their performance is evaluated in terms of their contributions in total surplus of the system. This evaluation implies to forecast the performance of each alternative over planning horizon and under each defined demand growth rate. Incremental total surplus is estimated at each year of planning horizon and its present value is obtained using a discount rate. Finally, it is computed an expected present value of incremental total surplus, for each alternative. Alternative with the larger expected present value is selected as fixed expansion.

Incremental total Surplus of the system at each time t over planning horizon T, is estimated through the following equations (in USD$/h):

$$\begin{aligned}\Delta TS_t = \sum_n \Delta CS_{n,t} + \sum_n \Delta PS_{n,t} \\ + \left[\left| \left(\sum_n \Gamma_{ln} P_{n,t} \right) * f_l \right|_2 \right. \\ \left. - \left| \left(\sum_n \Gamma_{ln} P_{n,t} \right) * f_l \right|_1 \right] \forall l \in L, \;\; \forall\, t \in \{1, \dots, T\}\end{aligned} \qquad (4\text{-}8)$$

First term of the right expression is incremental consumer surplus $CS_{n,t}$, at node n at time t, the second term is incremental producer surplus $PS_{n,t}$, at node n at time t, and the third term represents the contribution of incremental congestion rent produced by fixed expansion (sub-index 2) and the initial situation (sub-index 1). This term uses prices $P_{n,t}$ at time t. Incremental consumer surplus and incremental producer surplus are estimated by following expressions:

$$\Delta CS_{n,t} = -\left(P_{n,t_2} - P_{n,t_1} \right) * d_n \qquad (4\text{-}9)$$

$$\Delta PS_{n,t} = \sum_{i \in I_n} \left[\overline{(P_{n.t} - C_\iota) * q_\iota}_2 - \overline{(P_{n.t} - C_\iota) * q_\iota}_1 \right] \qquad (4\text{-}10)$$

Sub-indexes 2 and 1 in expressions (4-9) and (4-10) represent fixed expansion and base case, respectively. In addition, summation symbol includes all generator in node n.

To determine flexibility value, we consider an option to defer the flexible expansion additional to the fixed one until uncertainty about demand growth is resolved. To obtain the flexibility value we use a methodology based on Real Options.

The procedure requires to propose a size for the flexible expansion and to estimate the incremental total surplus of flexible expansion under defined demand growth rate.

We consider as underlying asset value (S_0), the expected present value of incremental total surplus of the flexible expansion because its behavior will act as signal to trigger flexible the expansion depending on its option value.

After, we make a Montecarlo simulation to evaluate the flexible expansion, using a base system that includes the fixed expansion. Demand growth rate at each node is the uncertain variable with a triangular distribution over planning horizon. Each simulation produces a projection of solutions of the optimization problem described by equations (4-1) - (4-7). We get incremental total surplus using equations (4-8) - (4-10) but in this case sub-index 2 represents results under flexible expansion plus fixed expansion and sub-index 1 represents a system with only fixed expansion.

When simulation is finished we obtain a matrix of $ns * T$ (where ns: number of simulations and T: planning horizon). These results let us to estimate a volatility factor that will govern evolution underlying asset S_0, through the planning horizon. This evolution is represented by a binomial tree like shown in Figure *4-3*.

Equations to estimate volatility are the following:

$$Z_t^i = ln\left(\frac{PV_t^i}{PV_0}\right)$$

$$\sigma_t = std\ dev.(Z_t^i)$$

$$\sigma_1 = \sigma_t/\sqrt{t}$$

Where:

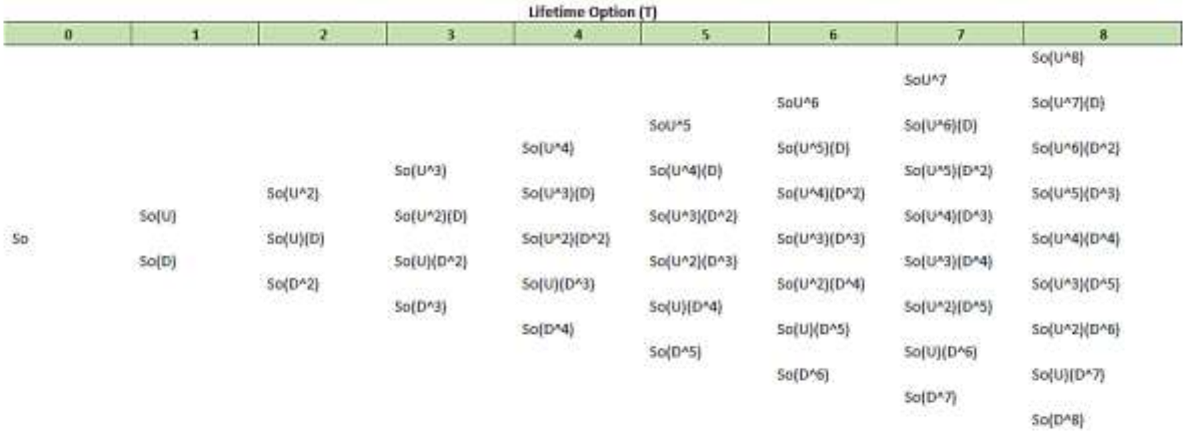
Z_t^i : Logarithmic cash flow return for t years, estimated at Monte Carlo simulation i.

PV_t^i : Present value of the project at period t at Monte Carlo simulation i.

t: It is any time at the future.

σ_t: Variability through time step *t*.

σ_1 : Volatility for one time step.



Lifetime Option (T)								
0	1	2	3	4	5	6	7	8
								So(U^8)
							SoU^7	
						SoU^6		So(U^7)(D)
					SoU^5		So(U^6)(D)	
				So(U^4)		So(U^5)(D)		So(U^6)(D^2)
			So(U^3)		So(U^4)(D)		So(U^5)(D^2)	
		So(U^2)		So(U^3)(D)		So(U^4)(D^2)		So(U^5)(D^3)
	So(U)		So(U^2)(D)		So(U^3)(D^2)		So(U^4)(D^3)	
So		So(U)(D)		So(U^2)(D^2)		So(U^3)(D^3)		So(U^4)(D^4)
	So(D)		So(U)(D^2)		So(U^2)(D^3)		So(U^3)(D^4)	
		So(D^2)		So(U)(D^3)		So(U^2)(D^4)		So(U^3)(D^5)
			So(D^3)		So(U)(D^4)		So(U^2)(D^5)	
				So(D^4)		So(U)(D^5)		So(U^2)(D^6)
					So(D^5)		So(U)(D^6)	
						So(D^6)		So(U)(D^7)
							So(D^7)	
								So(D^8)

Figure 4-3. Binomial tree appearance with δt =1 year and planning horizon of 8 years

In Figure *4-3*, evolution of the underlying asset value, S_0, can go up or down due to the realization of the uncertainties in the model. When the value goes up it is multiplied by a *U* factor, which is a number larger than 1. On the other hand, when the value goes down, it is multiplied by a *D* factor smaller than 1. *U* and *D* are calculated as follows:

$$\mathrm{U} = \exp(\sigma_1\sqrt{\delta \mathrm{t}})$$

$$\mathrm{D} = {}^{1}\!/_{\mathrm{U}}$$

A key assumption in this approach is to establish a planning horizon, T, as maturity time of the option, so at the end of maturity time we can estimate option value.

The last nodes of the binomial tree, i.e. at the end of maturity time, contain the range of possible values that the underlying asset can take when the option expires (These values are from SoU^8 to SoD^8 if $T = 8$ as in Figure *4-3*. To determine the option value to delay flexible expansion until maturity time we use the following maximization criterion:

$$\mathrm{OV}_{\mathrm{T,j}} = \max\{\mathrm{PV}_{\mathrm{T,j}} - \mathrm{X}_{\mathrm{T}} - Penalty, 0\} \qquad (4\text{-}11)$$

Where:

X_t: Exercise price or strike price, i.e. investment needed to obtain the PV of the project at period t.

$\mathrm{PV}_{\mathrm{T,j}}$: Reached value of the underlying asset at time T at node j (the upper node is $j = 1$).

$Penalty$: Lost opportunity cost because not expanding (It will be zero if there is not congestion).

We include a penalty term because congestion reduces social welfare in all markets including electric markets. Penalty magnitude is estimated as incremental total surplus produced by the flexible expansion if such expansion is made in the period of analysis.

By backward induction we obtain option value at each stage of binomial tree until we reach $t = 0$.

Option value ($OV_{t,j}$) for earlier periods than planning horizon are estimated applying the following maximization criterion:

$$\mathrm{OV_{t,j}} = \max\{\mathrm{PV_{t,j}} - \mathrm{X_t} - Penalty, \mathrm{DV_{t,j}}\} \tag{4-12}$$

Where $DV_{t,j}$ is the expected discounted value of not exercising the option in period *t* and waiting until next period to decide:

$$\mathrm{DV_{t,j}} = [\mathrm{p} * \mathrm{OV_{t+\delta t,j}} + (1 - \mathrm{p}) * \mathrm{OV_{t+\delta t,j+1}}]\mathrm{e}^{-\mathrm{Rf}*\delta \mathrm{t}} \tag{4-13}$$

p: it is a probability adjusted by risk (Mun, 2006) and it is estimated by:

$$\mathrm{p} = \frac{\mathrm{e^{Rf}} - \mathrm{D}}{\mathrm{U} - \mathrm{D}}$$

Where R_f is the risk free rate of return.

It is possible to invest a stage t if $PV_{t,j} - X_t > DV_{t,j}$

When $t = 0$ is reached, we obtain a Present Value with Options (PVO) that contains option value to delay flexible expansion. To estimate option value at time 0 ($OV_{0,1}$) we have to subtract from PVO the value of the project without flexibilities, $PVWF$ ($PVWF = S_0 - \mathrm{X}_0$):

$$OV_{0,1} = PVO - PVWF \tag{4-14}$$

4.3.2. Robustness

We use results from equations (4-1) - (4-10) to evaluate the performance of candidate lines in three scenarios of demand growth. At each scenario incremental total surplus provided by candidate lines are estimated. The maximum value of incremental total surplus is selected as optima under the scenario evaluated. After, at each scenario a regret function is estimated for each candidate line:

$$Regret_{i,j} = |\Delta TS_{i,j} - \Delta TS^{*}{}_{j}| \tag{4-15}$$

Where:

$Regret_{i,j}$: Regret function for candidate line i at scenario j.

$\Delta TS^{*}{}_{j}$: Incremental total surplus for optimum at scenario j.

The robust solution is given by:

$$\min_i\left[\max_j(Regret_{i,j})\right] \tag{4-16}$$

4.4. Results

Performance evaluation of system illustrated in Figure *4-2* suggests congestion between nodes 4 and 6, so we evaluate inclusion of new transmission lines in this path. Candidate lines are shown in the following table (Table *4-8*)

Demand Growth Rate	**Total Surplus in millions**			**Optimal value**
	350 MW - Investment $89.4	2,000 MW - Investment $223.5	2,350 MW - Investment $312.9	
2.0% (0.3)	$27,000	**$41,102**	$40,948	**$41,102**
2.5% (0.4)	$27,356	$59,752	**$60,651**	**$60,651**
2.7% (0.3)	$25,512	**$69,862**	$68,495	**$69,862**
Expected Value	$26,696	$57,190	$57,093	
Net value	$ 26,607	$ 56,966	$ 56,780	

Table 4-8. Results of candidate lines (money in millions of dollars)

The table shows three alternatives for transmission expansion with their respective investment costs. The alternative of 2,350 MW is a combination of the other two. Also, performance of these alternatives is shown in terms of total surplus in three scenarios of demand growth rate (probabilities are in parenthesis). Last column shows maximum values of total surplus under each scenario. Finally, last row shows expected total surplus for each candidate line.

4.4.1. Flexibility approach

We evaluate 350 MW and 2,000 MW for fixed expansion; these are shown in Table *4-9*:

Max flow – MW (Proposed lines)	**X_l**
350	0.0742
2000	0.0176

Table 4-9. Proposed expansion of transmission lines

Reactances of candidate lines are estimated from Table *4-5* (Pozo et al., 2013) adjusting an equation to those data (Figure *4-4*):

Fmax	Xl
1200	0,0423
1300	0,0209
1300	0,0316
500	0,1381
400	0,0602
200	0,1604
800	0,033
700	0,0261
300	0,0452
250	0,0648
250	0,0994
550	0,027
215	0,1018
215	0,2182

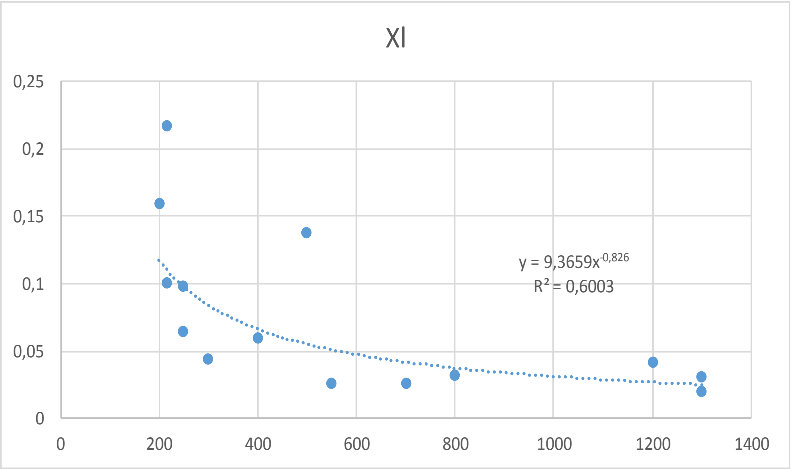


Figure 4-4. Adjusted curve from system data

Those values are included as parameters in equation (4-3) to estimate flow through new lines.

A fixed expansion of 2000 MW is selected as solution of congestion between node 4 and 6 because present a net value of $56,966 millions of dollars against USD$26,607 millions of dollars of 350 MW transmission line (Table *4-8*):

As flexible expansion we select a transmission line of 350 MW (other alternative could be selected). Estimations of incremental total surplus due to this flexible expansion over the system with fixed expansion is shown in Table *4-10* . In consequence, the underlying asset value (S_0) was estimated in USD$ 2,361 millions of dollars.

	Demand Growth rate			**Expected Value**
	2%	2.50%	2.70%	S0 (Millions of USD/y)
Flexible Expansion	$1,075.41	$2,567.76	$3,370.10	$2,360.76

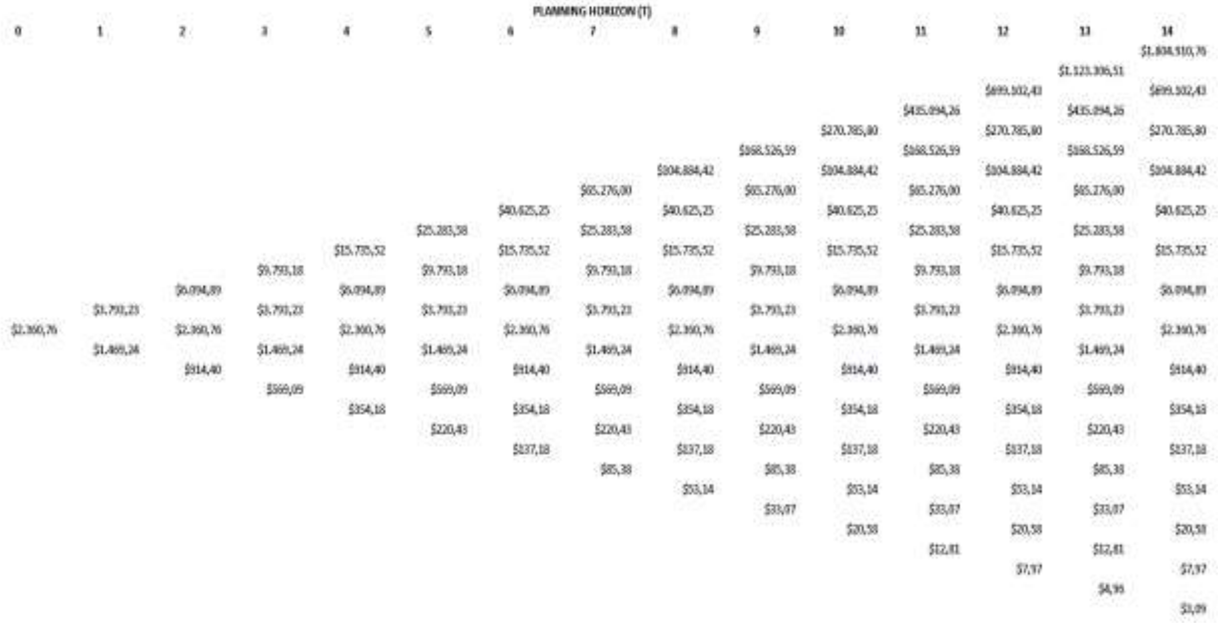
Table 4-10. Results of flexible expansion

From Montecarlo simulation we obtain the following values (we use a risk free rate Rf = 0.03) (Table *4-11*):

Parameters	**Values**
$\boldsymbol{\sigma_{14}}$	1.774
$\boldsymbol{\sigma_{1}}$	0.474
$\boldsymbol{U}$	1.607
$\boldsymbol{D}$	0.622
$\boldsymbol{p}$	0.414

Table 4-11. Results from Montecarlo simulation

This volatility let us to build a binomial tree that shows evolution of the underlying asset through the planning horizon (Figure *4-5*) because of uncertainty in demand growth rate.



							PLANNING HORIZON (T)							
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
														$1.804.910,76
													$1.123.306,51	
												$699.102,43		$699.102,43
											$435.094,26		$435.094,26	
										$270.785,80		$270.785,80		$270.785,80
									$168.526,59		$168.526,59		$168.526,59	
								$104.884,42		$104.884,42		$104.884,42		$104.884,42
							$65.276,00		$65.276,00		$65.276,00		$65.276,00	
						$40.625,25		$40.625,25		$40.625,25		$40.625,25		$40.625,25
					$25.283,58		$25.283,58		$25.283,58		$25.283,58		$25.283,58	
				$15.735,52		$15.735,52		$15.735,52		$15.735,52		$15.735,52		$15.735,52
			$9.793,18		$9.793,18		$9.793,18		$9.793,18		$9.793,18		$9.793,18	
		$6.094,89		$6.094,89		$6.094,89		$6.094,89		$6.094,89		$6.094,89		$6.094,89
	$3.793,23		$3.793,23		$3.793,23		$3.793,23		$3.793,23		$3.793,23		$3.793,23	
$2.360,76		$2.360,76		$2.360,76		$2.360,76		$2.360,76		$2.360,76		$2.360,76		$2.360,76
	$1.469,24		$1.469,24		$1.469,24		$1.469,24		$1.469,24		$1.469,24		$1.469,24	
		$914,40		$914,40		$914,40		$914,40		$914,40		$914,40		$914,40
			$569,09		$569,09		$569,09		$569,09		$569,09		$569,09	
				$354,18		$354,18		$354,18		$354,18		$354,18		$354,18
					$220,43		$220,43		$220,43		$220,43		$220,43	
						$137,18		$137,18		$137,18		$137,18		$137,18
							$85,38		$85,38		$85,38		$85,38	
								$53,14		$53,14		$53,14		$53,14
									$33,07		$33,07		$33,07	
										$20,58		$20,58		$20,58
											$12,81		$12,81	
												$7,97		$7,97
													$4,96	
														$3,09

Figure 4-5. Binomial tree of underlying asset for Colombian case (millions of dollars)

This result is not enough because we have to determine if it is convenient to make the flexible investment and in what conditions. To do that we need to subtract at each stage the investment of flexible expansion and penalty factor. The investment of flexible expansion is USD89.4 millions of dollars (Table *4-9*). Penalties are shown in Table *4-12*. This table shows values of incremental total surplus by addition of flexible expansion at each time and under defined demand growth rate. The binomial tree with net values is shown in Figure *4-6*.

	Penalties (millions of dollars)				
Time	**0**	**1**	**2**	**3**	**4**
2.0%	$0.00	$0.00	$0.00	$0.00	$0.00
2.50%	$0.00	$0.00	$0.00	$0.00	$0.00
2.70%	$0.00	$0.00	$0.00	$0.00	$0.00
Weighted average	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Time	**5**	**6**	**7**	**8**	**9**
2.0%	$0.31	$0.25	$357.00	$357.00	$357.00
2.50%	$0.24	$2.18	$357.00	$357.00	$357.00
2.70%	$2.10	$2.25	$357.00	$357.00	$357.00
Weighted average	**$0.82**	**$1.62**	**$357.00**	**$357.00**	**$357.00**
Time	**10**	**11**	**12**	**13**	**14**

2.0%	$357.00	$357.00	$357.00	$357.00	$357.00
2.50%	$357.00	$357.00	$357.00	$3,518.49	$2,541.80
2.70%	$357.00	$357.00	$3,521.17	$2,544.33	$2,827.12
Weighted average	**$357.00**	**$357.00**	**$1,306.25**	**$2,277.79**	**$1,971.95**

Table 4-12. Penalties

In Figure *4-6* there are conditions where investment on flexible expansion produces negative contribution on values of total surplus, so in these cases it is not convenient to invest. But that figure not answer when to delay the investment because it is possible that despite contribution is positive it is better to wait, that is to delay the investment. In order to identify when it is convenient to delay flexible investment we have to build the option value binomial tree.

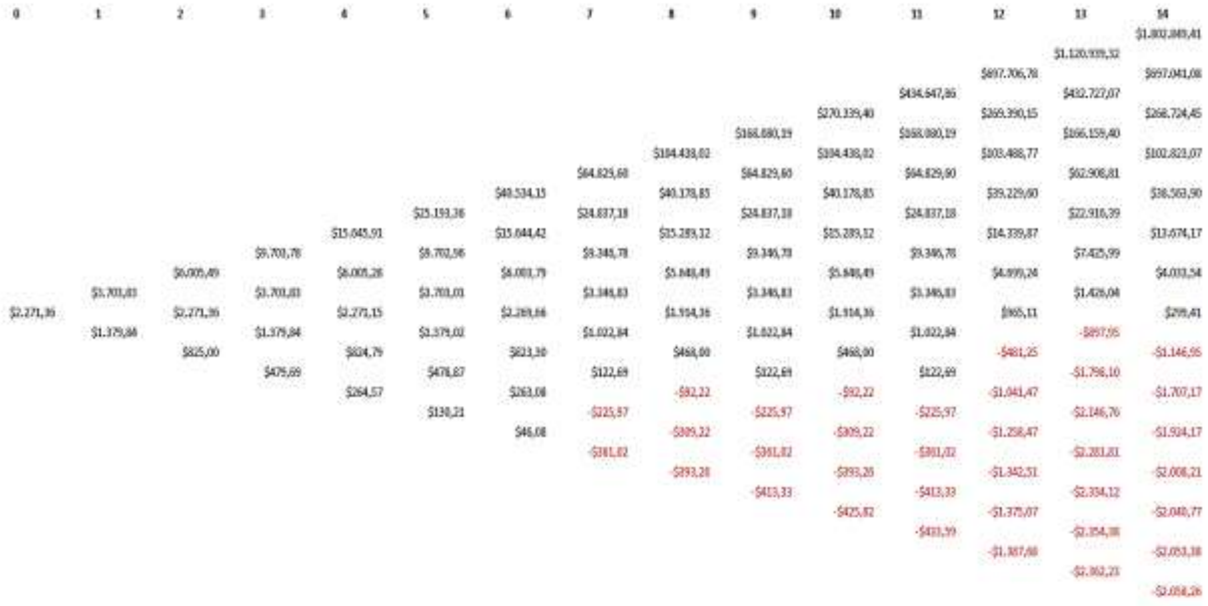


Figure 4-6. Binomial tree of underlying asset net value (millions of dollars)

The option value binomial tree is shown in Figure *4-7*. These values result of application of criteria contained in equations (4-12) and (4-13). If investor decides to delay flexible expansion until the end of maturity time (period 14 in the figure) there are conditions where it is not convenient to expand because the option to delay does not have any value. But if the value is positive that means that delaying was convenient but it is possible that be better to invest before. In consequence we have to understand values in intermediate periods. Intermediate values are obtained by comparison of the execution of the expansion project in a given time against to defer the investment until next period. The option value binomial tree contains the larger value from comparison. It is not evident which of them is registered in the figure, so a new illustration is added in order to explain it (see Figure *4-8*).

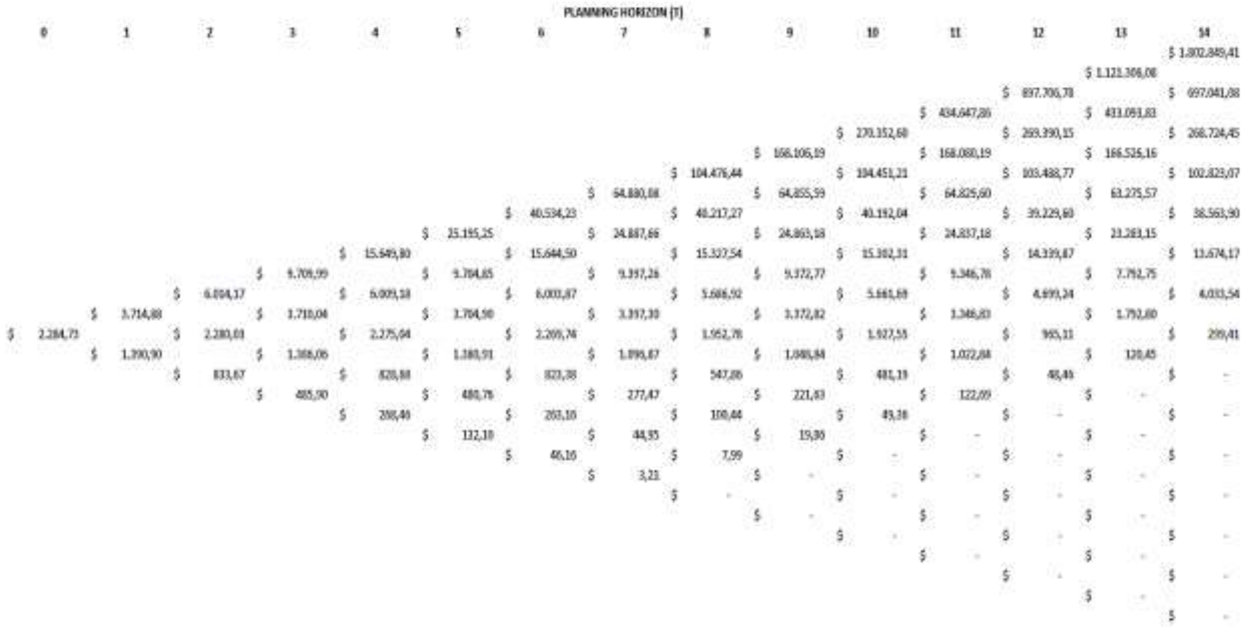


Figure 4-7. Option value binomial tree (millions of dollars)

Figure *4-8* is easily obtained comparing values on Figure *4-7* against respective values on Figure *4-6*. For example the first value on period 11th in Figure 4-7 is USD$ 434,648 millions of dollars, the value in the same position in Figure *4-6* is equal, that means it is better to make flexible expansion because the registered value will be the contribution of the expansion to total surplus, so Figure *4-8* contains “INVEST” in that position. In contrast, the first value in period 10 in Figure *4-7* is USD$ 270,352.6 (this is PVO) while the value in the same position in Figure *4-6* is USD$ 270,339.4 (this is $PVWF$) that means it is better to delay the expansion or to “WAIT” as shown in Figure *4-8*, because if you wait the contribution might be higher. The same logic is applied at the beginning of decision (period 0), if flexible investment is made in that period the net contribution would be USD$ 2,271.4 millions of dollars, but if decision is delayed the contribution might increase in USD$13.37 millions of dollars. This value results by subtracting 2,271.4 (Figure *4-6*) from 2,284.7 (Figure *4-7*) and represent the option value to delay flexible expansion.

Note in Figure *4-8* that after a decision to “INVEST” is made it does not matter what happens because the options was exercised, so these actions are in subdued color.

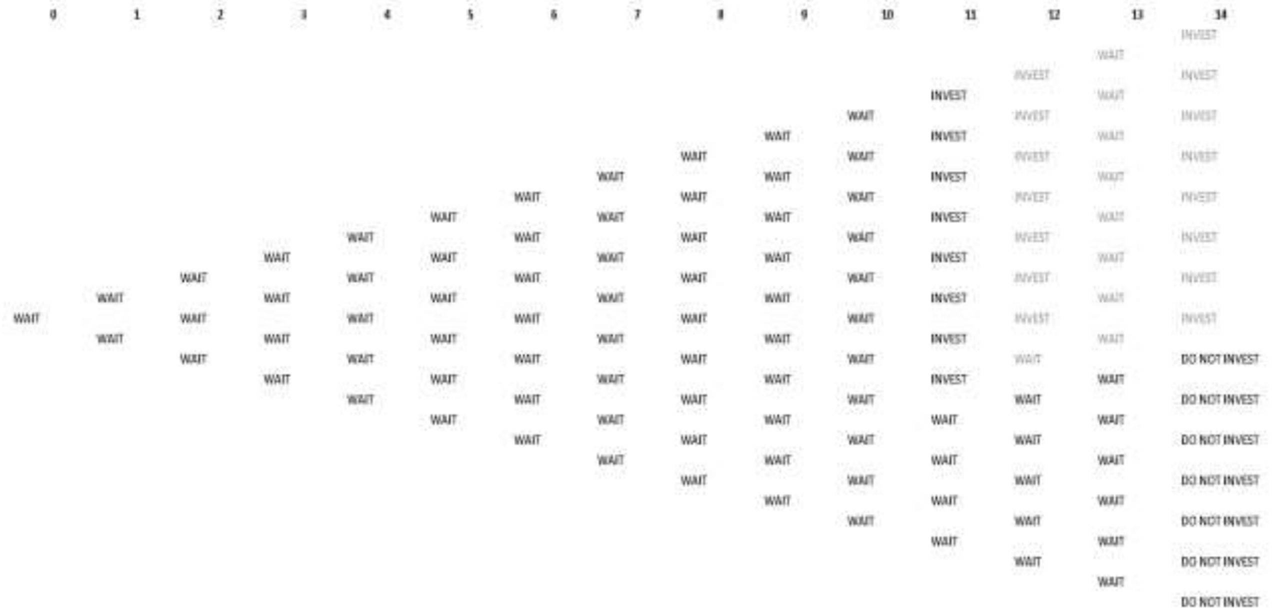


Figure 4-8. Decision at each period

The investor will decide to work with this approach only if the value of initial investment (additional to fixed expansion) to receive this future expansion is lower than the option value. That means the option value to delay a flexible expansion become a referent to those required investment to provide the system with adaptation ability.

4.4.2. Robust approach

Results obtained from equations (4-15) and (4-16) are shown in Table *4-13*:

Demand Growth Rate	Regret |TS -TS*|		
	350 MW	2000 MW	2350 MW
2.0%	$ 14,101	$ -	$ 153.5
2.5%	$ 33,294	$ 898.5	$ -

2.7%	$ 44,350	$ -	$ 1,366
Maximum Regret	$ 44,350	$ 898. 5	$ 1,366
MINIMAX		$ 898.5	

Table 4-13. Results from regret function

The final result suggests that a unique expansion of 2,000 MW (robust expansion) is required to support demand growth scenarios. Perhaps this is an unexpected solution because it could expect under a scenario of demand growth rate of 2.7% the best solution should be 2,350 MW. In order to explain this, it is convenient to remember that total surplus is obtained by the sum of consumer surplus, producer surplus and rent of congestion. In this case a comparison among these terms shows that expansion from 2,000 to 2,350 MW reduces incremental consumer surplus, increases incremental producer surplus but this increase does not compensate the reduction of incremental consumer surplus and reduces incremental rent of congestion (those details are not included here).

According to Figure *4-8*, there are future conditions that justify an additional investment because social welfare can increase. Apparently to make a decision under robust approach coincides with fixed expansion but the difference comes from the intentional nature of flexibility, i.e. if flexibility is not considered from the beginning the opportunity of future expansion is lost because additional investment to make flexible the initial expansion does not occur.

4.5. Chapter Conclusions

We apply an approach based on Real Options (RO) to estimate flexibility value in Colombian TEP. This flexibility was introduced by a transmission expansion divided in a fixed expansion and a flexible expansion. Fixed expansion is built at the beginning and it works well under normal conditions of demand growth and flexible expansion would be built if conditions at the future are appropriate. Results show that an option to delay the flexible expansion has value, i.e. introduce flexibility in Colombian TEP increases the value of transmission projects from a perspective of social benefits.

However, this kind of flexibility requires making an additional initial investment over fixed expansion to provide adaptation ability to the system. This overinvestment was not quantified here, but we obtain a limit value of this additional investment.

The referent or limit value is obtained through an option value to delay the flexible investment. In consequence, the application of a Real Option approach become a useful tool to identify limit values for investment intended to provide a system with adapting ability.

This conclusion is reinforced by the fact that flexibility approach allows taking advantage of future favorable conditions; in consequence, it showed a better performance than robustness approach in the case analyzed here.

Analysis of Colombian transmission expansion process led to conclude that flexibility introduction does not require important structural changes in that process. Only UPME has to change its methodology. This change will affect public tender and maybe how the bidder’s income is estimated.

As a result and because flexibility is worth it is necessary to analyze how UPME can introduce flexibility in its planning process.

We assume a lead time of one year to expand the system, so it is necessary to include realistic time to this analysis and its impact on solutions.

Another issue is the estimation of option value. Option value is highly dependent of volatility of the system, so it is necessary to explore its sensitivity to changes in volatility.

CHAPTER 5

5. Findings and Conclusions

5.1. Introduction

This research was set out to estimate flexibility value in Electric Transmission Expansion Planning (TEP) by using a flexible strategy based on traditional transmission assets (i.e. transmission lines) that allows deferring investment until uncertainties are revealed. Flexibility approach was valued through a methodology based on Real Options, in particular an option to defer an expansion until conditions are appropriate.

Two reasons justified this research:

- TEP is a complex task and plagued of uncertainties; although several techniques have been employed to handle uncertainties in this field, most of them do not consider managerial ability to adjust decisions.
- Flexibility is a useful approach to cope with uncertainties, although it has not been commonly used in TEP.

Consequently, this research aimed to estimate managerial flexibility value in TEP from a social welfare perspective and how this flexibility can be introduced; so, planners can adjust their decision in the future when uncertainty is resolved

5.2. Results

Results of this research are framed into the proposed 4 specific objectives as follows:

1) To define a methodology to estimate the value of flexibility, a process of two stages was developed:

First, the meaning of flexibility is very wide so it was necessary to characterize the term in a context of decision-making. The literature review showed there are different alternative approaches to deal with uncertainties, as well as methodologies to introduce flexibility in investment decision-making processes; however, flexibility presents a key characteristic that is different from the other approaches. Flexibility is a reflection of the natural behavior of managers when they make decisions and those decisions must be adjusted because conditions are different from planned. In consequence, flexibility is conceptually a valid approach to manage uncertainties and reduce risks. On the other hand, flexibility must be intentional in order to be effective, i.e. uncertainties have to be identified from the beginning and several options are also established from the beginning in response to contingencies.

Secondly, because of flexibility must be intentional a flexible strategy based on two conventional transmission expansions was designed. One of them is necessary to solve congestion problems under expected demand growth and the other one is deferred until future conditions are appropriate to expand. The option value to defer was estimated by using real options methodology and by using a binomial tree technique. This flexible strategy was applied on a binodal case. The underlying asset value was defined as the impact that produces the second expansion on the social welfare. If this expansion is not executed at specific period and it is required, the benefit will not be received; so, it is necessary to introduce a penalty term in the formula to estimate the value of the underlying asset through the time. Montecarlo simulation was used to estimate the volatility that binomial tree requires to be built. We use two volatilities; the first one was estimated by Montecarlo simulation in the same manner as is available in the literature; the second one was estimated in a novel way using a Montecarlo simulation at each node of the binomial tree to model the effect of a change in the sources of uncertainties.

An important conclusion is extracted: It is not the same introducing flexibility to estimating its value. To introduce flexibility in TEP, methodologies like Multistage Stochastic Optimization, Adapting Costs or Real Options can be used, but to measure flexibility value only Real Options are useful because they determine the increment of the present value of a cash flow due to flexibility.

Our contributions in this objective are highlighted:

- Flexibility is intentional, that means, flexibility cannot be an improvised decision when an unpredictable event arises because an economical adaptation or adjustment cannot occur because the system is not prepared from the beginning to receive such changes. This conclusion implies flexibility has a cost and this cost must be estimated. In other words, the cost of making a system with the ability to be adjusted in the future must be considered.
- A penalty term is introduced in the formula to estimate the value of the option taking into account the underlying asset was defined as the incremental total surplus given by the expansion. If such expansion is not made, the incremental benefit will not occur.
- A Montecarlo simulation was applied to estimate volatility at each node of the binomial tree. A non-recombining binomial tree results of this procedure.

2) To compare results from a model that involves flexibility against traditional models used in TEP, we used a common TEP approach, i.e. robustness. Robust approach was estimated using as criterion the minimization of maximum regret. This comparison showed that flexibility approach has a better performance than robustness approach in the case analyzed here because flexible approach allows taking advantage of future favorable conditions to expand.

   Although the same solution can be obtained by robust and flexible approaches, there is an important difference in the physical system. The physical system designed under a robust approach cannot be expanded economically in the future because it is built minimizing all its costs. In contrast, the physical system designed under a flexible approach can be expanded in the future because this possibility is admitted from the beginning (remember the intentional nature of flexibility). This ability implies an extra cost that is not included in the robust investment, so the limit for this extra cost is provided by the option value to defer this flexible expansion. This is the meaning of the option value and this is one of the main contributions of this research.

   An interesting implication is inferred from the above statement; for example, the planner does not know the future behavior of demand growth so prepares a transmission plan considering the best knowledge about that growth, additionally, the planner decides to have the ability to adjust, adapt or change the size of the initial transmission plan if future demand growth is higher than expected. This flexibility is embodied in another transmission expansion, whose investment cost is $89 millions of dollars, which will be executed in the future if conditions are appropriate; as a result, an option to defer is built, and its value is estimated in $13.3 millions of dollars. Under the current knowledge, planning with flexibility is a good decision because it increases the value of the project. However, the initial expansion must be able to withstand the second expansion if this is executed. This ability costs money that is not included by the second investment. In other words, higher or wider transmission towers, with more construction material, and perhaps more land surface are required for the initial expansion in order to have the ability to support the second expansion. Assuming that the extra cost is $15 millions of dollars, planning with flexibility is no longer a good decision because the extra cost is greater than option value to defer.

3) To describe current TEP process in Colombia to identify barriers to apply flexibility. It was necessary to characterize organizational structure of Colombian electric system to identify market agents as well as their roles, and to visit web pages of organisms in charge of planning and regulation in order to be familiar with the TEP process in Colombia. In parallel, revision of planning methods in transmission was useful to recognize which of them is applied in Colombia according to information extracted from the Colombian TEP process. This kind of information allows concluding that Colombia does not require important structural changes in TEP process to implement flexibility. In other words, it is only necessary to change the model used by the planner to identify eligible lines. This change might affect public tender and how the bidder’s income is estimated.

   As a result, it is possible to introduce a flexible approach in Colombian TEP because it does not affect the general procedure to define expansion plans. This is another contribution of this research work.

According with these results, the following questions can be answered:

1. Is flexibility value important in TEP, in terms of social welfare? The application of options increase the present value of total surplus, it means flexibility has value as approach to handle uncertainties. Now, this increase comes from the option value to defer in this case and it becomes a referent point to establish limits to that necessary extra investment for a flexible plan. To put in another way, a plan requires additional initial investments to be flexible; so, in our opinion, the option value is the upper limit for those initial investments.

2. How does a planner introduce flexibility in TEP? Literature review identified several mechanisms, but in this case a transmission expansion plan was divided in a fixed expansion and a flexible expansion. The latter is the response to contingencies; therefore, if future conditions are appropriate, it will be done.

5.3. Limitations of present study

A binodal case was the base to develop a flexible strategy based on a set of sequential transmission expansions. Although some complexities like game theory and two different objective functions were introduced, the simplicity of the model left out electrical phenomena that occur in complex systems as for example Kirchhoff laws.

On the other hand, a reduced version of Colombian electric system was used in order to ease the development of a flexible strategy and to obtain an interpretation of flexibility meaning. The reduced version grouped generator plants with dissimilar characteristics that affect marginal costs assuming generators do not have a strategic behavior and their marginal costs do not change over time. This was a strong assumption because energy price are affected by generator plants and generator behavior. Future analysis may improve this assumption.

In addition, some issues require future attention; for example, what changes in Colombian TEP process to introduce a flexible approach are necessary, and what their effects on transmission investment are. Other assumptions deserve future revision such as the inclusion of realistic lead-time for transmission projects, investment costs, and extra costs for flexible capability. Similarly, other methodologies to introduce flexibility and estimation of volatility are open for analysis

Another limitation comes from the assumption of only a single transmission is made to introduce flexibility. It is possible and more realistic the introduction of a portfolio of investment transmission projects.

Finally, the assumption that underlying asset (incremental total surplus) follows a random walk allows building a binomial tree. This assumption can be checked at future research.

5.4. Recommendation

In future research, if underlying asset is defined as the contribution of the investment project to any attribute, a penalty factor must be introduced in the formula to estimate the value of an option because the binomial tree shows the evolution of underlying asset. If the project is not made, the contribution will not occur.

5.5. Suggestion for further research

The following issues pose new challenges to be solved in future research:

- In this research, a flexible strategy based on a set of sequential transmission expansion was proposed. However, other strategies to incorporate flexibility must be studied. Additionally, it should be useful proposing a methodology that helps on the identification of flexible strategies.
- A strategy based on a set of fixed expansion and flexible expansion, both with predefined size, was proposed. However, we left as a future research determining the optimal joint fixed and flexible expansion. Similarly, it is possible to explore the optimal capacity of the flexible investment as the outcome of an optimization formulation.
- A comparison among the methodologies based on Multistage Stochastic Optimization, Adapting Costs and Real Options is open in order to define their scope, limitations, compatibilities and incompatibilities.
- In the context of Real Options, the effect of assuming a continuous time path for the evolution of the underlying asset is open. Similarly, other techniques for estimating volatility may affect the option value; in consequence, a study to explore these effects is valid. In the same way, other techniques such as Least Square Montecarlo for estimating the value of waiting may affect the value of the option so a research in this field is justified.
- The implications of any change in the Colombian TEP process justify the needs of revisiting the estimation of the flexibility value but without assumptions made in this research.
- Under the assumption that Colombia changes its TEP process introducing flexibility, a research focused on determining revenues to transmission investor will be necessary

5.6. Conclusions

TEP process is surrounded by uncertainties and complexities. Although other approaches have been widely used to handle uncertainties, this research has shown an approach based on flexibility is a valuable alternative to cope with them.

However, it was also shown that not every time a flexible approach is the best decision. To support this statement is enough to remember that flexibility is costly.

In Colombia this approach has not been widely used, but we have shown that it is a useful alternative to apply because it increases the value of investment when the value is estimated in terms of total surplus. Current state of the Colombian TEP process suggests that improvements can be done, but more research is needed. Some of the issues that can be explored are mentioned above.

On the other hand, introducing flexibility in TEP is not a standard procedure; in this research, flexibility was introduced by a set of sequential investments, but other alternatives are possible. In consequence, a plan to introduce flexibility in TEP must be designed before the planner makes a decision. The plan should take into account the characteristics of flexibility mentioned in chapter 2.

In this research, flexibility value was measured by RO, but other methodologies to introduce flexibility different than RO can be applied. In our opinion, those methodologies are not mutually exclusive so a mix of them can be used to improve the power of flexibility.

Flexibility is a current trend in power system expansion planning mainly because of distributed generation and renewable penetration; in consequence, it is a hot topic of worldwide interest.

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