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Dynamics of power-transmission capacity expansion under regulated remuneration

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ABSTRACT

Efficient provision of electricity requires timely expansions of power transmission capacity. However, regulation does not always send the right signals to generate the required (and timely) investments. Therefore, it is important to evaluate the effect of alternative regulations on investment on transmission capacity. In this paper, considering regulated remuneration, we perform this evaluation with a behavioral simulation model of the transmission capacity expansion, in which capacity is endogenously determined by the demand/supply relation. Two planning approaches were considered: centralized planning where the investments are fully coordinated by a central organism, and decentralized planning where the capacity expansions are driven by the investors' rationality on the power market evolution. The model is applied to the Colombian case. The decentralized approach has lower costs (usage charges) than centralized expansion, but lower transmission capacity margins. As low transmission capacity margins create supply risks in high demand periods, regulators can increase coordination in decentralized planning by directly promoting investments that increase security of supply.

1. Introduction

Electricity markets need timely transmission capacity expansions to maintain the security of supply. Efficient expansion prevents blackouts and shortages that generate price rises, welfare losses for demand and generators, and increases in operating and maintenance (O&M) costs for grid operators. Defining such expansions is a complex task. Under traditional market conditions, the expansion considers technical, economic, and environmental issues, taking into account uncertainty about electricity demand, capital constraints, and environmental impacts, among others [1]. Nowadays, the new role of the transmission in modern electricity markets must consider distributed generation from renewable sources [2,3], and the regional planning in a context of markets integration [4]. Besides, electricity transmission exhibits negative externalities [5,6] and economies of scale [7–9] that complicate the allocation of transmission costs to market players and the estimation of the profitability of investments. As a result, it is possible to face an excess or a lack of investment in transmission capacity [10,11]. These features are crucial when planning and defining mechanisms for capacity expansion in power transmission.

Expansion of transmission capacity can be centrally planned so that investments in transmission and generation are fully coordinated using capacity auctions. This is normally the approach in regulated and vertically integrated monopolies, or in deregulated markets with a central transmission capacity planner. The goal in this approach is to minimize the long-term system cost (the social cost) while ensuring security of supply [12]. The main drawback of centrally planning expansion is that expansion alternatives respond to reliability criteria. Then, intuitively, the emphasis on maintaining reliability could lead to over investment and increased consumer costs. Additionally, traditional centralized planning are reactive [13], therefore it does not respond to market competition along the value chain of the power industry.

Decentralized planning has been proposed to attract investment from third parties (merchant expansion) in deregulated markets [14,15]. Under decentralized planning, market agents can plan and build transmission projects by themselves. Decentralized expansion of transmission is associated with nodal pricing markets in which new investments are compensated by the value of congestion [16,17]. However, it is difficult, if not impossible, to have a fully decentralized expansion of transmission in current markets [18] because some investments, such as the investments required for maintaining and upgrading facilities, can only be implemented by the incumbent and, therefore, they are not open for competition. Moreover, network externalities and uncertainty increase the risk of not recovering investment costs [19,20] and regulation is still needed to control market power and free riding [14,18], and for offering incentives to develop

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Nomenclature

Parameters

ω	desired margin of transmission capacity (%)
α	construction delay (years)
β	useful life (years)
γ	planning delay (years)
μ_1	sensitivity of usage charges to installed transmission capacity (COP/(kW * kWh))
μ_2	sensitivity of usage charges to electricity demand (COP/kWh^2)
μ_3	sensitivity of compensations to the ratio between the desired transmission capacity margin and the current margin (COP/(kW^2 * h))

Exogenous variables

$E_d(t)$	electricity demand in the year t (GWh)

Stock variables

$C_{uc}(t)$	capacity under construction in the year t (MW)
$I_{tc}(t)$	installed transmission capacity in the year t (MW)

Auxiliary variables

$P_d(t)$	power demand in the year t (MW)
$C_m(t)$	current transmission capacity margin in the year t (MW)
$C_o(t)$	compensations in the year t (COP/MWh)
$D_m(t)$	desired margin of transmission capacity in the year t (MW)
$E_c(t)$	expected capacity in the year t (MW)
$I(t)$	level of investment in the year t (MW)
$I_{uc}(t)$	investment driven by usage charges in the year t (MW)
$I_{co}(t)$	investment driven by compensations in the year t (MW)
$R_c(t)$	rate of construction in the year t (MW/year)
$R_d(t)$	rate of decommissioning in the year t (MW/year)
$R_i(t)$	rate of investment in the year t (MW/year)
$U_c(t)$	usage charges in the year t (COP/MWh)

projects that increase the systems' efficiency [16].

The aim of this paper is to assess the long-term behavior of transmission capacity expansion under both scenarios: centralized planning with auctioning competition and market-driven decentralized planning. Comprehensive surveys and models for power transmission expansion can be found in [1,4,21,22]. Most studies approach the problem of planning expansions and focus on minimizing transmission costs (including expansion), subject to physical constraints and including the future supply and demand projections [23,24]. The expansion problem is formulated as a mathematical optimization problem and solved using techniques such as genetic algorithms [25–27], tabu search [28,29], among others. Although these models effectively support decision making, they do not focus on the dynamics of capacity expansion in particular, or on the dynamics of over and under investment that may lead to capacity cycles similar to the ones observed in power generation [30,31].

Behavioral simulation, also called system dynamics, has been used to simulate the evolution of investment in generation capacity in deregulated energy markets under different regulatory and market scenarios, see for example [30,32–36]. In this paper, a similar methodology is used, where a stylized system dynamics model is developed that captures the essential current conditions based on market incentives for investments in transmission capacity. The analysis focuses on the investment decision in a market with regulated remuneration. The proposed model is calibrated for the Colombian market and capacity evolution is simulated for different regulatory and demand scenarios.

The following section (Section 2) discusses the proposed system dynamics model, with a focus in how the investment decision is made for each planning approach. Section 3.1 discusses transmission capacity expansion in the Colombian market, while Section 3.2 presents the main modelling assumptions for capacity expansion. Section 4 presents the results from running the model and discusses the performance of centralized and decentralized planning. A planning method that combines features of centralized and decentralized planning is also evaluated in Section 4.3. Finally, Section 5 discusses results and their policy implications.

2. Modelling dynamics of capacity expansion

The dynamic model presented in this section is based on the premise that transmission capacity is endogenously determined by the relationships between demand, supply and the planning approach. We followed standard business or system dynamics approach [37], considering first the formulation of the dynamic hypothesis by using a causal loop diagram, and then we developed the formal differential (behavioral)-equation model which is tested in Section 3.

2.1. Dynamic hypothesis

Fig. 1 shows a causal loop diagram[1] of the transmission capacity expansion. A remuneration scheme is assumed, where transmission companies receive regulated payments (usage charges) based on their existing assets (installed capacity), and pay penalties (compensation charges) when these assets are insufficient to maintain a predefined service level.

Usage charges pay transmitters for the annual capital and operating costs of their existing assets. Usage charges are defined for three demand blocks: high, medium and low so that unit charges (per MWh) reflect the higher costs of operating assets during peak-load hours. Usage charges are fixed for the year and are recalculated when new capacity is added. For simplicity, usage charges in the model are average usage charges.

To maintain the reliability of the power transmission, the regulator charges transmitters a compensation penalty if the availability of their assets falls below a predetermined level. Compensations are associated with close capacity margins, and are interpreted as a signal for increasing capacity.

The dynamics of the capacity expansion is represented by one reinforcing loop – *profits* (R1) – and three balancing loops: *reliability* (B1), *control* (B2), and *compensations* (B3). The *profits* loop represents the causal relationship between usage charges and investment in capacity. Users pay transmission charges proportional to the transmission capacity. As transmission capacity increases, the usage charges for asset owners also increase. Assuming efficient costs, the increment in usage charges rise the profitability of transmission, and therefore it increases the willingness to invest in transmission capacity. Installed capacity increases after new projects are completed, taken into account the planning and construction delay.

The second mechanism for investment comes from the *reliability* loop (B1), where investment increases with the margin gap between the desired transmission capacity margin and current power demand. This mechanism requires a regulator to open bids for expansion projects whenever investors fail to make the expansions needed for achieving a safety transmission capacity margin. The *control* loop (B2) represents a

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[1] It is a map that shows the cause-effect and feedback relationships among the variables in one domain.