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A Literature Review on Electricity Transmission Expansion Planning: The Mexican Case

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Résumé

Le réseau de transmission est le moyen de transport de l'électricité des centrales électriques vers les consommateurs. Généralement, les lignes de transmission deviennent saturées quand un excès dans la demande d'électricité surpasse la capacité de transmission, causant ainsi une congestion. D'un côté, la saturation des lignes engendre une interruption de service, un délestage, ou plus grave encore, des pannes qui affectent le bon fonctionnement de tout le système. D'autre part, la congestion des lignes est un phénomène qui génère la perte d'efficacité économique d'un système électrique. En guise d'illustration, considérons l'exemple suivant : soit deux centrales électriques alimentant une ville. La première est située dans la ville même et la deuxième à bonne distance de cette ville, mais tout de même, connecté au réseau de transmission. Supposons que la centrale la plus éloignée soit plus efficace, car elle produit de l'électricité à un coût moindre, ainsi, son prix de vente est plus bas. Si un problème de congestion se produit dans le réseau de transmission électrique, la ville sera dans l'impossibilité d'en importer l'énergie. Dans ce cas, la congestion dans le réseau de transmission favorisera la centrale moins efficace en lui donnant le pouvoir du marché et en lui permettant de vendre à un prix plus élevé.

Ce rapport de recherche s'inscrit dans la littérature sur l'expansion des réseaux de transmission. Il présente une revue littéraire de deux méthodologies destinées à en planifier l'expansion. Le cas du Mexique sera traité, car ce pays fait face à un problème de congestion dans son réseau de transmission électrique. À la différence de la méthodologie mono-objective utilisée par les autorités mexicaines en ce moment (basé sur la minimisation du coût investissement/construction), ce rapport de recherche explorera une approche différente, déterminée par un critère multi-objectif. En particulier, trois objectifs seront considérés dans la méthodologie multi-objective: 1) le coût total du système, 2) le coût investissement/construction et 3) l'analyse de contingence ou d'éventualité. Dans un problème d'optimisation, ces trois objectifs seront sujets aux contraintes du réseau électrique pour trouver une expansion optimale aux lignes de transmission. Toutefois, ce rapport n'inclut pas d'application pratique de cette nouvelle méthodologie au cas particulier du système de transmission mexicain.

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1. Introduction

In the surface, the electricity system presents an easy approach, Jamasb and Pollit (2007) describe the four principal activities in the following way: [Generation comprises production and conversion of electric power; transmission involves long-distance transportation of electricity at high voltage; distribution is transportation for low-voltage electricity from the transmission system to customers premises; retailing function consists of metering, billing and sale of electricity to end-users.], p.6164.

It is generally accepted that generation and retailing are activities regarded as potentially competitive, while transmission and distribution (network activities) are viewed as natural monopolies due to the high degree economies of scale.[1]

The idea behind an electricity reform is to separate the four main segments, introducing competition into generation and retailing, while regulating in the other hand, the transmission and distribution activities.

The natural monopolistic characteristics in the network activities, particularly in transmission, affect the whole performance of the electric power sector. Madrigal and Cagigas (2003) explain that [transmission systems become particularly important to foster an effective competition within the power system. The reason is that capacity limited transmission lines transport the energy produced by generators, which is considered a competitive activity, to final users, which is also a competitive activity. A transmission system presenting high congestion

[1] Carlton and Perloff (2004), state that [When total production costs would rise if two or more firms produced instead of one, the single firm in a market is called a natural monopoly.], p. 104, (in Joskow 2005).
The idea behind a natural monopoly is that when the efficient size of a firm is relatively large related to the size of the industry, the equilibrium market would just support a relative few number of firms.

levels or minor localized congestion, limits the possibility of effective competition in a market environment and therefore restricts benefits to all participants.], p.1012. Consequently, the management and expansion planning of the transmission network result a key issue in any electricity system that needs to be studied properly.

In particular, the Mexican transmission network is presented as the reference case given that it is currently having problems meeting efficiently a growing electricity load demand. As a result, congestion in transmission lines isolate important regions in the south-east and north of the country, by limiting the number of generators that generally supply local consumers (Hartley and Martinez-Chombo, 2002; Rosellón, 2007).[2]

Investments in the Mexican transmission capacity are likely to be necessary to minimize congestion costs, power losses, to maintain reliability and to mitigate market power in local generators.[3] Nevertheless, liberalization has haunted the Mexican electric power sector for a decade, since a presidential proposal in 1999 supported the opening of the Mexican electricity market to competition. Ever since, Mexican Congress has rejected every restructuring initiative to promote a transition from state-owned electric utilities towards a competitive electricity market. Despite the constant refusal, there is still no agreement on any other alternative to restructure the electric power sector today.

Nowadays, the Mexican electricity sector is vertically integrated by two state monopolies: Comisión Federal de Electricidad (CFE) and Luz y Fuerza del Centro (LyFC).

[2] Rosellón (2007), describes that [Congestion in transmitting electricity is relatively acute in Mexico, totaling 1.4 billion US dollars in congestion rents per year.], p.3003.
[3] Joskow and Tirole (2000), explain that local market power in electric generation exists [Because there are few generators inside the congested area, these generators may have market power when imports are constrained.], p.451.

Under this scheme, both electric utilities own and control the four primary supply activities in the chain value: generation, transmission, distribution, and retailing.[4]

Under a centralized transmission expansion planning carried out by a sole agent, as in the Mexican case, there are not enough investment incentives to achieve an optimal expansion of the network based on a cost minimization methodology.[5]

This study introduces multi-objective optimization theory, generally used for optimizing objectives with conflicting or uncertain relationships (Alseddiqui and Thomas, 2006), as an alternative to the current transmission expansion planning used in Mexico.

This study is organized as follows. In section 2 an introduction of electricity systems is presented, as well as a literature review on transmission congestion and transmission expansion planning. Section 3 summarizes the historical background and current situation of the Mexican electricity system, giving a special attention to the transmission system, describing the current methodology used for transmission pricing and the procedures on central transmission planning. Section 4 outlines a new methodology for transmission expansion planning based on multi-objective optimization theory. Section 5 exposes the conclusions.

[4] In 1992, an amendment was introduced allowing private investment in the generation of electricity in the form of self-supply, co-generation, independent production and small production (not exceeding 30MW), under a single buyer or monopsony scheme, giving the government the exclusive right to buy excess electricity from the private producer. To promote the development of clean energy (based on renewable resources), the Mexican Congress approved on November 2008 an increase of private investment for generation activities.

[5] Rosellón (2007) suggest that [transmission tariffs in Mexico are set according to the cost of service per megawatt-mile. This method provides no proper effective incentives for expanding the grid and relies instead on a subjective way of allocating costs among consumers according to their so-called permuted impact on the grid.], p.3003.

2. Introduction to electricity systems

Imagine a commodity that is difficult and expensive to store, so it has to be produced practically at the same time that it is consumed. Imagine a commodity whose supply and demand have to be balanced at all time, but its demand holds stochastic and cyclic attributes, while supply is subject to technical rigidities. Imagine a commodity that given its lack of storability, losses have to be considered in the supply process, so in order to achieve balance, demand must always equals supply minus losses. However, losses are in some cases hard to identify, making balance a difficult task to realize. Such commodity is electrical power.

The first process in the delivery of electricity to consumers is electricity *generation*, it consist of production and conversion of electric power using falling water, internal combustion engines, steam turbines powered with steam produced with fossil fuels, nuclear fuel and various renewable fuels, wind driven turbines and photovoltaic technologies, (Jamasb and Pollit, 2007; Joskow, 1998).

To transfer electricity from generation plants to final consumers, an electricity system has transmission and distribution lines (network activities), made up of high, medium and low voltage conduction lines. In this sense, the second process is the *transmission* of electricity, an important activity that makes possible commercial trading of electric power.[6]

[6] Joskow (1997), explains that [The transmission of electricity involves the use of wires, transformers, and substations facilities to effect the high-voltage "transportation" of electricity between generating sites and distributions centers, which includes the interconnection and integration of dispersed generating facilities into a stable synchronized AC (alternating current) network, the scheduling and dispatching of generating facilities that are connected to the transmission network to balance the demand and supplies of electricity in real time, and the management of equipment failures, network constraints and relations with other interconnected electricity networks.], (p.121).

The third process is electricity *distribution*, an activity that transports the low-voltage electricity once converted from the transmission system to customer's premises.

Finally, the *retailing* activity, designed to provide services such as metering, billing and sale of electricity to end-users, (Jamasb and Pollit, 2007).

The nature of electricity systems is quite particular since it exposes two opposite economic features: competition and monopoly. In one side, electricity *generation* and *retailing* are competitive activities; in the other, *transmission* and *distribution* (network activities) are natural monopolistic segments.

The vertical structure of the electricity system has contributed to vertical integrated monopolies on electric utilities. Nevertheless, electricity sector reforms have involved unbundling measures to separate the four main activities.

The idea is to introduce an unregulated competitive environment into generation and retailing services, with competing generation suppliers and open entry.[7]

The network activities on the other hand, remain regulated due to their monopolistic characteristics.[8]

[7] In reference to electricity reforms, Joskow (1997) suggests that [The key technical challenge is to expand decentralized competition in the supply of generation services in a way that preserves the operating and investment efficiencies that are associated with vertical and horizontal integration, while mitigating the significant costs that the institution of regulated monopoly has created] p. 127.

[8] Yoon and Ilić. (2001), mention that [The regulator is typically a government agency whose responsibility is to verse the operation and the planning of the network by the transmission provider directly and/or indirectly.], p.1052.

2.1. Introduction to transmission systems

Joskow and Schamalensee (1983), in a reference book on electricity deregulation in the U.S., "Markets for Power", reveal the importance of the transmission activity calling it "the hearth of a modern power electric system".

Economists and engineers agree that transmission systems play a critical role reducing electricity costs in the one hand, and in the other, providing reliability to the system.[9] This is because transmission represents a high voltage transportation network that moves power from dispersed generating stations to load centers (distribution companies or marketers buying on behalf of retail consumers, or large industrial customers buying directly). This way, transmission system puts together demand centers and a large number of generating facilities, isolated between each other over wide geographic areas. At the same time, the transmission network has to be continuously monitored and adjusted to accommodate changing flows, voltage levels and losses in order to maintain the reliability and stability of the system, (Kirby et al., 1995).[10]

[9] Blumsack et al. (2007) explain that [reliability reflects the goal that the system should be redundant enough to avoid service interruptions even in the face of contingencies. Examples of some common reliability metrics are: 1) the N-k criterion; whether the system can continue to provide uninterrupted service to customers in the face of a contingency in which k out of N pieces of equipment are lost, damaged, or otherwise disconnected from the network; 2) the Loss of Load Probability (LOLP), defined as the probability over some period of time that the network will fail to provide uninterrupted service to customers; 3) the Loss of Energy Expectation (LOEE), and Loss of Energy Probability (LOEP), defined as the expected amount and proportion of customer demand not served over some time frame. These are also known as the Unserved Energy Expectation or Probability], p.74.

[10] Transmission of electricity shows specials constraints such as the called loop flows. Kirby et al. (1995), explain that [In general, power flows through many paths when moving between two points. The flows along different paths are inversely proportional to the impedance of each path. Contract arrangements on the other hand, often specify only a single path. Parallel flows that spill over onto the lines of a third party can impose a burden on the third system. Such unplanned power flows often called loop flow, can fill a transmission line's capacity, blocking the flow of electricity to other sources], p.1198.

The management of electricity flows is made by the transmission system operator (TSO).[11] Basically, the TSO provides four main services: 1) economic dispatching, 2) automatic protection of the grid required for controlling the frequency and voltage levels, 3) development of transmission network, and 4) coordination between neighboring TSOs.[12] In a deregulated environment where generating units compete, generally an independent system operator (ISO) exists.[13] For a formal introduction to transmission systems you will be referred to the Annex.

2.2. Transmission congestion

Basically, transmission congestion comes from network constraints characterizing a finite network capacity, (Wang et al., 2008).[14]

Following Joskow and Tirole (2005), assume a simple situation in which load serving entities in the South (say a large city) buy their power generation sources in the North given a less expensive price. Suppose that a transmission line from North to South has a fixed capacity (K), limiting the amount of power that generators in North are able to supply at a lower price to

[11] Rious et al. (2008) comment that [The management of electricity flows by transmission grid operators comprises three principal missions with duration lasting from the very short term (several minutes to several hours) to the very long term (5-20 years)…First, in the shortest time horizon, we have the short-term management of externalities between flows of electricity. Second, over a longer horizon, we have the planning of the development of the transmission grid. Finally, since electric transmission grids are increasingly open to direct transactions between each other, a third element is the management of border effects across TSO zones.], p.3324.

[12] Kirby et al. (1995) mention that [Economic dispatch is a continuous real-time decision-making function in which the system operator, given the actual mix of generating units and power purchase/sell opportunities, attempts to meet current customer demands at the lowest variable cost… The system operator adjusts the output from each unit to minimize the total variable cost of generation], p.1194.

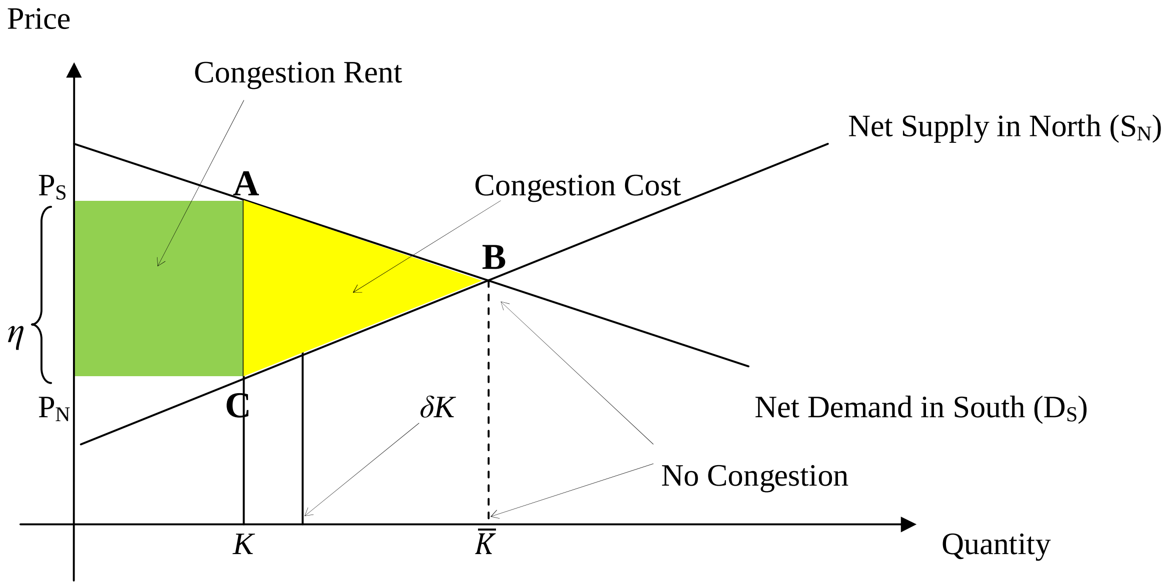
[13] Joskow and Tirole (2005) mention that [an ISO operates a real time balancing market and allocates scarce transmission capacity using bids to increase or decrease generation or demand at each node. That is, ISO takes all of the bids (generation and demand) and finds the 'least cost' set of uniform market-clearing price bids to balance supply and demand at each generation and consumption node on the network using a security constrained dispatch model. This establishes day-ahead quantity commitments and nodal prices that reflect both congestion and marginal losses], p.237.

[14] Kumar et al. (2005) precise that the [Existence of transmission system constraints dictates the finite amount of power that can be transferred between two points (nodes) on the electric grid. In practice, it may not be possible to… supply all pool demand at least cost as it may lead to violation of operating constraints such as voltage limits and line over-loads. The presence of such network or transmission limitation is referred as congestion.], p.153.

the South. Also, suppose that an excess of load serving entities in the South forces the system operator to dispatch generators in the South with a higher price given the capacity constraint K. The rationing of the scarce North-South capacity is implemented by setting two nodal prices, P_S and P_N that clear the markets in the South and the North, respectively.

Figure 1 shows the difference in nodal prices $\eta = P_S - P_N$, representing the shadow price of the transmission capacity constraint. The area ηK is the congestion rent while the triangle ABC is the congestion cost. The cost of running more costly generation in the south because less costly imports from the North are limited by transmission congestion is how congestion cost is defined. Now consider a marginal (unit) increase in transmission capacity (δK). This unit increase allows one more kWh to flow from North to South, replacing a marginal generator in the South with cost P_S by a cheaper generator in the North producing the cost P_N. That is, the social value of the investment is given by the reduction in the area ABC in Figure 1.

Figure 1: Congestion cost and Congestion rent



Source: Joskow and Tirole (2005)

The previous example announces the possibility that generators in the south are able to exert local market power when transmission congestion exists. In order to reduce generators market power, transmission expansion becomes essential, (Joskow and Schamalansee, 1986; Léautier, 2001).[15]

Literature on transmission congestion generally exposes two approaches to reduce and control congestion based on time horizon: the short-term management and the long term management, (Wang et al., 2008; Brunekreeft et al. 2005).

The short-term management deals with transmission congestion for a lapse of time that goes from minutes to hours. The most accepted method for an optimal allocation of the grid's limited capacity is the "nodal spot pricing".[16] Differences in nodal prices allow efficient dispatching of generating units by signaling where it is preferable to generate or consume an additional megawatt subject to the grids externalities as constraints, (Rious et al., 2008).

The long-term management looks for the optimal transmission expansion scheme to reduce and control transmission congestion. However, there are no agreements regarding the optimal long-term expansion of the transmission network.[17] The dispute turns around the optimal

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[15] As electricity demand grows, expansion of transmission network becomes necessary to reduce four main costs derived by an insufficient transmission capacity: 1) higher than optimal congestion, 2) higher than optimal power losses, 3) lower than optimal reliability, 4) imperfect competition in generation, (Joskow and Tirole, 2000; Léautier, 2000).

[16] In the literature, the nodal spot pricing is also known as locational marginal pricing (LMP). Brunekreeft et al. (2005) explain that [For short-run optimal use of the network the benchmark is locational marginal pricing (LMP), also known as nodal spot pricing or a fully coordinated implicit auction. To achieve efficiency this requires that generators submit efficiently priced bids (i.e. a schedule of short-run marginal cost, SRMC, up to full capacity). The dispatch algorithm can then determine the efficient dispatch and the associated nodal shadow prices (which, if generators cannot increase output, can considerably exceed short-run marginal cost). Both generation and load would face these locational prices, although there would need to be additional grid connection charges to recover the balance of the regulated costs.], p.75.

[17] Brunekreeft et al. (2005) explain that, [Locating Marginal Prices (LMP's) are unlikely to recover fixed costs and additional charges are required. Deep connection charges could cover some of these additional costs if they can be

way for attracting investment for long-term expansion of transmission networks. Two different analytical structures are generally proposed for the transmission expansion, 1) the merchant investment model based on financial transmission-rights (FTRs), and 2) the incentive-regulation model.

The merchant investment model relies on competition and free entry of merchant investors, which in return for additional transmission capacity receive transmission rights (TRs) to cover the capital and operating costs. [18] In the incentive regulation model, transmission companies (Transcos) responsible for building, owning and operating transmission facilities are subject to economic regulation.[19] Brunekreeft et al. (2005), make clear that [efficient network expansion and operation (including losses, congestion and balancing) imply the importance of understanding and designing incentive mechanisms for the system operator.], p.74.

2.3. Centralized and Decentralized network expansion planning

Analyzing the optimum transmission capacity expansion, it is important to distinguish the type of market structure that we deal with. Transmission planning under a centralized network (regulated monopoly) with social welfare as objective, would lead to a different optimal expansion plan than a decentralized network (merchant transmission), a model based on market forces with a

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properly identified and are mainly required to compensate for the difficulty of reflecting all the other attributes of transmission service (particularly reliability) in the nodal prices], p.90.

[18] Chao et al. (2000), make clear that [a transmission right is a property that allows its holder to access a portion of the transmission capacity. Generally, a property right consists of three components: 1) the right to receive financial benefits derived from use of the capacity, 2) the right to use the capacity and 3) the right to exclude others from accessing the capacity.], p.40. Joskow and Tirole (2003) carry out criticism to the merchant transmission model. A detailed discussion can be found in Joskow and Tirole (2005).

[19] Joskow and Tirole (2005) explain that [The regulated Transco model is necessarily subject to the classical challenges of regulated monopoly, namely how to specify and apply regulatory mechanisms that provide good performance incentives to the regulated firm while minimizing the economic rents that the regulated firm can derive from its superior information.], p.234.

profit maximizing objective.[20] However, contrary to what we might expect, centralized and competitive unbundled systems usually support their transmission expansion planning on just one objective: cost minimization (investment cost and/or operation cost).[21]

Quite recently, some authors have proposed a new approach for transmission expansion planning using Multi-Objective optimization (Alseddiqui and Thomas, 2006, and Wang et al., 2008).[22] Multi-Objective expansion planning (MOTEP) is a methodology that handles several objectives simultaneously, balancing in an efficient way the usually conflicting planning objectives.

Alseddiqui and Thomas (2006) expose four main objectives for transmission expansion planning that are generally conflicting among each other: 1) Total operating cost, 2) Investment/Construction cost, 3) Network constraints and 4) Contingency analysis.

For the long-term network expansion planning one of the most important objectives is to minimize the total system operating cost. Total operating cost refers to the expenditure in generation required to meet the demand. For example, when there is congestion in the system, the total operating cost increase as well as locational marginal prices (LMP) at each bus or node.

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[20] Cagigas and Madrigal (2003) comment that [Traditionally, before considering a competitive environment in the electricity sectors, the transmission expansion planning was a centralized activity, carried out by a sole agent based on the demand forecast and the associated expansion plans for generation and associated capacity. These determined the optimal number of lines that should be added to an existing network to supply the forecasted load as economically as possible subject to operating constraints.], p.1014.

[21] Several authors have criticized this view, for example, Cagigas and Madrigal suggest that [In a competitive environment, it may exist or not several institutions in charge of the transmission planning, and sometimes planning decisions are taken primarily by market participants, whether generators, final users or transmission grid owners. The classic tools used in centralized planning are no longer useful in a competitive environment. Thus, it becomes necessary to design new planning tools.], p.1013.

[22] Alseddiqui and Thomas (2006), explain that [Objectives for transmission expansion planning are often conflicting and the need for multi-objective optimization is important for the decision making purpose. All papers found in 1985-2005 treat the transmission expansion planning problem as a single-objective optimization, and objectives other than investment cost and/or operation cost are rarely mentioned.], p.1

In addition, the minimization of the construction cost of the transmission lines is essential for expansion planning. However, the network constraints (i.e. voltage magnitude on buses, thermal limits and real and reactive power generation limits), and contingency analysis which evaluates the state of the system after some components of the network fail, increase total operating such as investment costs, (Alseddiqui and Thomas, 2006).

3. The Mexican Electricity Sector

3.1 The historical context

The history of the electricity supply industry in Mexico dates back to the late 19th century. Encouraged by the Mexican government, introduction and expansion of electric lighting was possible mostly through foreign private companies under vertical integrated regional monopolies.[23]

During the Mexican revolution period (1910-1917), private utilities were not particularly damaged by war. Nevertheless, new power-generating capacity diminished given the lack of investment in the country.

Once the civil war ended, political instability followed the 20’s, affecting capital-intensive industries such as electric companies.

[23] Carreón et al. (2003) comment that [Investors, mainly from firms based in foreign countries, built power systems in areas where they thought they could earn a profit, mainly mining and textile industrial areas as well as the largest cities, while leaving aside most rural areas.], p.1.

The first public electricity supply company 'Comisión Federal de Electricidad' (CFE), was created on August 14, 1937 by the federal government of Mexico due to an increasing electricity demand and insufficient private investment in the electricity sector.

Nationalization of the electricity industry took place in 1960, through a constitutional amendment to Article 27, it is now stated in paragraph 6 that: *"It is the exclusive responsibility of the Nation to generate, transmit, transform, distribute and supply electricity that is intended for public service use."*

In the 60's, another public electric utility was created 'Luz y Fuerza del Centro' (LyFC), with the idea to supply electricity exclusively to Mexico City and the surrounding states of Puebla, Hidalgo and Morelos.

It was not until 1992, that the Public Electricity Service Act (Ley del Servicio Público de Energía Eléctrica, or LSPEE) was modified by Congress, allowing private investment in the generation of electricity through an independent power producer scheme. Private electricity generation was allowed in the form of self-supply, co-generation, independent production and small production (not exceeding 30MW), under a single buyer or monopsony scheme, which gives CFE the exclusive right to buy excess electricity from private producers.[24]

Liberalization has haunted the Mexican electric power sector for a decade, since a presidential proposal in 1999 supported the opening of the Mexican electricity market to

[24] The Public Electricity Service Act (Ley del Servicio Público de Energía Eléctrica, or LSPEE) prevents the trade of electricity by giving CFE the exclusive right to buy power surpluses from private producers. In the case of independent power producers, the government's expansion planning has taken an approach that relies on build, lease and transfer (BLT) projects. Under this approach, private investors build the new plant, lease it under a long term contract with CFE and lastly transfer the plant to government ownership at a specified future date, (Hartley and Martínez-Chombo, 2002; Rosellón 2007).

competition. Ever since, Mexican Congress has rejected every restructuring initiative to promote a transition from state-owned electric utilities towards a competitive electricity market. Despite the constant refusal, there is still no agreement on any other alternative to restructure the electric power sector today.[25]

Quite recently, to promote development of clean energy technology (based on renewable resources), Mexican Congress approved on November 2008, an increase of private investment exclusively for generation activities.

3.2 The Mexican electric power condition

As previously mentioned, electricity in Mexico is nowadays supplied by two vertical state-owned utilities: Comisión Federal de Electricidad (CFE) and Luz y Fuerza del Centro (LyFC).

In order to evaluate efficiency on any electricity system, Joskow and Schmalensee (1983) consider that two questions must be answered. First, the electricity supplied today as well as the one that is going to be supplied tomorrow, is it offered at the lowest possible cost? Second, the electricity charged to consumers, does it properly reflect production costs such that consumers decisions related to the use of electricity reflect properly this cost?

Hartley and Martinez-Chombo (2002), in a substantial study of electricity demand and supply in Mexico, conclude that [there are substantial differences between electricity prices in Mexico and the marginal costs of supply. In particular, the regional and temporal variation of

[25] Electricity restructuring in Mexico is not a simple task, the new political configuration in the country delays the implementation of structural reforms. Joskow (1997) remarks the point that [Electricity restructuring…is likely to involve both costs and benefits. If the restructuring is done right…the benefits…can significantly outweigh the costs. But the jury is still out on whether policymakers have the will to implement the necessary reforms effectively], p.136.

prices is not closely related to the corresponding variations in marginal costs. As a result, consumers are not receiving accurate signals about the benefits of changing their location, or the timing of their electricity demands, so as to reduce the costs for the system as a whole.], p.49.[26]

Hartley and Martinez-Chombo (2002), observe that prices of electricity in Mexico do not vary much by location or time of demand, so it is not surprising that subsets of consumers are either being taxed (charged with a price above marginal cost), or subsidized (charged with a price below marginal cost), affecting the efficient use of the resource. The authors suggest that consumers as well as potential generators of electricity are not receiving the accurate information in terms of costs and benefits of changing electricity demands or supplies at different locations on the network or at different times of the year.

In this sense, it can be stated that the Mexican electricity system is not efficient. In fact, the current model of the Mexican electricity system could be unsustainable in the long-run, since current investment and regulatory schemes are unable to meet efficiently a growing demand and to maintain reliability, (Madrigal, 2005). Investments in generation and transmission network are required to replace older and less efficient technology with the objective to improve performance and expand capacity. Regulating schemes are necessary to minimize the overall costs of a state monopoly and to mitigate locational market power by generators.

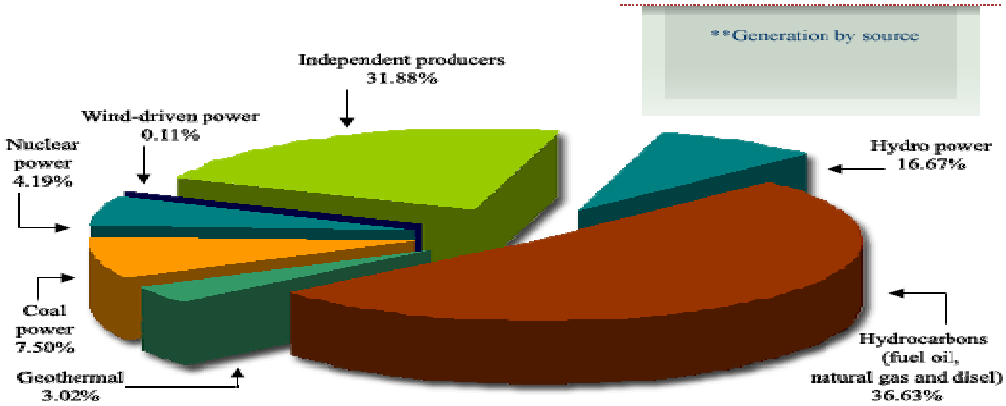
It is important to mention that some measures to mimic competitive market pressures have been applied in the Mexican electricity sector.[27]

[26] In their analysis, Hartley and Martinez-Chombo (2002) remark two more conclusions: 1) Substantial investment is needed to meet growing demand for electricity over the next decade. If the electricity remained fully publicly owned, the government of Mexico would need to raise significant revenue to fund these investments. 2) Hydroelectric generating plant in Mexico is quite valuable as a mechanism to smooth temporal and geographical variations in marginal cost of generation. However the benefits of hydroelectricity are limited given a weak existence of transmission network. Transmission congestion is a recurrent issue, so upgrading the transmission links becomes a major priority.

In terms of generation power in Mexico, the generation mix is composed in the following way: 36.63% hydrocarbons, 31.88% independent producers, 16.67% hydro, 7.50% coal, 4.19% nuclear, 3.02% geothermal, 0.11% wind.

Figure 2 shows generation of power for public service according to CFE's information published in January, 2009.

Figure 2: Composition of generation capacity in Mexico



Source : Comisión Federal de Electricidad (2009)

[27] Rosellón (2007) states that [despite the lack of any major reforms in the Mexican electricity sector, an internal (or shadow) market is being implemented by the CFE in a nodal manner since September 2000. This virtual market seeks to emulate a competitive market. It employs a merit-order rule for generation dispatch in a one –day market as well as in a real-time market. It employs a merit order rule for generation dispatch in a one-day-ahead market as well as in a real-time market. The one-day-ahead market establishes production, consumption, and price schedules for each hour of the following day. The differences between predicted an actual schedules are cleared at real-time prices. Bids are actually submitted to the system operator Centro Nacional de Control de Energia (or Cenace), by the CFE's various "programmable" generation plants, which are separated administratively to function as different power producers.], p. 3005.

3.3 Regulation in the Mexican electricity sector

Regulation is quite a new thing in the Mexican economy and the energy sector is not the exception. Mexican government controls the electricity system through the Energy Ministry and Energy Regulatory Commission.[28]

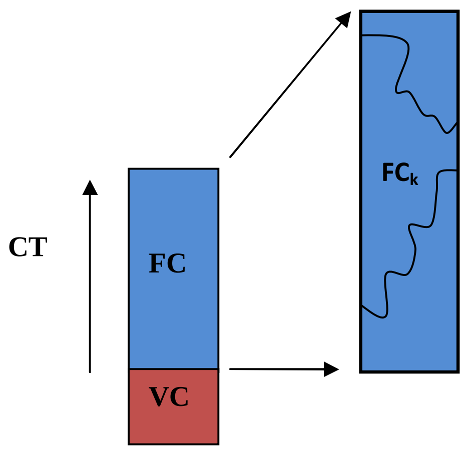
The Energy Regulatory Commission (CRE) created in 1995, is in charge for the establishment of methodologies to open access transmission rates that the public companies will charge to the network users, (Madrigal, 2006).

To understand the regulatory mechanism applied on the transmission system, Madrigal et al. (2006) explain that [The general economic principle governing the Mexican open-access transmission tariff methodologies are based on long-term cost recovery of transmission investment costs. The long term transmission investment cost (CT) is then allocated to all the users of the transmission system according to the transmission pricing methodology issued by the Energy Regulatory Commission (CRE). Among the several variations existing to allocate transmission costs, three mayor categories can be identified: (i) pancaking or simple license plate cost allocation, (ii) cost allocation based on transmission usage, and (iii) cost allocation based on marginal cost information. The methodology used in Mexico to price transmission services for third-parties using the national transmission and distribution networks... distributes the long term transmission cost (CT) based on a modified Megawatt-Mile method (category i) that takes into account the intensity of transmission usage (category ii) by each party; variable cost incurred by transmission losses are also allocated to transmission users.], p.1, 2.

[28] Madrigal et al., (2006) state that [Power system planning in Mexico is part of a national energy planning process, which in turn defines fuel policies and diversification strategies to coordinate the execution of alternative projects, such as hydroelectric, geothermal and nuclear power plants.], p.3.

Currently, the megawatt-mile method charges for transmission services for tensions equal to or greater than 69 kV calculated as the maximum between "fixed costs plus variable costs" and "operation and maintenance costs". Administrative fixed costs are then added to this amount. Fixed costs are basically the long-run incremental costs of the transmission network. They are allocated among consumers of the current grid and consumers of the future expanded grid according to their impact across the entire network, (Madrigal and Cagigas, 2003; Madrigal et al, 2006; Rosellón, 2007). See figure 3.

Figure 3: Transmission pricing in Mexico: Fixed costs and Variable costs allocation, based on a modified Megawatt Mile and Transmission Usage Method.



The fixed cost (FC) is allocated to recover the long-term transmission investment costs (CT); while the variable cost (VC) is set to recover the transmission losses generated by each transaction. The fixed cost allocated to transaction k, (FC_k) is based on transaction's use of the transmission system. A Megawatt Mile cost is assigned to each transmission element used.

Source: Madrigal et al. (2006)

In general terms, fixed cost is allocated to according the use of the transmission system and a $/MW mile cost representation of the transmission system the use of the transmission system. The use of the transmission system is measured in terms of the impact in transmission flows of each transaction; the more congestion is cause in the system, the more it pays for the use of the system.

Formally,

The fixed cost to be paid by each third-party usage of the transmission to each transaction *k*, *(FC_k)* is computed by identifying the use of the transmission system through a classic "with and without transaction" power flow impact scenarios. In particular, the fixed cost allocated to each transaction is determined as the cost-usage ratio:

$$FC_k = \left[\frac{FC}{FC_{k,with} + FC_{k,without}}\right] FC_{k,with} \tag{1}$$

The fixed cost is therefore fully distributed to the third parties users of the transmission system (with the transaction). The correspondent cost impact, with and without the transaction, is evaluated by multiplying the transaction impact in each line *ij* transmission flow and its $/MW Mille cost, such that:

$$FC_{k,with} = max\left\{\sum_{\forall ij} w_{ij}\left(F_{ij,with} - F_{ij,without}\right), 0\right\} \tag{2}$$

Where,

$$FC_{k,without} = \sum_{\forall ij} w_{ij} F_{ij,without} \tag{3}$$

$F_{ij,with}$ and $F_{ij,without}$ are the maximum power flows in transmission line *ij* when transaction *k* is considered and not considered respectively.

The variable cost allocated to each transaction *k*, (VC_k) is set in the following form:

$$VC_k = \rho_e\left[\left(\sum_{\forall ij}\left(F_{ij,with} - F_{ji,with}\right) - \sum_{\forall ij}\left(F_{ij,without} - F_{ji,without}\right)\right)\right] \tag{4}$$

This expression estimates the transmission losses in each network element incurred when adding the transaction in the system. ρ_e stands for a short-run marginal valuation of the energy cost.

3.4 The Mexican transmission system

The national transmission network is formed by a system based on 400, 230, 161 and 150 kilovolts (kV) lines that cover most of the country. By the end of November, 2008 the length of transmission network has reached 49,004 km.

Table 1 shows the composition of the transmission system.

Table 1 Length of transmission lines (km)

Voltage level (kV)	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008*
400	12,399	13,165	13,695	14,504	15,998	17,790	18,144	19,265	19,855	20,364
230	21,224	21,598	22,645	24,060	24,773	25,687	27,148	27,745	28,164	28,093
161	456	508	508	646	470	475	475	475	547	547
150	0	0	0	0	0	0	0	0	0	0
Total	34,079	35,271	36,848	39,210	41,241	43,952	45,767	47,485	48,566	49,004

Source: Comisión Federal de Electricidad (2009)

Through electricity substations conversion of electricity (voltage and current) occurs. This process known as transformation helps moving electricity from transmission to distribution centers. By late November 2008, a total capacity of 187,296 MVA was available, out of which 76.7% are transmission substations and 23.3% distribution substations.

Table 2 offers a description of substations capacity by types.

Table 2: Substations capacity (MVA)

Type of Substation	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008*
Transmission	104.5	107.8	113.5	119.7	125.0	128.8	134	137.0	141.7	143.7
Distribution	29.8	31.6	33.0	36.2	37.7	38.7	39.7	41.0	42.7	43.6
Total	134.4	139.5	146.6	155.9	162.7	167.6	174.4	178.0	184.4	187.3

MVA = million volt-amperes

Source: Comisión Federal de Electricidad (2009)

The national network is managed by the transmission system operator (Centro Nacional de Control de Energía or CENACE), through eight control centers that coordinate the operation at regional level, and a national center that defines the operation policies and the security standard, (Madrigal et al., 2006).

The state-owned electric utility CFE is in charge to perform expansion power planning, finding out the optimal capacity structure to be developed in generation and transmission in Mexico.[29]

The Mexican transmission network capacity is having problems meeting efficiently a growing electricity load demand. As a result, congestion in transmission lines isolate important regions in the south-east and north of the country, by limiting the number of generators that generally supply local consumers (Hartley and Martinez-Chombo, 2002; Rosellón, 2007). Hence,

[29] Madrigal et al. (2004) state that [One of CFE's main reasonability is to perform the centralized technical planning of the electricity energy sector; this resulting generation and transmission plan is then evaluated by the minister of Energy and the minister of Finance in order to find the best investment arrangement to cope with the need of the plan.], p.1.

investments in the Mexican transmission capacity are likely to be necessary to minimize congestion costs, power losses, to maintain reliability and to mitigate market power in local generators.[30]

Some areas of the country such as the southeast and the peninsular regions (Yucatan and Baja California), remain isolated given the limited transmission capacity. The links to the main national grid are small overcrowded lines, which make these regions to experience an overfull transmission congestion and market power of generators inside the congested areas.[31]

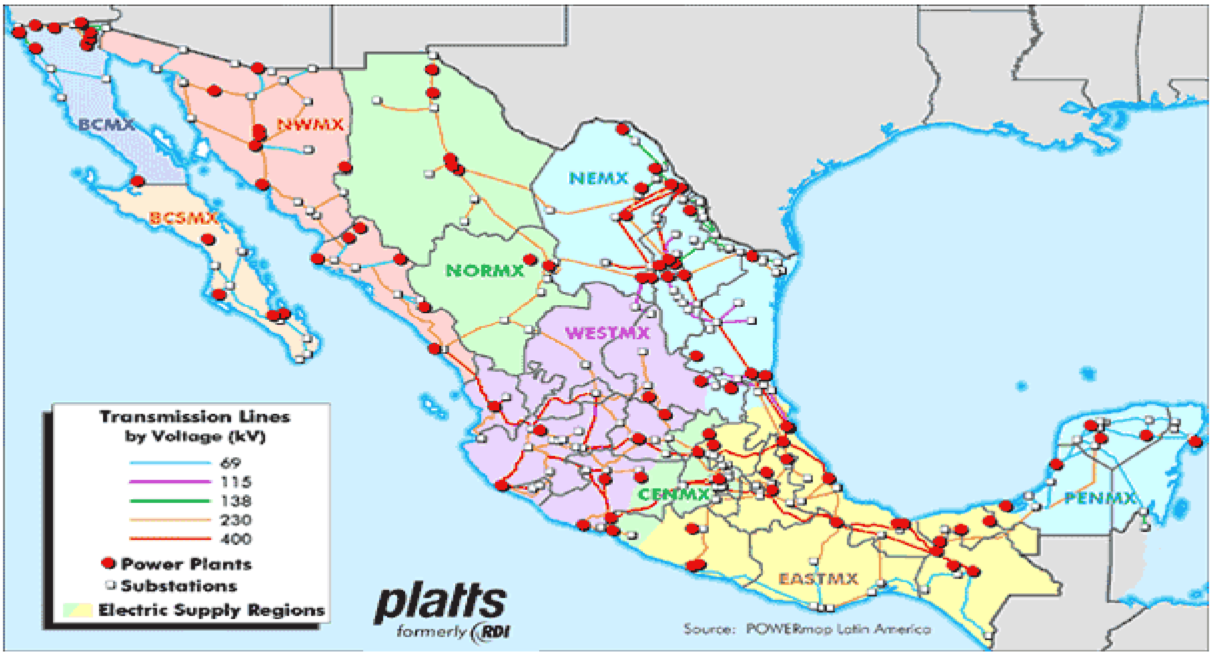
In terms of transmission congestion, Rosellón (2007) mentions that congestion rents in Mexico are equivalent to 1.4 billion dollars US each year.

Figure 4 shows the Mexican transmission network for the 32 regions of the Mexican electricity system.

[30] Rosellón (2007) states that [To meet an annual growth rate of 5.6% in electricity demand projected between 2002 and 2011, transmission capacity has grown from 12,740 MW in 2001 to 25,985 MW in 2006, an average annual growth rate of about 21%. This rate represents a huge increase compared with the historic 3.7% annual growth rate of transmission capacity. This trend has required annual investments of 3 billion dollars, which have been carried out directly either through public budgets (46%) or through financed public projects known as Pidiregas (54%).], p. 3005. Based on the approach that relies on build, lease and transfer (BLT) projects, Pidiregas are contracts for public projects that the Mexican government offers to private investment under a competitive bidding process carried out by CFE. The projects are paid with public funds through long-term contracts where final ownership is public.

[31] Hartley and Martinez-Chombo (2002), state that [The value of additional links in Mexico is even more apparent in the Baja California peninsula. Currently, there are two systems in Baja that are not connected to the rest of the Mexican grid, although the system in the north of Baja is connected to the United States via California. The marginal costs of generation are in Baja California higher than they are anywhere else in the country.], p.31.

Figure 4: Mexican electricity transmission network



Source: Global Energy Network Institute (2009),

The Mexican transmission expansion planning is based on a minimum cost analysis that selects projects which are least cost options. Basically, the methodology contains four stages: 1) the definition of a group with feasible generation scenarios, 2) development of minimum cost transmission plans for all the generation scenarios, 3) schedule of transmission programs required during the corresponding period, identifying both, priorities and optimum timing to develop each project, 4) classification of transmission projects for implementation purposes, identifying robust programs, when these exist, (Madrigal et al., 2004).

As previously stated, transmission tariffs in Mexico are set by a megawatt-mile method. However, Rosellón (2007) considers that [This method provides no proper effective incentives for expanding the grid and relies instead on a subjective way of allocating costs among consumers according to their so-called permuted impact on the grid.], p.3003.

The Mexican transmission system highlights the need of an alternative in transmission expansion planning. Different objectives in the planning process have to be considered in order to determine the optimal expansion of the grid, guaranteeing: 1) balance among forecasted electricity supply and demand, 2) minimization cost that include investment, operation and loss of load costs, 3) reliability, and 4) that network constraints are satisfied.

This situation favors a methodology based in multi-objective optimization technique for transmission expansion planning in Mexico.

4. The Model

This section follows Alseddiqui and Thomas (2006).

4.1 Notions

The transmission expansion planning optimization problem will focus three main objectives: i) total operating cost, ii) investment/construction cost and iii) contingency analysis. Those objectives will be subject to network constraints.

Basically, total operating cost is related to the cost of generation needed to meet the demand; so the total operating cost problem of a system with "n" buses considering both real and reactive power can be expressed as:

$$\min_{P_g,Q_g} \sum_i^n f_{1i}\left(P_{gi}\right) + f_{2i}\left(Q_{gi}\right) \tag{5}$$

Otherwise, if only real power is included in the cost, the problem is formulated as follows:

$$\min_{P_g} \sum_i^n f_{1i}\left(P_{gi}\right) \tag{6}$$

Where:

n: Number of buses

f_{1i}: Real power generation cost for generator at "i"

f_{2i}: Reactive power generation cost for generator at "i"

P_{gi}: Real power generated by generator at bus "i" (if no generator at bus "i", P_{gi}=0)

Q_{gi}: Reactive power generated by generator at bus "i" (if no generator at bus "i", P_{gi}=0)

Now, to identify those projects that embody the least cost options, minimization of investment/construction cost is essential in any transmission expansion planning methodology.

This objective can be represented in the following way:

$$\min_u u^t\, c(x) \tag{7}$$

Where:

u: Binary decision vector for plan choice

$c(x)$: Investment/construction cost function

The contingency analysis objective in the other hand, verifies the state of the system when a hypothetical failure of a component arrives. The most commonly method used is the n-1 contingency analysis, designed to simulate the power system after one component is taken out from the system, checking if the network constraints still hold once the system is re-run.

The network constraints are the system limits that have to be satisfied at all times in every electricity system, in order to ensure reliable and secure the system operation. Two sets of limits are considered: a) Power balance equations that are the basic constraints to be satisfied for a feasible power system operation. ii) Physical limits of the equipment, such as voltage magnitude on buses, thermal limits and real and reactive power generation limits.

The mathematical expressions for the network constraints are:

$$P_i(V,\vartheta) - P_{gi} + P_{Li} = 0 \qquad (8)$$

$$Q_i(V,\vartheta) - Q_{gi} + Q_{Li} = 0 \qquad (9)$$

$$|S_{mn}| \leq S_{mn}^{max} \qquad (10)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad (11)$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \qquad (12)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \qquad (13$$

Where (10) and (11) are the power balance equations

$$P_i(V-\vartheta) = V_i \sum_{l=i}^{N} \left[V_l[g_{il}\cos(\delta_i-\delta_l) + b_{il}\sin(\delta_i-\delta_l)]\right] \qquad (14)$$

$$Q_i(V-\vartheta) = V_i \sum_{l=i}^{N} \left[V_l[g_{il}\sin(\delta_i-\delta_l) + b_{il}\cos(\delta_i-\delta_l)]\right] \qquad (15)$$

$$g = \frac{r}{r^2+x^2} \qquad (16)$$

$$b = \frac{-x}{r^2+x^2} \tag{17}$$

Where,

V_i: Voltage magnitude at bus "i"

δ_i: Voltage angle at bus "I"

r: Resistance

x: Reactance

V_i^{min}: Minimum voltage magnitude limit at bus "i"

V_i^{max}: Maximum voltage magnitude limit at bus "i"

P_{gi}^{min}: Minimum real power generation for generator at bus "i"

P_{gi}^{max}: Maximum real power generation for generator at bus "i"

Q_{gi}^{min}: Minimum reactive power generation for generator at bus "i"

Q_{gi}^{max}: Maximum reactive power generation for generator at bus "i"

P_{Li}: Real power load at bus "i"

Q_{Li}: Reactive power load at bus "i"

S_{mn}: Complex power flow on line from bus "m" to bus "n"

S_{mn}^{max}: Maximum complex power flow on line from bus "m" to bus "n"

4.2 Problem Formulation

The expansion planning optimization problem faces three objectives subject to transmission constraints. It is assumed that the total operating cost takes the form of a quadratic generator cost curves, while the construction cost function is assumed to be linear. Given the nature of the contingency analysis, it will not be directly included into the multi-objective optimization; however, it will be considered for each Pareto solution obtained from the multi-objective optimization.[32] The proof that Pareto-optimal solutions stay Pareto-optimal after contingency analysis is given in Alseddiqui (2005).

The formulation of the multi-objective optimization problem can be stated as:

$$\min_{P_g,u}\begin{pmatrix}\sum_i^n f_i(P_{gi})\\ \sum_j^p u_j c\end{pmatrix} \tag{18}$$

Subject to:

$$P_i(V,\delta)+\sum_j^p u_j \Delta P_j^i(V,\delta)-P_{gi}+P_{Li}=0 \tag{19}$$

$$P_i(V,\delta)+\sum_j^p u_j \Delta P_j^i(V,\delta)-P_{gi}+P_{Li}=0 \tag{20}$$

$$\left[\sum_j^p u_j\right]-1=0 \tag{21}$$

$$|S_{mn}| \le S_{mn}^{max} \tag{22}$$

$$u^T|S_c| \le S_c^{max} \tag{23}$$

$$V_i^{min} \le V_i \le V_i^{max} \tag{24}$$

[32] Alseddiqui (2006), remarks that [In multi-objective optimization, “optimal” solutions are called “Pareto-optimal” solutions. A solution vector x^* is Pareto-optimal if there does not exist another solution vector $x \epsilon S$ such that:
$f_i(x) \le f_i(x^*)$, for all objectives $i=1,2,\ldots$, number of objectives.
$f_j(x) \le f_j(x^*)$, for at least one objective j.
Where:
S: feasible region
Whereas, a solution vector x^* is weakly Pareto-optimal if there does not exist another solution vector $x \epsilon S$ such that:
$f_i(x) < f_i(x^*)$, for all objectives i
Note that every Pareto-optimal point is an equally acceptable solution for the multi-objective optimization and the choice is left for the decision maker.], p. 4, 5.

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad (25)$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad (26)$$

Where:

p: Number of plans in binary decision vector u

$\Delta P_j^i(V,\delta)$: Change in the $P^i(V,\delta)$ term at bus "*i*" when plan "*j*" is chosen

$\Delta Q_j^i(V,\delta)$: Change in the $Q^i(V,\delta)$ term at bus "*i*" when plan "*j*" is chosen

S_c: Complex power flow on constructed line

S_c^{max}: Maximum complex power flow on constructed line

A single-objective formulation of the multi-objective problem is needed to solve the multi-objective problem. A modified weighted metrics single-objective is used in this case in the form:

$$\min_{P_g,u} \left\{ w\left[\sum_i^n f_i\left(P_{gi}\right) - z_{opcost}^{**}\right]^2 + (1-w)\left[\left[\sum_j^p u_j\, c\right] - z_{ccost}^{**}\right]^2 \right\}^{1/2} \quad (27)$$

Subject to:

$$P_i(V,\delta) + \sum_j^p u_j \Delta P_j^i(V,\delta) - P_{gi} + P_{Li} = 0 \quad (28)$$

$$P_i(V,\delta) + \sum_j^p u_j \Delta P_j^i(V,\delta) - P_{gi} + P_{Li} = 0 \quad (29)$$

$$\left[\sum_j^p u_j\right] - 1 = 0 \quad (30)$$

$$|S_{mn}| \le S_{mn}^{max} \quad (31)$$

$$u^T |S_c| \le S_c^{max} \quad (32)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{33}$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \tag{34}$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \tag{35}$$

Where:

w: Weight specified by multi-objective optimization

$z^{**}{}_{opcost}$: Utopian vector element of minimum total operating cost objective

$z^{**}{}_{ccost}$: Utopian vector element of minimum investment/construction cost objective

The Pareto-optimal solutions for the non-convex optimization problem presented here are "locally" Pareto-optimal. Alseddiqui (2005) discusses the possibility of multiple local minimum Optimal Power Flow solutions.

4.3 Multi-Objective Optimization

To solve multi-objective optimization problems, concepts of ideal vector z^* and utopian vector z^{**} are used as reference points. Assuming the conflicting aspect of the three objectives, the utopian vector z^{**} characterizes an impossible scenario that serves to find a feasible solution as close as possible to z^{**}.[33]

[33] Alseddiqui and Thomas 2006 justify that [The utopian vector z^{**} is used because it is easier to get the "utopian" total operating cost of the system in a full AC optimal power flow; it will be the optimal power flow; it will be the optimal power flow with no losses and no congestion. Another reason for choosing the utopian vector as the reference vector is because there is uncertainty over conflicts between objectives; sometimes they might be conflicting, other times not.], p.6.

The elements of the ideal vector z^* are the minimum possible values for each objective (in the case of minimization problems), such that:

$$z^* = \min_x f_i(x) \tag{36}$$

Subject to:

$$x \in S \tag{37}$$

Where:

x: Decision vector

S: Feasible objective space

In the other hand, the elements of the utopian vector z^{**} are the same values as the elements of the ideal vector z^*, but with a positive number subtracted from them (in the case of minimization problems); i.e.

$$z_i^{**} = z_i^* - \xi_i \tag{38}$$

A comparison between different methods used to solve multi-objective optimization problems is presented in table 3.

In particular, the Weighted Metrics Method will be used given the advantage of generating Pareto-optimal solutions.

Table 3: Comparison between different methods for solving Multi-Objective Optimization Planning (MOOP)

Method	Characteristics		Example
	Advantage	Disadvantage	
No preference Methods	MOOP is solved using simple methods.	Not all solutions found are Pareto-optimal.	Multi-objective Proximal Bundle Method.
A posterior Methods	Generates Pareto-optimal solutions.	Difficult and computationally intensive.	Weighted Metrics Method.
A priori Methods	Decision maker preferences are taken into consideration before MOOP is solved.	Decision maker preferences may be infeasible.	Goal Programming, Lexicographic Ordering Method.
Interactive Methods	Decision maker preferences are taken into consideration.	Decision maker preferences and choices have to be available “interactively” during the solving process.	GUESS Method, Light Bearn Search Method.

Source: Alseddiqui and Thomas (2006)

Essentially, the weighted metrics method solves a multi-objective optimization problem by transforming it into a single-objective optimization problem, and minimizing the distance between some-chosen-reference point and the feasible objective space. The single-objective optimization problem for the Metric method can be expressed as:

$$\min_x \left(\sum_{i=1}^{k} \left|f_i(x) - z_i^{ref}\right|^p\right)^{1/p} \tag{39}$$

Subject to:

$$x \in S \tag{40}$$

Where:

x*:* Decision vector

p*:* the metric used to measure the distance between the reference point and the objective feasible region.

S*:* Feasible region

$f_i(x)$*:* Objective function for objective "i".

z_i^{ref}*:* Element "i" (for objective "i") of the reference vector.

k*:* Number of objectives

As previously stated, the Weighted Metrics Method generates a set of Pareto-optimal solutions. With this method, each objective receives a weight and the Weighted Metrics (a technique in the field of Compromise Programming), single-objective is solved several times (as desired) to generate different Pareto-optimal solutions. The Weighted Metrics single-objective optimization problem can be seen as:

$$\min_x \left(\sum_{i=1}^{k} w_i \left|f_i(x) - z_i^{ref}\right|^p\right)^{1/p} \tag{41}$$

Subject to:

$$x \in S \tag{42}$$

Where:

w_i*:* Weight for objective "i"

$0 < w_i < 1$

$$\sum_{i=1}^{k} w_i = 1$$

Provided that the weights $w > 0$, any solution found using the weighted Metric technique is a (locally) Pareto-optimal solution. Given that the optimization problem is considered nonconvex, the solutions found are locally Pareto-optimal, (Alseddiqui, 2006).

4.4 Single-Objective Optimization Problem

Since the multi-objective optimization problem will be transformed into a single objective optimization, it becomes necessary to choose a proper technique to solve the single-objective minimization problem, taking in consideration the quality of the solutions and the rate of convergence. In this sense, the mixed-inter-algorithm chosen is a Modified Nonlinear Branch and Bound algorithm.

Particularly, Alseddiqui, (2006) explains that [The Branch and Bound algorithm creates a tree structure of nodes and uses a deterministic search approach to find a solution for the (relaxed) minimization problem (using the Newton-Based Trust Region Method). A fundamental concept of Branch and Bound is fathoming; fathoming is a set of criterions that stop the search down a sub-tree of a node if one of the criteria is applicable to that higher than any discrete solution found, or if the relaxed solution at a node has integer values for the discrete decision variables, then no search down the sub-tree of that node will take place; those are fathoming conditions. The initial upper bound z^{upper} for the Branch and Bound algorithm will be selected as the initial total system cost and the most expensive line to invest-in/construct. That is:

$$z^{upper} = \left(\sum_{i}^{n} f_i\left(P_{gi}\right)\right) + \max\left(u^T c\right) \tag{39}$$

The upper bound z^{upper} will be continuously updated by the algorithm as it finds better solutions. (Note: when modifying the terms in the single-objective formulation for numerical purposes, such as normalization, the appropriate modifications on z^{upper} have to be considered). It is imperative to change the fathoming conditions accordingly to suit the nature of the nonlinear problem since the generic Branch and Bound fathoming conditions work best for linear problems. A shortcoming of the Branch and Bound algorithm is its speed; it is definitely not fastest mixed-integer solver. Nevertheless, it has a good solution quality and it is faster than complete enumeration because of the fathoming conditions and the relaxation], p. 6.

4.5 Multi-Objective Optimization for Transmission Expansion

In terms of the metric p used for the Weighted Metrics method, Alseddiqui and Thomas (2006) assumed 2, while for the reference vector z^{ref} he choose the utopian vector z^{**}.

The utopian vector z^{**} presented as follows:

$$z^{**} = \begin{bmatrix} z^{**}_{op\ cost} \\ z^{**}_{c\ cost} \end{bmatrix} = \begin{bmatrix} \min_{P_g} \sum_i^n f_i(P_{gi}) \\ 0.9\min(c) \end{bmatrix} \tag{40}$$

Essentially, the objective of the single-objective optimization problem is to minimize the distance between the potential solution and the reference solution. In order to achieve this goal, normalization of the distances will be used so that the single-objective optimization considers “relative” distances in the calculations.

Finally, the model for the single-objective optimization problem can be stated as follows:

$$min\left\{w\left[\frac{\left(\sum_i^n f_i(P_{gi})-z_{op\,cost}^{**}\right)}{z_{op\,cost}^{**}}\right]^2+(1-w)\left[\frac{\left(\sum_j^p u_j c\right)-z_{c\,cost}^{**}}{z_{c\,cost}^{**}}\right]^2\right\}^{1/2} \tag{41}$$

Subject to:

$$P_i(V,\delta)+\sum_j^p u_j\,\Delta Q_j^i(V,\delta)-P_{gi}+P_{Li}=0 \tag{42}$$

$$Q_i(V,\delta)+\sum_j^p u_j\,\Delta Q_j^i(V,\delta)-Q_{gi}+Q_{Li}=0 \tag{43}$$

$$\left(\sum_j^p u_j\right)-1=0 \tag{44}$$

$$|S_{mn}|\le S_{mn}^{max} \tag{45}$$

$$u^T|S_c|\le S_c^{max} \tag{46}$$

$$\mathrm{V_i^{min}}\le \mathrm{V_i}\le \mathrm{V_i^{max}} \tag{47}$$

$$\mathrm{P_{gi}^{min}}\le \mathrm{P_{gi}}\le \mathrm{P_{gi}^{max}} \tag{48}$$

$$\mathrm{Q_{gi}^{min}}\le \mathrm{Q_{gi}}\le \mathrm{Q_{gi}^{max}} \tag{49}$$

4.6 Assessing Network Security after Contingency

As previously stated, the contingency analysis part can be done after the multi-objective optimization of total system cost and investments/construction cost is made, preserving the Pareto-optimal solutions.

This means that the contingency analysis will be applied to the Pareto-optimal solutions, under the criteria that if a single contingency leads to a system failure then the whole network is not n-1 reliable, and if all the contingencies (individually) do not lead to any system failure then the network is n-1 reliable.

In a particular way, it is required that the voltage and flow in the network remain within limits to prevent a cascade failure for the whole system. Therefore, reliability of the network is assessed offline for different loads (usually peak-load, but that does not mean the network will be n-1 reliable if the load was less than peak-load and a contingency occurs).

5. Conclusions

Nowadays, expansion of the Mexican transmission grid depends solely in a minimum cost objective. However, a new formulation was proposed for transmission expansion planning in the Mexican electricity system to reduce congestion problems. The new methodology reveals the chances to optimize transmission expansion using several objectives and constraints.

Specifically, a multi-objective transmission planning model is considered focused on three main objectives (assuming conflict or uncertainty issues among them): 1) total system cost, 2) investment-cost and 3) contingency analysis. The multi-objective optimization problem faces network constraints defined as a set of limits that have to be satisfied at all times, in order to secure system operation and maintain reliability.

The methodology comprises a non linear mixed-integer multi-objective and single objective optimizer. Based on the Pareto optimality criteria, the methodology first locates the Pareto-optimal set comprised in the solution space. Then, ranks the Pareto-optimal set according to a specific preference structure, resulting a model that guides the transmission expansion economically and reliably.

Cases studies have to be carried out on the Mexican electricity system to prove the effectiveness of the methodology proposed in this study. That will be part of a further research, focusing on the uncertainty parameters presented in the transmission expansion planning.

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Annex

The following section follows Léautier (2000).

Consider a N-node, L-line power network for $n = 1, \dots N$ and l=1,…,L

q_n^S q_n^D, and $q_n = q_n^S - q_n^D$ are respectively the real energy generated, the real energy consumed, and the net real energy injected at node n. at any instant, z_l cannot exceed the capacity of line l, denoted K_l. unless specified otherwise, q_n, z_l are measured in Megawatts-hours (MWh), while K_l is measured in Megawatts (MW).

$q \in R^N$ is the vector of net injections, $z \in R^L$ and $K \in R^L$ the vectors of z_l and K_l. The capacity vector K is our proxy for the stock of capital. Without loss of generality, we assume that K lies within a rectangular box $\Omega \in R^L$.

To describe the laws that rule power networks, three issues must be considered: energy balance, power flow equations, and transmission capacity constraints.

Energy Balance: at every instant, power generation equals power consumption plus transmission losses

$$\sum_{n=1}^{N} q_n^S = \sum_{n=1}^{N} q_n^D + \hat{L}(z)$$

Where

$\hat{L}(z)$ are the transmission losses for a vector $z \in R^L$ of power flows.

Only (N-1) net injections are independent. As is customary in the power engineering literature, we write the power flow equations as a function on only the (N-1) independent net injections, and call the node which is not represented the "swing node" or "swing bus". Without loss of generality, we choose it to be node N. $q \in R^{N-1}$ is the truncated vector of net injections.

Power flows equations suggest that, the power flow on a transmission line is a highly nonlinear function of the difference between the phase angles at the extremities of the line. For most purposes, planners use a linear representation of power flows, known as the DC Load Approximation, power flows are proportional to a line's admittance Y, and the difference between phase angles at the extremities of the line δ.

$$z = Y \cdot \delta$$

The admittance is determined by the physical characteristics of the line, see Glover and Sarma (1993) for details.

Schweppe et al. (1988) show that we can write the power flows z_l as linear functions of the net injections q_n

$$z = H \cdot q$$

Furthermore, Schweppe et al. (1988) show the transmission losses are a quadratic form in q

$$\hat{L}(z) = L(q) = q^T \cdot B \cdot q$$

Where $B \in R^{N-1} \times R^{N-1}$ is symmetric

(mathematical expressions for the matrices H and B are provided n the Appendix)

Transmission capacity constraints take in consideration that the oriented power flow on each transmission line cannot exceed the capacity of a line.

Transmission capacity limits arise from two causes: physical limits on the lone (thermal, voltage, and steady-state stability constraints), and operating limits. Thermal constraints for example, imply that after a certain threshold, called the rated capacity, the line heats up and its probability of failure increases dramatically. Operating limits arise from the need to protect the system against contingency. For example, the loss of a generating unit would instantaneously redistribute power on all transmission lines, and the resulting flow would exceed the physical limit.

Grid operators can choose among different techniques to increase the capacity of a transmission path, depending on the cause of the constraint, and on the cost and feasibility of different alternatives. The simplest technique is to add another set of cables to a line, if the towers can bear the additional weight. Alternatively, the existing cables can be replaced by cables with higher capacity (against subject to tower carrying capacity).

Congestion cost can be defined as the difference between the price paid to generators and the price that would have been paid absent congestion. From this definition, it can be stated the following lemma.

Lemma The total operational Out-turn is the sum over all generation nodes of the integral of the marginal generation cost ($c_n(x)$), minus the “unconstrained” price (p), where the integral is taken between the “unconstrained” and the constrained generation:

$$U = \sum_{n=1}^{N} \int_{q_n^{su}}^{q_n^{s*}} [c_n(x) - p]dx$$

Where q_n^{su} is the unconstrained generation at node n, and q_n^{s*} is the constrained generation at node n], p.72.

Transmission line load flow model

The following section follows Hogan (2002).

In essence, every alternating current (AC) electrical network contains two types of power flows: real and reactive. The real power flow is defined as the average value of the instantaneous power and is the active or useful power, measured in Mega-Watts (MWs). In the other hand, reactive power represents a nonactive power that travels back and forth over the line and has average value of zero. The reactive power flow is measured in Mega-Volt-Amperes-Reactive (MVARs).

The combination of real and reactive power flow is the apparent power in Mega-Volt-Amperes (MVA), which is a measure of the magnitude of the total power flow.