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Optimal Transmission Planning under the Mexican New Electricity Market

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Abstract

This paper addresses electricity transmission planning under the new industry and institutional structure of the Mexican electricity market, which has engaged in a deep reform process after decades of a state-owned vertically-integrated non-competitive closed industry. Under this new structure, characterized by a nodal pricing system and an independent system operator (ISO), we analyze welfare-optimal network expansion with two modeling strategies. In a first model, we propose the use of an incentive price-cap mechanism to promote the expansion of Mexican networks. In a second model, we study centrally-planned grid expansion in Mexico by an ISO within a power-flow model. We carry out comparisons of these models which provide us with hints to evaluate the actual transmission planning process proposed by Mexican authorities (Prodesen). We obtain: 1) the Prodesen plan appears to be a convergent welfare-optimal planning process, and 2) incentive regulation in Mexico could further help to implement such an optimal process.

Palabras clave: **Keywords: Electricity market reform, vertical and horizontal disintegration, transmission planning, nodal prices, Mexico**

Resumen

Este trabajo tiene por objetivo analizar el proceso de planeación de la transmisión eléctrica en el contexto del nuevo esquema del mercado eléctrico en México, que ha entrado en un profundo proceso de reforma después de décadas de tener una estructura verticalmente integrada donde la empresa estatal controlaba todo el sector. Bajo esta nueva estructura, que permite el uso precios nodales y la existencia de un operador independiente (ISO), analizamos la óptima expansión de la red de transmisión utilizando dos estrategias de modelación. Se propone un primer modelo de regulación por incentivos, precio máximo, para promover la expansión de la red. El segundo modelo plantea la existencia de un planeador central que utiliza modelos de flujo de energía para tomar las decisiones de expansión. Se realizan comparaciones entre ambos modelos con el fin de proporcionar pistas que permitan evaluar el proceso actual de expansión de la red (Prodesen) propuesto por las autoridades mexicanas. Se obtiene que: i) el plan propuesto por el Prodesen parece ser un proceso de planeación de maximización de bienestar convergente y ii) la regulación por incentivos puede contribuir a la implementación tal proceso óptimo.

Palabras clave: **Reforma del mercado eléctrico, desintegración horizontal y vertical, planeación de la transmisión, precios nodales, México**

Introduction

Until 2015, Mexico had been characterized by an industrial structure with a vertically integrated state owned monopoly, the Comisión Federal de Electricidad (CFE), which exclusively carried out almost all activities in electricity generation, transmission, distribution and marketing, as well as the operation of the entire electricity system.[1] The idea of the Mexican electricity reform, passed by congress by mid-2014, is to now evolve from this closed system with asymmetrical information between CFE and the energy regulator (Comisión Reguladora de Energía-CRE) to a more open and transparent one, where the generation sector is liberalized so that new private generators enter the market to compete with incumbent CFE's generating plants.

The new electricity market in Mexico starts operations in January 2016. For the first time in many decades, actual commercial exchange between private generators and consumers will then be possible. This in itself represents a significant change in the organization of Mexican electricity markets. Moreover, another deep transformation implied by the reform relates to electricity system operation. This function is now to be taken out from CFE's hands and left to an *independent* system operator (ISO), the Centro Nacional de Energía (CENACE), which will be in charge of both the short and long-run system operation as well as of electricity-grid expansion planning. The rest of the industry areas --including transmission, distribution, marketing activities and supply in the retail market-- remain within CFE, but with the aim of sub-contracting private agents through competitive tenders.

Another crucial decision of the reform is radical transformation of the electricity pricing system, evolving from a complex regressive subsidize system (see López-Calva and Rosellón, 2002) to a more transparent pricing scheme based on nodal prices, financial transmission rights (FTRs), and direct lump-sum subsidies.

The Mexican electricity reform of course also requires both expansion and reshaping of the current transmission network to specifically accommodate the expected growth in electricity generation, and the integration of increasing renewable energy sources of electricity. The foreseen growth in electricity demand for 2003-2028 (85%) can be compared against the corresponding expected growth of transmission capacity (18%). In its recent 15-year plan, CFE has in fact gauged 19.3 billion USD in transmission projects including 19,555 circuit-km of new lines. Compared to its main North American trade partners (USA and Canada), where electricity transmission capacity usually expands faster than demand growth, it is evident that Mexico should become much more aggressive in promoting investment in transmission lines, both in terms of planning and regulatory measures.

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[1] Only some cogeneration and self-supply activities were allowed to private generators under restrictive conditions on their surplus power (that had to mainly be sold to CFE). Since 1992, independent-power-production (IPP) projects were also allowed, but only to sell under long-term contracts all of its power to CFE, who subsequently sold it to final consumers.

The approach of Mexican authorities to transmission expansion is to design a national transmission development plan (Prodesen) based on projected electricity demand and generation supply for an extended period (see CENACE, 2015). This projected supply and demand is ex-ante forecasted by the Mexican energy ministry (SENER). CENACE will be actually taking care of grid expansion planning based on a power-flow program that considers in an integrated fashion generation dispatch and transmission expansion.[2] This exercise is to be repeated annually, and will provide CFE (and subcontracted private agents) a guidance on which transmission links to expand. Once a new transmission expansion project is being built, the CRE will regulate it aiming to reach a balance between risk management and incentive provision in the actual process of expanding networks according to Prodesen. The CRE preliminary plans to use a system of tenders (ex-ante competition) to select the private market agents that would cooperate with CFE to develop new transmission links.[3] These tenders would define the transmission tariffs that will be regulated through cost-plus regulation with additional periodical efficiency adjustments based on international price and performance transmission benchmarks.

In this document, we address welfare-optimal expansion of the Mexican transmission grid under a nodal-pricing system. The issue of optimal transmission expansion has been addressed through a range of different regulatory schemes and mechanisms that have been proposed and applied (e.g., Léautier, 2000, Kristiansen and Rosellón, 2006, Tanaka, 2007, Léautier and Thelen, 2009, Hogan et al., 2010). Finding optimal regulatory mechanisms is difficult given the specific physical characteristics of electricity networks like negative local externalities due to loop flows, i.e. electricity flows obeying Kirchhoff's laws. One approach to transmission expansion has been traditional central planning, either carried within a vertically integrated utility or by a regulatory authority. A usual alternative has been cost-of-service regulation. In contrast, transmission decisions could also be determined in a decentralized non-regulated way. The Hogan-Rosellon-Vogelsang price-cap mechanism (Hogan et al. 2010, HRV) is an example of a decentralized regulatory regime which combines merchant and regulatory structures to promote the expansion of electricity networks. The HRV incentive mechanism has been show to promote network expansion in a welfare superior way to cost-plus regulation or no-regulation in a number of studies, even under realistic demand patterns and large-scale renewable integration (e.g., Rosellón and Weigt, 2011, Rosellón et al, 2011, Ruiz and Rosellón, 2012, Schill et al, 2015, Egerer et al, 2015, Neumann et al, 2015).

In this paper we firstly propose a bi-level programming model to study the use of incentive price-cap HRV regulation to incentivize the expansion of Mexican networks. Secondly, we analyze optimal centrally-planned expansion of the Mexican network through the use of a power-flow stylized model where an ISO maximizes

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[2] Integrated transmission planning is not a trivial issue. There are other systems that carry out the transmission expansion process decoupled from generation dispatch, usually resulting in inefficient excessive capacity investments (see Kemfert et al, 2015).

[3] The CRE has only recently published a set of preliminary transitional transmission tariffs based on three-year CFE's transmission costs. The final regulatory methodology for electricity transmission is expected to be announced in the near future.

welfare (the sum of consumer and producer surpluses plus congestion rents), and minimizes the cost of expanding networks. Both models are further compared each other, also relying on simulations for other systems in North America. This exercise provides clues on the welfare-efficiency properties of the expansion plans proposed by CENACE in Prodesen, a planning process which relies purely on a cost minimizing approach. We further show that incentive regulation results in an welfare-optimal expanding process, and therefore should provide the CRE with a hint on how to implement its final regulation on transmission tariffs.

This document is organized as follows. We initially present in section 1 the details of the Prodesen plan, which is based on transmission-cost minimization. In section 2 we develop our models, including data and results. First, 2.1-2.3 present the bi-level regulatory price-cap HRV model that aims to incentivize convergence of transmission tariffs to a welfare-optimal benchmark. Data used is further shown in 2.4, while 2.5 depicts the results of our regulatory model in terms of capacity expansion, congestion and nodal-price convergence. We additionally carry out a comparison of the expansion promoted by the HRV price-cap model in Mexico with similar expansion processes in other regions in North America, as well as with the welfare-optimal planning model of an ISO which centrally decides network expansion. Section four concludes with hints derived from our analyses on the welfare properties of the Prodesen plan, as well as with discussion on needed future research.

The Prodesen plan

The Mexican electricity sector was in 2015 mainly based on fossil-fuel generation capacity (74.1%, 48,530 MW), with the rest of capacity coming from “clean” sources (25.9%, 16,921 MW) including hydro and nuclear. 83% of the total capacity was in hands of CFE (including private IPPs that offer all of their generation to CFE), while the resting 17% capacity belonged to private investors (self-supply, cogeneration, small production and export projects).

The transmission system is composed of 53 regions, 49 of them are interconnected, while 5 regions in northern Baja California region are also connected to the US California system (CAISO) (see Fig. 1). The resting 4 regions conform an isolated group in southern Baja California. In 2014, the total length of transmission lines in tensions from 230 to 400 Kv was 52,815 km, and with tensions between 69 kV and 161 kV was 58,660 km. To keep up with growing electricity demand, CFE recently calculated the need to expand the national network in around 19.3 billion USD of transmission projects, including 19,555 circuit-km of new lines.

FIGURE 1.Transmission regions in Mexico in 2015

Source: SENER

The most recent plan for expanding the national transmission system during 2015-2029, *Prodesen*, relies on a nodal pricing system for the country and on assumptions on development of generation capacity for 2015-2010 (see Fig. 2). Other crucial assumptions are made on projected GNP, fuel costs, energy consumption and demand, clean and renewable energy goals, natural-gas pipeline infrastructure, and renovation of existing old generation plants.[4] In its medium scenario, SENER estimates a need of 59,986 MW of additional generation capacity for 2015-2019, 45.7% of which should come from conventional technologies (27,433 MW), and 54.3% from clean technologies (32,552 MW). It is also estimated that CFE (and its IPPs) would cover 28.9% of these investment needs, while 32.4% should be covered by private entrants to the new electricity market.[5]

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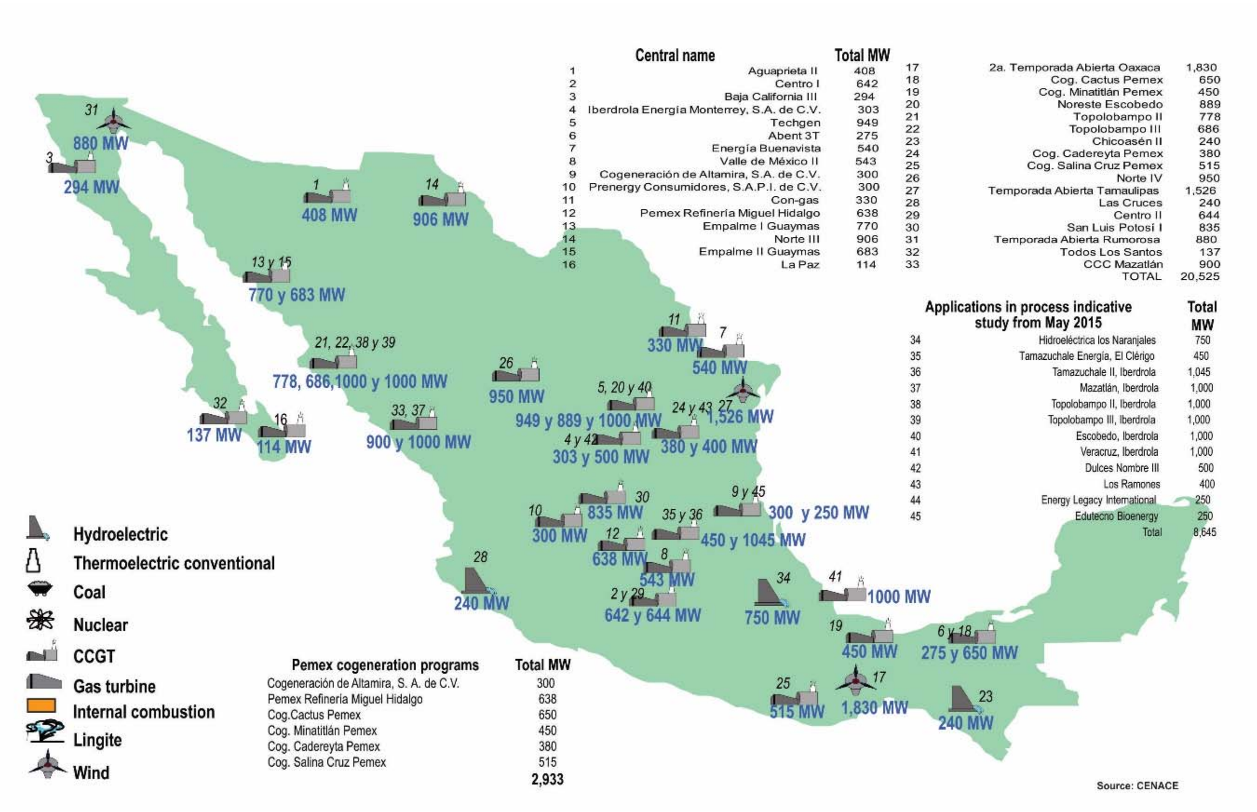
[4] More specifically, *Prodesen* considers three possible macroeconomic scenarios in terms of medium, high and low respective increases of fuel prices, GNP, demand, generation investment (including clean technologies) as well as general system investment costs. The medium scenario, for example, considers an estimated annual GNP growth of 4% in Mexico during 2015-2029, as well as increases of 6.8%, 7.6% y 2.9% in West-Texas-Intermediate (WTI) oil, Mexican-exporting-oil and South-Texas-natural-gas prices, respectively. Further increases in 4% and 3.5% are assumed during the next 15 years for national demand and consumption, respectively, as well as a 13% reserve margin, a 10% discount rate and a 13.5% rate of return.

[5] The rest would be covered by self-supply, cogeneration and small production projects.

FIGURE 2. Main planned generation units for 2015-2020



	Central name	Total MW
1	Aguaprieta II	408
2	Centro I	642
3	Baja California III	294
4	Iberdrola Energía Monterrey, S.A. de C.V.	303
5	Techgen	949
6	Abent 3T	275
7	Energía Buenavista	540
8	Valle de México II	543
9	Cogeneración de Altamira, S.A. de C.V.	300
10	Prenergy Consumidores, S.A.P.I. de C.V.	300
11	Con-gas	330
12	Pemex Refinería Miguel Hidalgo	638
13	Empalme I Guaymas	770
14	Norte III	906
15	Empalme II Guaymas	683
16	La Paz	114
17	2a. Temporada Abierta Oaxaca	1,830
18	Cog. Cactus Pemex	650
19	Cog. Minatitlán Pemex	450
20	Noreste Escobedo	889
21	Topolobampo II	778
22	Topolobampo III	686
23	Chicoasén II	240
24	Cog. Cadereyta Pemex	380
25	Cog. Salina Cruz Pemex	515
26	Norte IV	950
27	Temporada Abierta Tamaulipas	1,526
28	Las Cruces	240
29	Centro II	644
30	San Luis Potosí I	835
31	Temporada Abierta Rumorosa	880
32	Todos Los Santos	137
33	CCC Mazatlán	900
	TOTAL	20,525

	Applications in process indicative study from May 2015	Total MW
34	Hidroeléctrica los Naranjales	750
35	Tamazuchale Energía, El Clérigo	450
36	Tamazuchale II, Iberdrola	1,045
37	Mazatlán, Iberdrola	1,000
38	Topolobampo II, Iberdrola	1,000
39	Topolobampo III, Iberdrola	1,000
40	Escobedo, Iberdrola	1,000
41	Veracruz, Iberdrola	1,000
42	Dulces Nombre III	500
43	Los Ramones	400
44	Energy Legacy International	250
45	Edutecno Bioenergy	250
	Total	8,645

Pemex cogeneration programs	Total MW
Cogeneración de Altamira, S. A. de C.V.	300
Pemex Refineria Miguel Hidalgo	638
Cog.Cactus Pemex	650
Cog. Minatitlán Pemex	450
Cog. Cadereyta Pemex	380
Cog. Salina Cruz Pemex	515
	2,933

Source: CENACE.

The transmission planning process for 2015-2010 is based on a power-flow model that minimizes transmission expansion costs under these general assumptions. Fig. 3 illustrates the results of *Prodesen* at a national level. It can be seen that main transmission capacity increases would be needed in the Northern, North-Eastern and Southern regions of the country.[6] The interconnection of the main transmission system and the Northern Baja California's isolated system is a priority, as well as capacity increase in cross-border connections with the USA and Central America (Belize and Guatemala). This expected increase in transmission capacities should result in a decrease of congestion in the Mexican network. Fig. 4 presents the estimation made by SENER for the expected decrease in national nodal prices by 2020.

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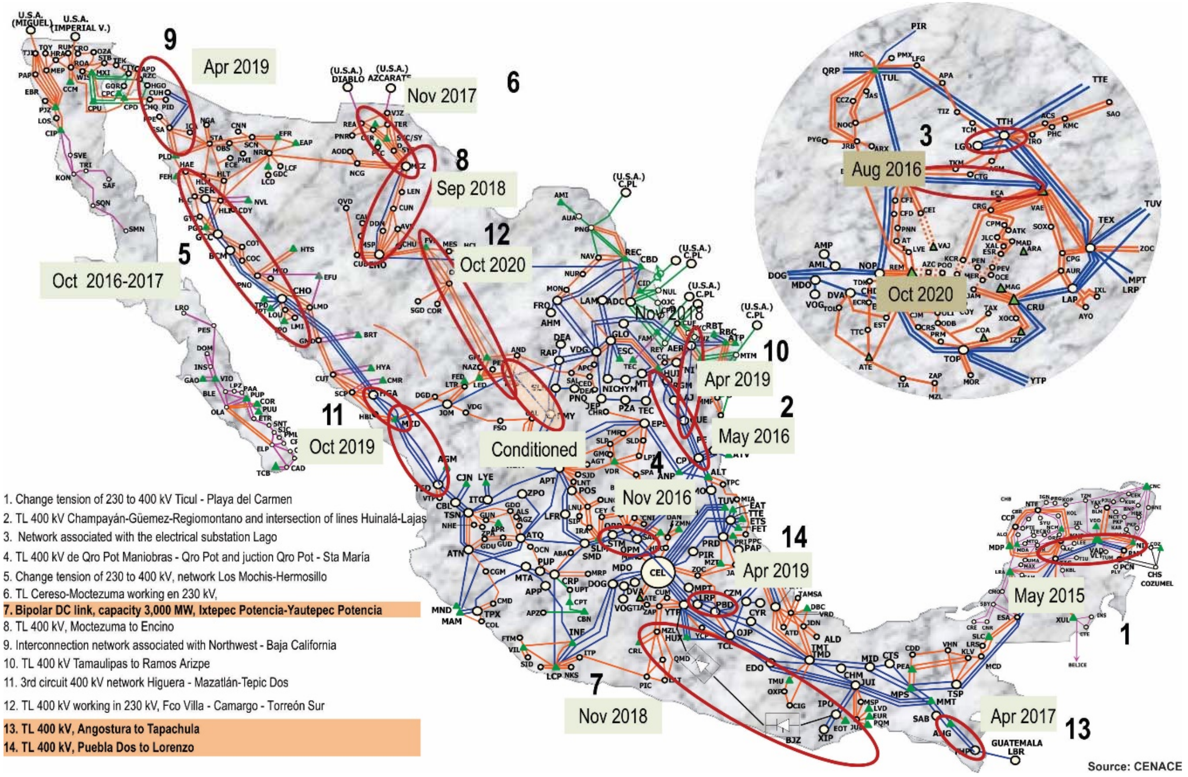
[6] Especially in the following links: Oriental-Peninsular, Champayán-Güemez, Los Mochis-Culiacán, Mazatlán-Tepic, Moctezuma-Chihuahua, Chihuahua-La Laguna, Chihuahua-Río Escondido, Temascal-Centro, Benito Juárez-Huesca, México-Guatemala.

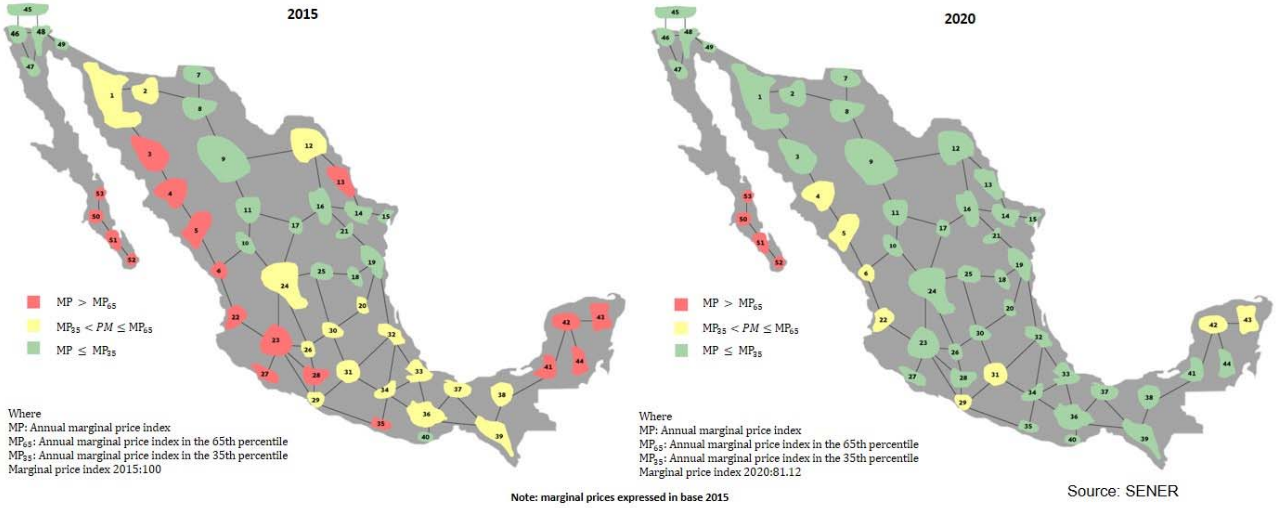
FIGURE 3. Electricity transmission capacity expansion in Mexico for 2015-2020



1. Change tension of 230 to 400 kV Ticul - Playa del Carmen
2. TL 400 kV Champayán-Güemez-Regiomontano and intersection of lines Huinalá-Lajas
3. Network associated with the electrical substation Lago
4. TL 400 kV de Qro Pot Maniobras - Qro Pot and juction Qro Pot - Sta María
5. Change tension of 230 to 400 kV, network Los Mochis-Hermosillo
6. TL Cereso-Moctezuma working en 230 kV,
7. **Bipolar DC link, capacity 3,000 MW, Ixtepec Potencia-Yautepec Potencia**
8. TL 400 kV, Moctezuma to Encino
9. Interconnection network associated with Northwest - Baja California
10. TL 400 kV Tamaulipas to Ramos Arizpe
11. 3rd circuit 400 kV network Higuera - Mazatlán-Tepic Dos
12. TL 400 kV working in 230 kV, Fco Villa - Camargo - Torreón Sur
13. **TL 400 kV, Angostura to Tapachula**
14. **TL 400 kV, Puebla Dos to Lorenzo**

Source: CENACE.

FIGURE 4. Expected decrease in electricity nodal prices in Mexico 2015-2020



Where
MP: Annual marginal price index
MP_{65}: Annual marginal price index in the 65th percentile
MP_{35}: Annual marginal price index in the 35th percentile
Marginal price index 2015:100

Where
MP: Annual marginal price index
MP_{65}: Annual marginal price index in the 65th percentile
MP_{35}: Annual marginal price index in the 35th percentile
Marginal price index 2020:81.12

Note: marginal prices expressed in base 2015

Source: SENER

Models, Data and Results

In this section we present two models that suggest ways to evaluate the welfare efficiency properties of the *Prodesen* plan. In subsections 3.1 through 3.3 we present an incentive price-cap regulation model that can be applied to the Mexican electricity grid so as to achieve welfare-optimal network expansion. In 3.5.2 we further develop a model of a centralized ISO that seeks to achieve the same goal, and that provides a welfare-optimal benchmark against which to compare both the HRV and the *Prodesen* approaches. In section 3.4, we show the (restricted) data we had access to, and in 3.5 we outline our results and comparisons.

Incentive Model

We next employ a quantitative bi-level power-flow modeling approach. The focus is to propose an incentive methodology that could be used by the CRE to regulate transmission tariffs. We rely on Hogan et al (2010) (HRV), a model which combines merchant and regulatory approaches, redefines the output of transmission in terms of point-to-point transactions (or, equivalently, in terms of FTRs), and applies Vogelsang (2001) for meshed electricity networks so as to efficiently lead the expansion of an electricity network to convergence to Ramsey-Boiteux equilibrium. This is basically achieved by means of a price cap on two-part tariffs of a Transco that promotes the intertemporal rebalancing of its fixed and variable charges within a process where potential loss of congestion rents (due to the expansion of the network) is compensated by controlled increases of the transmission capacity fixed fee. The regulatory model is further combined in a bi-level program with a power-flow model where an ISO achieves both technical flow simultaneous feasibility as well as financial revenue adequacy in the network system.

The regulatory and power-flow models then represent the upper and lower model levels, respectively, of a bi-level program. The sequence of movements is as follows:

1. Given an existing network, with information on historical prices, the regulator sets a price-cap constraint over transmission two-part tariffs.
2. Based on market information availability (regarding demand, generation, network topology, etc.), the transmission company (Transco) identifies the transmission links to be expanded.
3. The Transco auctions point-to-point FTRs based on the available network capacity.
4. The ISO handles actual generation dispatch according to a marginal-price merit–order rule, collects payments from loads and pays generators. The difference between these two last values represents the congestion rents of the system that are further redistributed to FTR holders.

5. Fixed charges are calculated from the price-cap regulatory restriction, based on congestion charges and paid by consumers.

We present in the following two sub-sections the upper-level and lower-level components of the HRV model. The definition of variables is as follows:

k_{ij}^{t} = line capacity between node i and node j at time t.

F^{t} = fixed fee at time t.

d_{i}^{t} = demand at node i at time t.

g_{i}^{t} = generation at node i at time t.

g_{i}^{max} = available generation capacity.

N^{t} = number of consumers at time t.

$p(.)$ = demand function.

c(k) = transmission cost function in terms of capacity.

RPI = inflation adjustment factor

X = efficiency adjustment factor

w = weight

mc_{i} = marginal generation costs at node i.

pf_{ij} = power flow on the line connecting i and j

q_{i} = net injections

Upper-level Problem

We rely on Rosellón and Weigt's (2011) reformulation of Hogan et al (2010) in terms of congestion rents as

$$\max_{k,F} \pi = \sum_{i}^{T}\left[\overbrace{\sum_{i} p_{i}^{t} g_{i}^{t} - p_{i}^{t} g_{i}^{t}}^{A'} + \overbrace{F^{t} N^{t}}^{B} - \sum_{i,j} \overbrace{c(k_{ij}^{t})}^{C}\right] \quad (1)$$

Subject to

$$\overbrace{\frac{\sum_{i}(p_{i}^{t} d_{i}^{w} - p_{i}^{t} g_{i}^{w}) + F^{t} N^{t}}{\sum_{i}(p_{i}^{t-1} d_{i}^{w} - p_{i}^{t-1} g_{i}^{w}) + F^{t-1} N^{t}}}^{D\prime} \leq \overbrace{1 + RPI + X}^{E} \quad (2)$$

In (1) congestion rent A' is expressed in terms of nodal-price differences between loads and generators: $p_i d_i - p_i g_i$. Term B denotes revenues from fixed charges, while term C represents expanding transmission. (2) shows the RPI-X weighted price-cap constraint (E) over transmission two-part tariffs (D').

Lower-level problem

An ISO maximizes social welfare *W* given restrictions on generation capacity, transmission-line capacity, and energy balance. It also makes sure that all electricity-engineering technical restrictions are met in a market with linear demand and constant generation marginal cost at each period *t*. The welfare maximizing problem for the ISO then looks like:

$$\max_{d,g} W = \sum_{i,t} \left(\int_0^{d_i^t} p(d_i^t) \mathrm{d}d_i^t \right) - \sum_{i,t} mc_i \, g_i^t \quad (3)$$

Sujeto a

$$g_i^t \leq g_i^{tmax} \ \forall i, t \ (4)$$

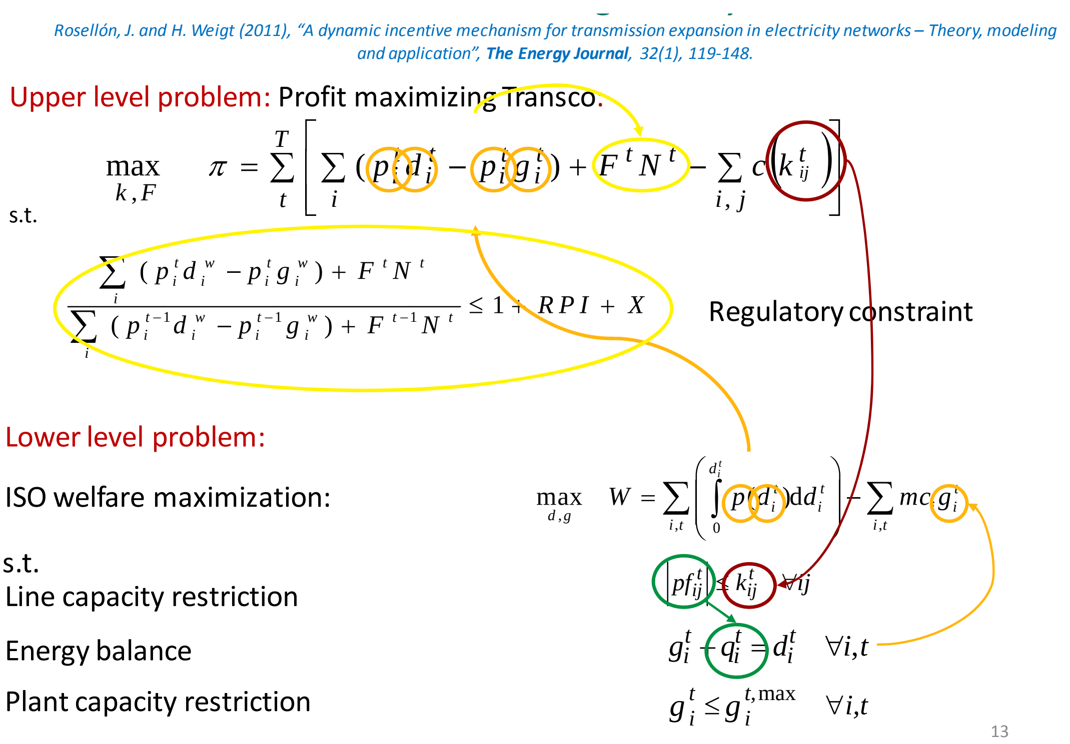
$$\left| pf_{ij}^t \right| \leq k_{ij}^t \ \forall i, j \ (5)$$

$$g_i^t + q_i^t = d_i^t \ (6)$$

Restriction (4) means that generation g at each node i cannot be greater than a predetermined maximum generation capacity $g^{\max}$. Equation (5) shows that energy flow pf_{ij} in a transmission link between nodes i and j may not exceed transmission-line limit k_{ij}. Last restriction (6) indicates that load at each local node is to be satisfied by generation supply at such a node, or from power imports from other nodes.

In the same fashion as in HRV and Rosellón and Weigt (2011), we follow the approach of an economic dispatch within a meshed DC-network topology. The Transco maximizes profits at each time t relying on the welfare-optimal solution derived from the ISO's economic dispatch program. Numerical iterations in the lower-level problem provide the optimal values of demand d, generation g and nodal prices p at each node i, which in turn feed up the upper-level program so as to determine the values of capacity K, and the corresponding fixed charge F (see Fig. 5).

Figure 5. A combined merchant-regulatory mechanism



*Rosellón, J. and H. Weigt (2011), "A dynamic incentive mechanism for transmission expansion in electricity networks – Theory, modeling and application", **The Energy Journal**, 32(1), 119-148.*

Upper level problem: Profit maximizing Transco.

$$\max_{k,F} \quad \pi = \sum_{t}^{T}\left[\sum_{i}\left(p_i^t d_i^t - p_i^t g_i^t\right) + F^t N^t - \sum_{i,j} c\left(k_{ij}^t\right)\right]$$

s.t.

$$\frac{\sum_{i}\left(p_i^t d_i^w - p_i^t g_i^w\right) + F^t N^t}{\sum_{i}\left(p_i^{t-1} d_i^w - p_i^{t-1} g_i^w\right) + F^{t-1} N^t} \leq 1 + RPI + X$$

Regulatory constraint

Lower level problem:

ISO welfare maximization:

$$\max_{d,g} \quad W = \sum_{i,t}\left(\int_{0}^{d_i^t} p\left(d_i^t\right) \mathrm{d}d_i^t\right) - \sum_{i,t} mc_i g_i^t$$

s.t.

Line capacity restriction

$$\left|pf_{ij}^t\right| \leq k_{ij}^t \quad \forall ij$$

Energy balance

$$g_i^t + q_i^t = d_i^t \quad \forall i,t$$

Plant capacity restriction

$$g_i^t \leq g_i^{t,\max} \quad \forall i,t$$

Source: Own elaboration.

This mechanism is applied to the Mexican transmission system during 8 periods (2012-2020) assuming linear inter-node transmission cost-functions, an expanding cost value of $130 per MW, a linear demand with price–elasticity value of – 0.25 at each reference node, and a depreciation factor of 8% (Table 1). A Price cap is set over the transmission two-part tariff weighted by previous period *Laspeyres* weights. Hourly results obtain as outcomes.[7]

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[7] In each period, the Transco's revenues are multiplied by 8760 so as to represent yearly revenues.

TABLE 1. Simulation values for all study cases.

	Values
Number of periods	8
Cost	linear
Inter-node cost functions	$c_{ij}^{t} = c_o \cdot (k_{ij}^{t} - k_{ij}^{t-1})$
Co (transmission line expanding cost value)	130 $/MW
Demand	lineal
Price elasticity of demand value	-0.25

Source: Own elaboration.

Data

The application of the above model to the Mexican electricity system comprises an aggregated representation of the Mexican power system (Fig. 6) that is inter-temporally optimized.[8] We consider 82 main generation plants in the country (see CFE, 2007, 2008 and 2011). Price in each generation plant is equivalent to an approximation of variable costs[9] reported by CFE (Table 2).

TABLE 2. Generation average costs in Mexico

Technology	USD per MWh (average)
Turbine Simple Cycle	140.883
Natural Gas Turbine	153.490
Turbine Combined Cycle	58.148
Internal Combustion	159.555
Coal	67.540
Nuclear	91.270
Geothermal	94.765
Hydroelectric	100.477
Wind Turbine	81.160
Photovoltaic	189.740

Source: Own elaboration based on CFE (2012).

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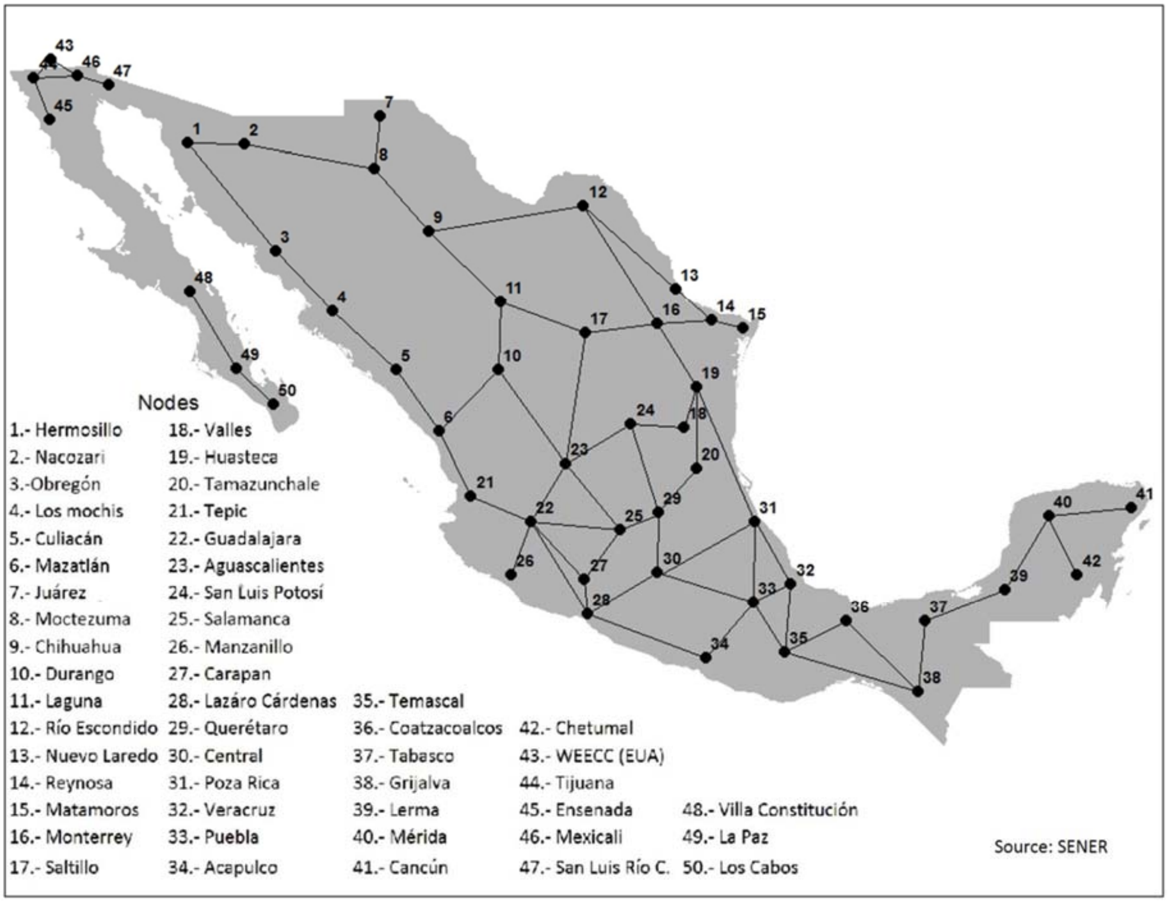
[8] This simplified model version strategy was chosen due to the available information that we were able to obtain from Cenace and Sener.

[9] The obtained data are not homogeneous for same types of technology. As opposed to Rosellón y Weigt (2011), prices were averaged.

For our simulations, we consider a simplified transmission network topology in Mexico which comprises 50 aggregated nodes, and 66 lines with capacity ranging from 90 to 3,500 MW (Fig. 6).[10] Nodes located in the central region of the country are part of a meshed network, while nodes at the north and south extremes generally belong to redial-line structures.

FIGURE 6. Transmission network topology in Mexico 2012



Source: SENER

Results

Nodal prices, and transmission congestion and expansion

From the lower level problem, we identify the transmission lines potentially congested for nodes located in North, North-Eastern and South of the national transmission network (fig. 7). Highest nodal prices correspond to nodes located in the north of the country which comprise important industrial areas of the country with high load requirements (Chihuahua, Laguna, Nuevo Laredo, Reynosa, Matamoros, Guadalajara,

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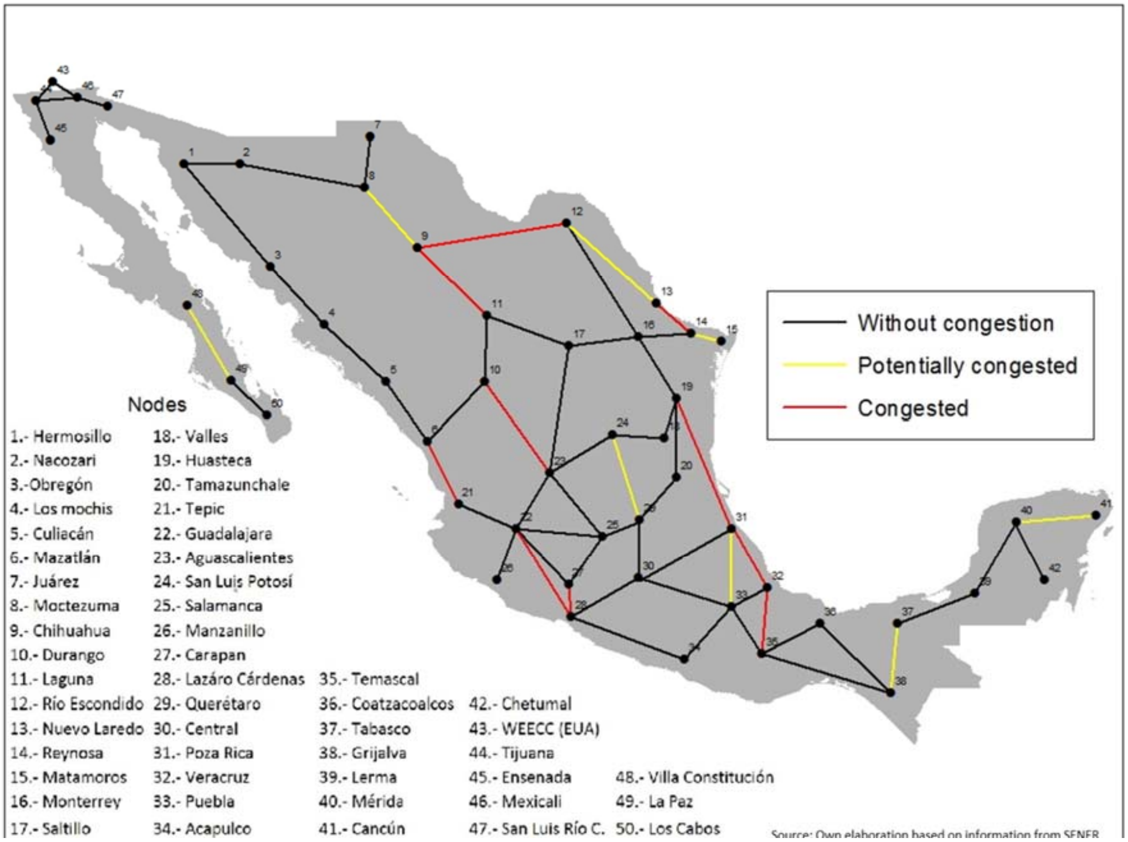
[10] To simplify the analysis we use power, as opposed to MVA, so as to determine transmission-line limits.

Veracruz, Tabasco, Mérida, Cancún). Our estimated congestion values somewhat differ[11] from the ones in *Prodesen*, figure 4, year 2015.

FIGURE 7. Congested zones in Mexico 2012



Source: Own elaboration based information from SENER.

The application of the HRV mechanism is shown to promote the expansion of transmission lines, decrease the energy cost in the north of the country, and incentivize nodal-price decreases in central regions. Prices in southern regions are however increased, but such an increase is compensated by price decreases in other regions. Fig. 8 shows the evolution of nodal prices over the 8 periods considered in our simulation. During the first period, nodal prices significatively diverge consequently resulting in high levels of transmission congestion rents. Nodal-price convergence starts to occur after eight periods. Initial average nodal price starts in USD 117. The average nodal price at the end of our simulation becomes USD 83.8, representing a decrease of 28% compared with the initial simulation period. Price increases in nodes with initially low generation costs are of course compensated with price reductions in resting nodes.

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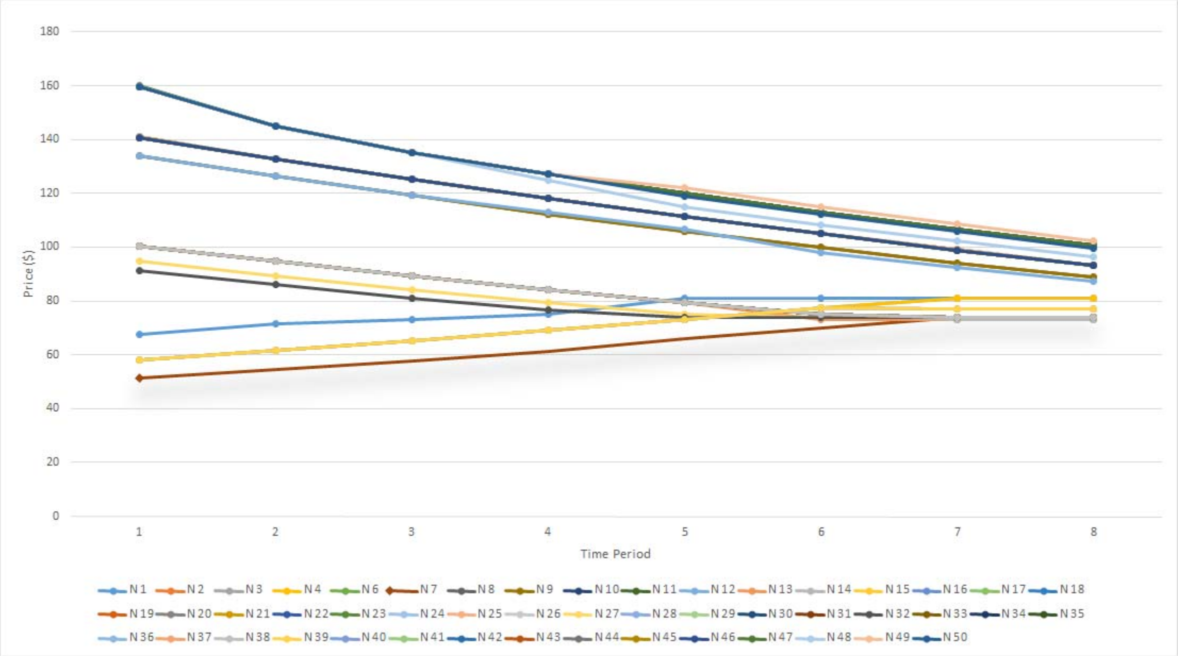
[11] One reason for such a difference might be that we only had access to data according to the 50-node 2012 Mexican network topology. The transmission system in *Prodesen* is based on 2015 initial data, and a corresponding network topology with 53 nodes.

FIGURE 8. Nodal-price developments in Mexico (2012-2020)



Source: Own elaboration.

Expansions in transmission links follow similar intertemporal dynamics to nodal prices: an extensive capacity increase during the eight periods, and then gradual convergence to limit capacity in the last period. Nodes that experimented considerable price decreases are located in the north (N8, N9, N11, N12, N13, N14, N15) and in the center (N10, N23, N24, N29, N6, N21, N22 and 28). In the Pacific coast nodal prices increase (N1 through N5) as well as in the south (N39).

Welfare

One relevant further question is the impact on social welfare due to the application of the HRV mechanism to incentivize the expansion of the Mexican transmission system. We present now such an analysis and, taking advantage of previous studies, compare it with analogous analyses for other systems in North America; namely, the electricity systems in Ontario, Canada, and in Pennsylvania, New Jersey, Maryland (PJM), United States.[12]

We also gauge for the three systems transmission capacity and average price changes derived from expansions in transmission links, and compare such values with a welfare-benchmark case of an ISO that centrally plans in each system the expansion of respective transmission grids. In this last setting, the ISO maximizes welfare

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[12] See Rosellón et al (2011), and Rosellón et al (2012).

(understood as the sum of consumer surplus plus producer surplus plus congestion rents) minus transmission expansion costs:

$$\max_{d,g} W = \sum_{i,t}\left(\int_{0}^{d_i^t} p(d_i^t)\,\mathrm{d}d_i^t\right) - \sum_{i,t} mc_i\, g_i^t - \sum_{i,j} c(k_{ij}^t) \quad (7)$$

Subject to restrictions (4), (5) and (6) in the lower-level problem. Resulting simulations are grouped into Table 3.

TABLE 3. Comparative welfare results for Mexico, PJM and Ontario

	Network without expansions			Hybrid regulatory mechanism (HRV)			Centralized ISO		
	México	PJM	Ontario	México	PJM	Ontario	México (e.g. *Prodesen*)	PJM	Ontario
Consumer surplus (MioUSD/h)	2.71	6.53	0.83	3.14	6.63	0.89	3.211	6.67	0.96
Producer surplus (MioUSD/h)	0.118	0.36	0.051	0.253	0.59	0.087	00.271	0.64	0.105
Congestion rent (MioUSD/h)	0.0073	0.067	0.013	0.019	0.01	0.00104	0.0168	0.006	0.0009
Total social welfare (MioUSD/h)	2.835	6.957	0.894	3.42	7.23	0.978	3.50	7.316	1.0659
Total network capacity (GW)	9.14	35.8	2.52	13.47	50.83	4.536	14.26	52.83	4.74

Source: Own elaboration based on Rosellón et al (2011) and Rosellón et al (2012).

Both for the HRV and the-centralized-ISO models, table 3 shows for the three systems general increases in consumer and producer surpluses, decreases in congestion rents and average prices, and increases in network capacity and total welfare as compared to the case of no-extension. Furthermore, in the three simulations the use of the HRV mechanism promotes convergence to the centralized ISO welfare-optimal benchmark. In the case of Mexico, compared to *Prodesen's* forecasts in figure 4, year 2020, the HRV mechanism seem to converge to decreased nodal-price differences at lower pace. Likewise, our analysis hints that the *Prodesen* plan is in fact converging to the welfare-optimal planning of program (7) subject to (4) through (6).

Conclusions

Our formal preliminary analyses in this paper suggest clues on the efficiency properties of the *Prodesen* plan, although these should be taken with reserve given the aggregated nature of the Mexican nodal-price system that we had to assume. However, although our initial estimated congestion values for 2012 --calculated with the model of a centralized ISO (program 7, subject to 4-6)—imperfectly approximate the ones in *Prodesen (*figure 4, year 2015), our analysis hints that the Prodesen plan is in fact converging to the welfare-optimal benchmark planning values by 2020 of the centralized-ISO program in terms of capacity expansion, congestion rent, consumer and producer surplus as well as nodal-price differentials. This is somewhat implied by the cost-minimizing power-flow program used in *Prodesen* as compared to our more general welfare-maximizing centralized ISO transmission expansion model.

Additionally, we also showed that incentive price-cap regulation converges to optimal welfare transmission expansion for the Mexican transmission grid. However, compared to *Prodesen's* forecast in figure 4, year 2020, the HRV mechanism seems to converge at lower pace to decreased nodal-price differences. This is also true when the HRV mechanism is compared to our centralized ISO model. This result is also in line to analogous previous research carried out for transmission systems elsewhere (e.g., Ontario, PJM, Peru, and North Western Europe) where convergence tightens as more periods are considered.[13]

The policy implications of our analysis are clear. Since it is based on a cost-minimizing power-flow model –which determines transmission capacity expansion projects based on an integrated approach to transmission expansion and generation dispatch—the *Prodesen* plan provides a reasonable planning to efficiently guide the development of the Mexican network. However, our results also strongly suggest that the CRE should consider the use of more incentives in its future transmission tariff regulatory methodologies. There is evidence that lack of incentives to actual performance of TSOs and Transcos might result in much less allocative and distributive efficiency than what a typical benevolent regulator would wish (see Kemfert et al, 2015).

Future research work should formally analyze in more detail the combination of transmission planning and tariff regulation used in the Mexican system, considering more atomization of the nodal-price Mexican system too. As argued before, the work presented in this paper relied on a stylized aggregated nodal system due to restricted information. Likewise, network planning modeling should be combined with alternative congestion management approaches, like redispatch of renewable and conventional generation. Moreover, the welfare implications of our analyses relied on a perfectly

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[13] For instance, Rosellón and Weigt (2011) considered twenty periods.

competitive electricity market under perfect information. However, in practice market participants may react to institutional changes by altering their bidding strategy.

Finally, another regulatory challenge for transmission planning in Mexico not considered in this paper is the design of efficient price regulation under large-scale integration of renewable generation. The main problems implied in such a process are fluctuating supply and demand characterizing such technologies (e.g., wind generation), as well as the external effects that renewable technologies have on congestion-rent signals to the transmission expansion process.[14]

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[14] See Schill et al (2015) and Egerer et al (2015).

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