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The role of regulatory learning in energy transition: The case of solar PV in Brazil

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Abstract

The analysis of institutional and technological dynamics is frequently tackled by defining several levels of nested decision-making processes. Those representations typically deal with institutions and technology practice separately. In this paper, we use the Institutional Analysis and Development (IAD) framework to study the coevolution between regulatory institutions and technology practice. Specifically, we use the IAD to show that technological routines are designed to fit into regulatory institutions ('rules shape technology'), but also that regulatory institutions adapt to changing technological routines ('technology shapes rules'). We use the electricity sector to illustrate this process. In the IAD, the main drivers to change rules (in our case, regulatory institutions) are the 'evaluative criteria' applied to outcomes. To that end, we model the evolution of an electricity sector in the process of introducing decentralized production where regulators apply three kinds of evaluative criteria: i) whether electricity is produced by the cheapest available technology nowadays; ii) whether new technology is introduced by niche markets; and iii) whether adapting institutions is necessary to avoid technological lock-in. Our simulations of a realistic power system show that, if evaluative criteria do not consider the dynamics of decentralized production, the electricity sector may be locked in to centralized technologies.

Key words: Energy transition; Institutional evolution; Path-dependence.
JEL: L43; L94; O31; O43.

1. Introduction

The electricity industry is undergoing major changes, having taken center stage in what is frequently called energy transition. For a variety of reasons, electricity industries all over the world are facing profound transformations, whose results are still difficult to foresee. Evolutionary arguments have already been widely recognized as relevant elements of policy analysis in the context of energy transition. Moreover, the importance of the co-evolution of technology and institutions is increasingly addressed in the literature, see for instance (Foxon, 2011), (Unruh, 2000) or (Nill and Kemp, 2009). On the other hand, the level of detail with which institutions are represented in the studies is still moderate. In particular, we are concerned with the evolution of rules. From a general point of view, we use the definition of rules provided in (Crawford and Ostrom, 1995): rules are prescriptions of what players involved "must" do, "must not" do, or "may" do, and the associated sanctions in case rules are not followed. One particular case of those rules is the regulatory framework. In this paper, we will analyze the fundamental elements of the dynamic process defining changes in the regulation of the electricity sector. In this regard, we consider that rules are not, in general, the result of a static, rational decision-making process, but they are emergent properties of the complex interaction between rule-makers and industries[1]. From this paper's point of view, a key point of our representation is considering bounded rationality in the process of making rules. In our analysis, rule-makers do not decide using deductive, rational reasoning but they use instead inductive reasoning, (Arthur, 1994a). Specifically, we represent that rule-makers, in a context of significant complexity, understand reality through simplified models that are then used to perform deductions. Such deductions may be interpreted as beliefs. Rule-makers also obtain feedback from the complex environment, which allows them to modify decisions according to their beliefs (their simplified models). This representation can be understood in the context of (Simon, 1959): rule-makers follow 'satisficing' routines: they will only change routines in case outcomes are no longer satisfactory.

In order to understand the main elements that define the previous process, we use the Institutional Analysis and Development (IAD) framework, (Ostrom, 2009). In the IAD, the main drivers to change rules (in our case, regulatory institutions) are the 'evaluative criteria' applied to outcomes. We connect the idea of evaluative criteria to rule-makers' beliefs in order to define how regulation change. Differently put, the main driver for regulatory change will be the evaluative criteria, i.e. rule-maker's simplified model against which outcomes are evaluated. Furthermore, we will point at the importance of coherence between institutions and technology practice, using the electricity industry as an illustrative example. In that view, our problem will be close to (Künneke, 2008), where it was argued that the restructuring process of the electricity industry, based on the implementation of market arrangements, created an incoherent situation: decentralized mechanisms were put into place to coordinate the activities of an industry based on a highly centralized technological practice. Although that view can be applied to several European and US electricity industries, it is not the case in many others. Latin American countries have been examples of significantly more centralized implementations of market arrangements. Moreover, the trend currently observed in Europe, and to some extent in the US, is to implement more centralized solutions. At the same time, during the last years, the optimal technical solution to produce electricity has become less clear. In particular, solutions to produce electricity in a decentralized manner have become increasingly attractive. The question that arises in that context can be posed as: can this decentralized technology enter into centralized market arrangements? The answer may depend on the particular rules governing the sector. We study the particular case of solar PV in Brazil, where the institutional framework for power generation (based on

[1] (Arthur, 2014), among others, provides a general framework to define emergent properties.

a centralized market design) contains barriers for distributed generation to enter the market. If rule-makers do not adapt to changing technologies, solar generation will (potentially) be locked in to concentrated PV technologies.

In order to analyze the previous questions, we propose to use a system dynamics model along the lines of (Forrester, 1968) to model the Brazilian electricity sector. The aim is showing the central role that evaluative criteria play in the evolution of rules. regulators apply three kinds of evaluative criteria: i) they observe only that electricity is produced by the cheapest available technology nowadays; ii) they observe that new technology is introduced by niche markets, without institutional adaptation; and iii) they observe whether adapting institutions is necessary to avoid technological lock-in. In that context, we show that the definition of the institutional framework, in a context of stress in the innovation system, is crucial for the development of new technologies. On the other hand, we show that understanding pathways for the evolution of the power sector is instrumental in the definition of adequate evaluative criteria that allows adapting the institutional framework to changing technological practice.

This paper is organized as follows. We develop our theoretical framework in section 2. In section 3, we describe the context of the Brazilian electricity system. Section 4 develops a simulation model aimed at analyzing the problem. Section 5 analyzes the corresponding numerical results. Section 6 concludes.

2. The dynamics of institutional and technological change

One of the main insights provided in (Künneke, 2008) is to identify the relevance that two sets of multi-level classifications are coherent, the first classification concerns institutional levels as identified by (Williamson, 1998). The other classification concerns technology practice, and it is defined by (Künneke, 2008) building on (Dosi, 1982). The two sets of levels should be coherent. As pointed out in (Künneke et al., 2010), the analysis of modes of governance will be an important part of the relationship between technology and institutions. In particular, they studied the alignment of modes of governance and technology in the case of network industries, as electricity. This study can be also put in terms of coherence: network industries are characterized by critical technical functions, so the modes of governance for the transactions associated with those critical functions must be coherent.

On the other hand, we are concerned with the dynamics of the previous decision-making process. In that context, we will use the description developed in (Langlois and Robertson, 2002) to define our theoretical context. They argued that a large part of the study of governance (namely, Transaction Costs Theory) is concerned with the idea of efficient coordination, where governance is introduced in order to align incentives and deal with conflict. That can be represented, in game-theoretic terms, by “commons’ dilemmas”, (Hardin, 1968), or equivalently, as pointed out by (Ostrom et al., 1994), by “prisoners’ dilemmas”. The basic problem described by those games is one where players fail to cooperate to obtain a better outcome when they played fulfilling only individual rationality. Nonetheless, as highlighted in (Langlois and Robertson, 2002), another critical functions to be performed is the coordination of resources, not only of incentives. To perform those functions, players (frequently firms) create a set of productive routines, which constitutes their capabilities. From that point of view, the kind of game that describes the previous decision-making process is the “coordination game”: games where there is no better solution, but if players do not act jointly, both of them lose. These two types of problems can be understood as “conflict” situations (commons’ dilemmas) and “coordination” situations (coordination games).

From the general framework above, we may identify the first kind of problem ("conflict" situations) with the ones primarily studied in the context of institutional economics. The second kind of problem ("coordination" situations) is studied in depth within the literature on technological practice. The purpose of this paper is to combine both streams of literature in order to understand the joint evolution of institutions and technology. To that end, we will look at a framework where all those kinds of games can be analyzed jointly. Moreover, both the institutional and the technological dimension can be described by different levels of analysis, (Künneke, 2008), so we will need to understand the interaction between the different levels. Consequently, we will use the framework defined by (Ostrom, 2009).

Situation type	Institutional level	Technological level
Operational-level situations	Resource allocation	Operation management
Collective-choice situations	Governance	Routines
Constitutional-level situations	Institutional environment	Technological trajectory
Metaconstitutional-level situations	Embeddedness	Technological paradigm

Table 1. Relationship between action situations and institutional and technological levels. Source: Own elaboration, based on (Ostrom, 2009), (Williamson, 1998) and (Künneke, 2008).

In the first column of Table 1, we represent the different levels of action situations, as defined by (Ostrom, 2009). The basic idea behind an action situation is very close to the definition of transaction in (Williamson, 1998). Together with the rules of the game, which can be thought of as the structure of the action situation, they form an action arena. This general framework can describe both the institutional levels developed in (Williamson, 1998) and the technological levels developed in (Künneke, 2008). The correspondence is represented in Table 1.

One of the insights provided by the Institutional Analysis and Development framework, (Ostrom, 2009), is that, even if the decision-making process of the four situation levels is nested (e.g. decisions at the operational level are framed by decisions at the collective-choice level), level-shifting strategies are crucial to understand the evolution of institutions. In this paper, we will include in this interpretation the importance of level-shifting to understand the evolution of technologies. From this paper point of view, we restrict ourselves to considering the relationship between the constitutional-choice level (where regulation is designed) and the collective-choice level (where governance is designed). Hence, a player will be choosing level-shifting strategies when she begins to consider the change of any of the constraints on the collective-choice level. The way the outcome impacts level-shifting strategies depends on the evaluation criteria.

The specific application of the previous concepts to our problem can be summarized as follows: we consider players in the power market deciding at the collective-choice level. Such action arena will be defined by an institutional level (as defined by (Williamson, 1998)) and a technological level (as defined by (Künneke, 2008)). Players at the collective-choice level will decide, for instance, on long-term power purchase contracts, fuel purchase agreements, appropriate level of reservoirs, etc. Such decisions at collective-choice level are framed by the decisions taken at the constitutional-choice level: regulation for the institutional dimension and technological trajectory for the technological dimension. More importantly, players can engage in level-shifting strategies to change the institutional dimension at the constitutional-choice level, i.e. change of regulatory framework. The application to our problem implies considering that regulators observe industry outcomes (prices and costs, but also organizational barriers, risks, etc.). If outcomes are not satisfactory according to their evaluative criteria, they will change the regulation accordingly. In that context, we model the evolution of an electricity sector in the process of introducing decentralized production of power, where regulators apply three kinds of evaluative criteria: i) they observe only that electricity is produced by the cheapest available technology nowadays; ii) they just observe that new technology is introduced by capacity (for instance by niche markets); and iii) they observe whether technology is introduced not just by capacity but by whether the rules in place are adapted to the new technology features. Our simulations of a simplified but realistic power system show that, if institutions are not adapted to consider decentralized production, the electricity sector may be locked in to centralized electricity technologies.

Our study is related to other works looking at the interrelation between technological and institutional lock-in, (Foxon, 2011), (Unruh, 2000) or (Nill and Kemp, 2009). As shown by (Arthur, 1994b), the technological lock-in is related to the existence of increasing returns to scale. One may observe them, besides in the existence of scale economies, in learning effects, adaptive expectations and network economies –understood as advantages that appear when several players adopt the same technology. Those increasing returns to scale would lead to technological lock-ins. On the other hand, one may find situations where certain institutional setting comes with increasing returns: an institutional lock-in. This concept builds on (North, 1990), who shows that the same reasoning applied to technologies can be applied to institutions: there are also economies of scale ("fixed costs" related to setting up a new institution), learning effects, adaptive expectations and network economies. Consequently, they will be also subject to the possibility of lock-in. In this paper, we describe in more detail the emergence of strategies to overcome lock-in as level-shifting strategies within IAD framework. Moreover, we show that the use of the myopic criteria to evaluate outcomes is a relevant piece of the lock-in mechanism, as the evaluation may facilitate the creation of barriers to the interaction between technology and rules. Consequently, we complement previous studies by showing that addressing lock-in implies designing the correct evaluation criteria, which in turn allows engaging in level-shifting strategies.

3. The regulatory framework in Brazil

Our study focuses on how regulators, after observing outcomes, may engage in regulatory changes. Consequently, this section describes the constitutional-choice level: both the regulatory framework of the Brazilian power sector as well as its technological trajectory. In this paper, we simplify technology dynamics in order to analyze in more detail the institutional dimension. Hence, we consider a very simplified situation where all technologies to produce electricity are mature ones, and the only possible technology evolution is related to solar PV. Besides, we also simplify these dynamics by summarizing them through a learning curve. In particular, we use an experience curve, (Rosenberg, 1982), which relates unit costs reductions to cumulative deployment of technology.

The regulatory framework of the Brazilian power system can be understood as consequence of the amount of hydro generation, of the characteristics if this technology, and of the historical evolution of the Brazilian reform and crises. The result is a set of market arrangements built on centralized choices, (Tolmasquim, 2012). First we will describe the mechanisms and then we will identify barriers to distributed PV generation. Level-shifting strategies will be a process set up to change regulation and alleviate those identified barriers.

3.1 General mechanisms

One of the most important points of this paper is that specific institutions play a central role in the dynamics of power industries. In particular, the adoption of generation technologies might be crucially affected by the institutional design. The aim of this section, hence, is to point out the basic characteristics of the Brazilian institutional setting. To that end, we will consider four basic sets of activities in an electricity industry, each of which will be coordinated by a specific set of institutions involving different sets of agents: planning, procurement, short-term operation and retailing. Note that these sets of activities are not related to the previous dynamic levels but to groups of activities involving different groups of equipment.

■ **Planning –** Planning based on the combination of a central planner studies, which uses as input distribution companies forecasts. Specifically, distribution companies are required to forecast the consumption of their consumers. Distribution companies are strongly incentivized to perform this forecast accurately, as they will face penalties for both over- and under-estimate their electricity requirements.

After that, all those forecasts are coordinated with the rest of the relevant data by the *Empresa de Pesquisa Energética* (the energy planning company). EPE is public enterprise attached to the Energy and Mines Ministry that determines administratively the long-term planning of the electricity industry. Finally, distribution companies are required to contract with power producers all the energy (and capacity) needed to serve their customers.

■ **Procurement –** The central coordination mechanism between power producers and the system operator is a long-term contract (often called Power Purchase Agreement in the power systems literature). It establishes the obligation for power producers to generate the amount of electricity the system operator decides at each point in time, up to the total amount contracted. Nonetheless, there are several types of procurement schemes depending on: (i) the amount of energy consumed by customers; (ii) the characteristics of power plants and (iii) whether the power plant is existing or new.

As for the former aspect (i), if consumers are "too small" (less than 3 MW), they are required to procure their electricity consumption through a single buyer. Otherwise, they are allowed to contract directly with a power producer. In any case, all consumption is required to be ensured by a contract. As for the of power plant characteristics (ii), the auctions may differentiate directly according to the power plat technology and the time scope of the contract. As for the latter aspect (iii), when new generation is required (according to the long-term planning), the national regulator ANEEL organizes auctions where potential new power plants competes *for* the market in price. The winner(s) enters into Power Purchase Agreements. Existing plants sell their energy either through specific auctions for existing capacity or through contracts with large customers.

■ **Short-term system operation –** After the long-term contracts are established, a central system operator (ONS) takes control of the entire system, including generation assets. All production is decided by the use of an optimization model that decides the dispatch. Differences between energy contracted and actual physical production is cleared at a price calculated by the optimization model. This optimization model decides also inter-temporal opportunity costs associated with hydro generation.

■ **Retailing** – Besides regional distribution companies, which sell electricity through the PPAs, retailers can compete for large customers over 3 MW (about a quarter of the market without interaction with the single buyer).

3.2 Incentives for distributed generation in Brazil

Distributed generation, the term often used to refer to relatively small power plants, typically connected to the distribution network (the "low-voltage" network), is difficult to include in the previous institutional setting. The main reason for that the PPA-based model described above work when the plants involved are large engineering projects, but it is more complicated when public tenders are required to build and operate small projects.

In fact, regulation has adapted to the particular features of distributed generation over time. For instance, the Decree 5.163/04 (which created the figure of Distributed Generator), established a different contracting environment for it: distributed generation would sell energy to distribution companies, instead of using auctions, by a public tender organized by the distribution company. In any case, the energy price would still be the regulated tariff that distribution companies applied to any electricity. In the case that they opted for selling to large consumers, they would be subject to the complex rules governing bilateral contracts. In that view, even with the simplified contracting environment, distributed generation faced differentiated incentives.

In order to facilitate the development of distributed generation, ANEEL issued the Resolution 482 ("Resolução Normativa 482, ANEEL"), which regulated micro- and mini-distributed generation. Two central incentives are introduced in this resolution. On the one hand, a measured often called "net metering" is introduced. Micro and mini photovoltaic generators can avoid paying for the amount of electricity they generated, thereby reducing the value of the electricity bill for the price final full of energy in its distributor. In practice, the generator distributed obtains a return in the form of savings in the electricity. The advantage of this system is that the economy is made at the final consumer price, which is significantly higher than the price in energy auctions.

Besides, the Resolution 482 defines extensively the procedures to access the distribution network, which are central in the facilitation of distributed generation (the one connected to the distribution network). Actually, one of the main aspects of access to the distribution network is to define who should bear the additional costs associated with connecting distributed generation. I order to facilitate its insertion, the Resolution 482 defined that the distribution company will be responsible for the impact analysis and the associated costs (including the bidirectional meter required to implement net metering).

Finally, the possibilities of specific financial aid for distributed generation in Brazil are limited. Although there exists some localized funds, the main financial institution for the construction of power plants (the Brazilian development bank, BNDES) has no specific product for distributed generation.

■ **Incentives faced by distributed generation –** In this section, our objective is to develop a comparison between large solar power plants and distributed photovoltaic generation.

Large power plants	Distributed photovoltaic generation
Planning	
Part of the environmental studies associated with projects are done by the government. Costs pass-through to final consumers	It does not require environmental analysis, but it does require project analysis whose costs are borne by the generator, without influence in the final energy price
All requirements in the implementation phase (including environmental licenses) are responsibility of generators	Some of the implementation costs are shared with distribution companies
Energy planning (by EPE) is focused on participation in the energy auctions	Residual role for distributed generation
Procurement mechanism	
Mainly regulated auctions	Compensation system only (direct sale to distribution companies)
Energy paid for by long-term PPAs, which results in low risk for generators (quantity contracted at pre-defined prices)	In the form of a credit to be discounted from the electricity bill. Subject to significant risk because it is exposed to end-user tariffs

Retailing	
It is possible to sell energy in the retail market, although such market is not liquid	Possible, but not viable for most of small generators. The remuneration when trading with distribution companies is done at the regulated tariff (which is too low). When selling energy to large consumers, they are seen as independent producers (and hence face severe difficulties)
Financing	
All projects in the auction have available financing with a BNDES subsidy	There is no BNDES specific product. Open position to market conditions

Table 2. Comparison between incentives for Large Power Plants and Distributed Photovoltaic generation. Source: (Mello, 2014).

From the analysis of the table above, one may observe that all aspects are negative to the distributed generation, except the one associated with environmental licensing (second point under "planning"). That means that distributed generation, in fact, is actually facing barriers when compared to larger power plants.

As, in this paper, we are concerned with the choice of technology, the incentive system in the current Brazilian power system clearly favors the introduction of concentrated PV over distributed PV generation.

4. The simulation model

In this section, we propose a methodology to analyze the effects of different policies to promote renewable technologies. We consider them in the context of the decision-making process of the power sector, in order to understand their interaction with the rest of the institutions that coordinate the electricity sector. Note that we have included in the framework the sets of measures to facilitate technology innovation except R&D policies. The methodology to understand the interaction will be based on the system dynamics framework, (Forrester, 1968). Other applications of system dynamics developed to study investment in power markets are proposed in (Sánchez et al., 2007), (Cepeda and Finon, 2011), (López-Peña et al., 2009) and (Cepeda and Finon, 2013).

4.1 General scheme

The quantitative analysis of the question posed in this paper is performed using the following (very simplified) description of the decision-making process:

1. With future expectations, players calculate future income streams. They will be calculated by using the simulation model described in the Appendix.
2. With learning curves, players calculate technology costs. Together with possible externality policies (e.g. carbon taxes), they calculate cash flows.
3. With regulation, players calculate discount rates. Rules define possible barriers that we simplify by including them in the perceived discount rate (not necessarily and equilibrium one). Together with possible technology policies, they decide on investment decisions.

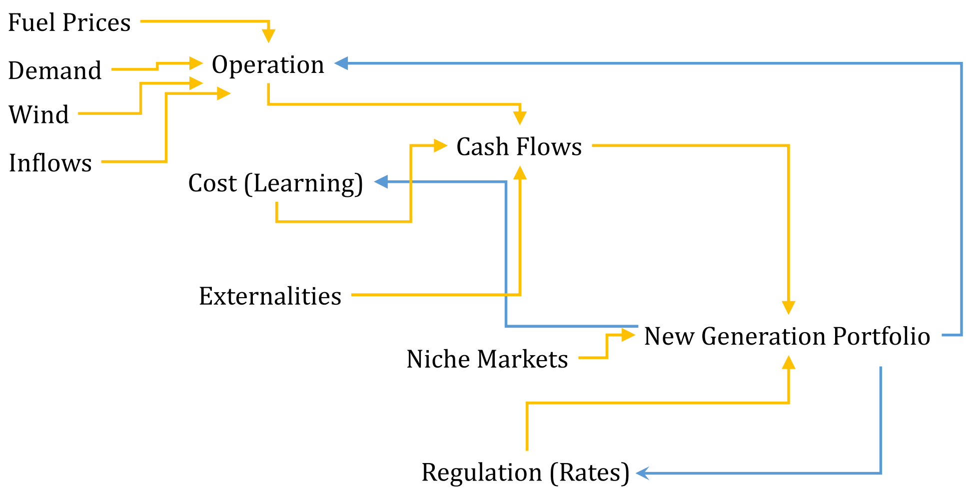

Figure 1. Framework to analyze renewable policies.

As the technology is the same (or at least that is what policy makers believe), one should observe the same penetration. If policy makers do not observe that, they revise their policy. So at the beginning of each step of the simulation, regulators may decide to equalize discount rates. They do so if investments decided by the two technologies have differences above a certain tolerance. Initially, concentrated solar enjoys better discount rates. If policies are not revised, distributed solar never enters the market (during the simulation scope). We will consider the simplified power system represented in Figure 2. This model is the same as the one used by the EPE (the Brazilian energy planning body) to perform the ten-year planning, see for instance (EPE, 2014).

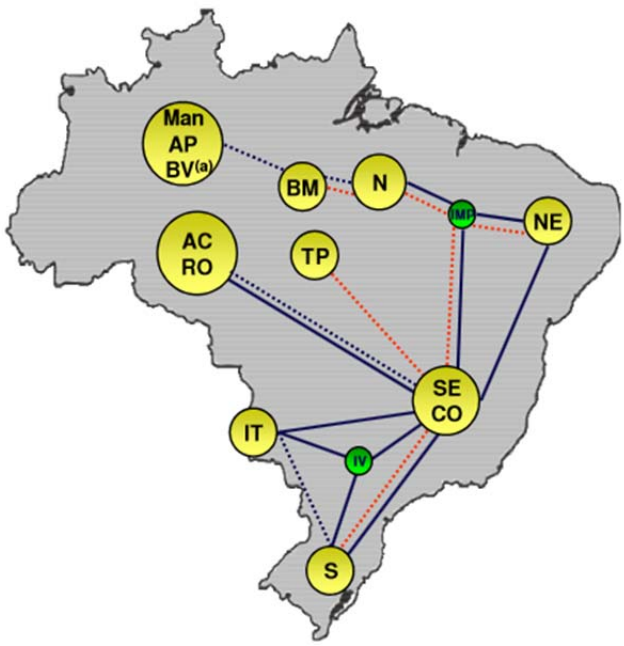

Figure 2. Representation of the Brazilian power system (Fonte: EPE).

The nodes represent the relevant zones in the Brazilian power system, and their code names are explained in

SE/CO -	Sudeste/Centro-Oeste	**IT** -	Itaipu
S -	Sul	**AC/RO** -	Acre/Rondônia
NE -	Nordeste	**BM** -	Belo Monte
N -	Norte	**TP** -	Teles Pires/Tapajós
MAN/AP/BV -	Manaus/Amapá/Boa Vista	**IMP** -	Imperatriz
IV -	Ivaiporã		

Figure 3. Code names for the nodes of the power system representation (Fonte: EPE).

4.2 Representation of power system operation

One of the main characteristics of the Brazilian power system organization is that the unit commitment is decided centrally. From this papers' point of view, that eliminates the need of representing strategic interaction between players (each of whom would own a particular generation portfolio). Consequently, we will consider aggregately both supply and demand (which allows simpler computation), at the cost of losing accuracy in the representation of system technical characteristics.

We will consider supply and demand concentrated in four nodes: SE (the largest node, where the majority of the demand is located), S, NE, and N. On the supply side, we will consider aggregately all generation at the node produced by technology. For instance, at node SE (South-East), we will consider four thermal power plants: one for all production from coal-fired power plants, one for gas-fired power plants, one for oil-fired power plants, and one for nuclear production. Additionally, at each of the four nodes, we will consider the corresponding hydro-based production. All required data is collected from the national planning, (EPE, 2014).

Two additional generation technologies are relevant in our study. On the one hand, wind production is a non-dispatchable technology. That is, power producers cannot decide when to produce with the wind farm, they are forced to produce when the wind blows. Consequently, wind production will be a special technology that will not be subject to producers' decisions. Instead, it will be understood as a stochastic input that modifies the actual system demand. In addition, we will consider that there is no solar capacity installed in the system (the capacity installed in 2014 is small enough to be disregarded). Consequently, all solar capacity in the system will be the result of producers' investment decisions, which are inn turn the result of the expectation of future system marginal costs.

Finally, it is necessary to transform the fuel prices into thermal plants variable costs. We model such transformation, in the study, as the price of just one forward contract of the curve multiplied by the efficiency of the plant. In particular, the variable cost will be the forward price of the contract expiring in three months, multiplied by the efficiency. The rationale behind this is that power producers need at least three months to get additional fuel, so their variable cost is the cost of refueling. All the modeling details are given in the Appendix.

4.3 Investment decisions

The next step, as represented in Figure 4 within our methodology framework, is transforming system operation results into expected cash flows. To that end, we will use the information contained in the optimization model, see the Appendix. In particular, the dual variable associated with the maximum output constraint $\boldsymbol{\rho}_{t,i}^{max}$ represents, by definition, the reduction in system costs if one more unit of capacity were available. Hence, such dual variable represents directly the infra-marginal rents of the corresponding power plant, see for instance (Vazquez et al., 2015) for a detailed description. Therefore, the dual variables $\boldsymbol{\rho}_{t,i}^{max}$ will be the expected profits (income minus short-term costs) of each power plant at each point in time.

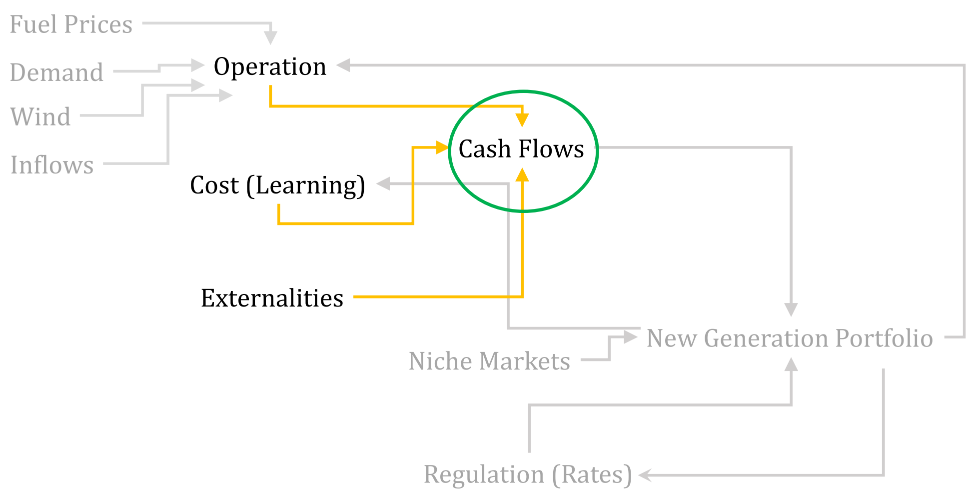

Figure 4. Cash flows and the system operation model.

As represented in Figure 4, there are more inputs required to calculate the expected cash flows, both of which are related to including long-term effects. In principle, in order to obtain the expected cash flows, we need to add fixed costs to the previous expected profits (given by the dual variables $\boldsymbol{\rho}_{t,i}^{max}$). Nonetheless, we consider two additional dimensions.

First, we consider 'learning curves' –we use the term 'learning' curve in a broad sense, not limiting them to represent learning-by-doing but also other types of learning (e.g. learning-by-using). The specific form in our model will be an experience curve, (Rosenberg, 1982), which relates unit costs reductions to cumulative deployment of technology, see for instance (Foxon, 2010) for a review of the application to climate change problems. In our context, learning processes of generation technologies will be represented by the learning rate, i.e. the reduction in unit costs for a doubling of cumulative output, using a power-law relationship between cost reductions and cumulative deployment. Besides, our methodology allows considering policies to reduce CO2 emissions (they would be an instance under the header 'externalities' in Figure 4). In this paper, we use a carbon tax, which implies a reduction of profits for emitting technologies. On the other hand, cap-and-trade mechanisms would require introducing a CO2 price in the system operation model, and hence considering such price as a fundamental driver. In the case studies, we will consider that a carbon tax is in place.

The last step of the reasoning would be to model new investment decision-making. The elements that we will consider are represented in Figure 5. Besides the cash flows obtained above, we need to represent the discount rate for the investment decision. The analysis of section 3.2 becomes crucial in this task.

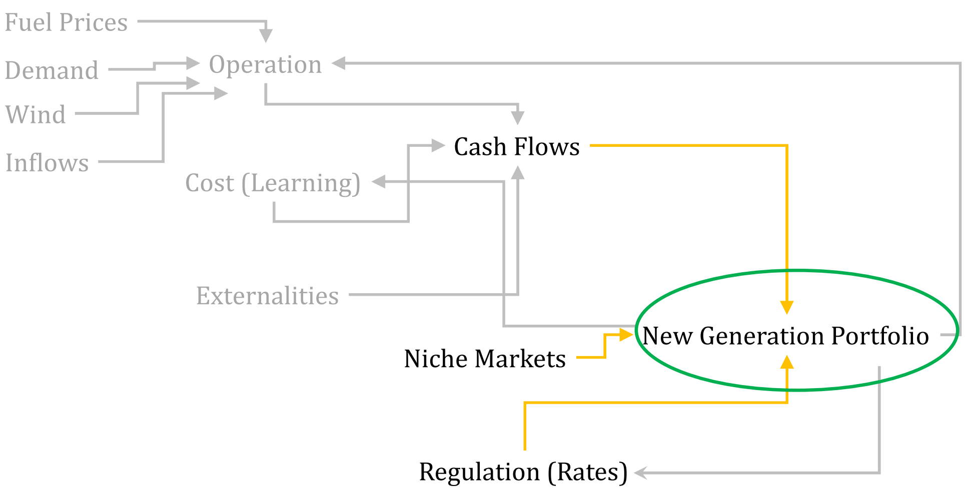

Figure 5. Dimensions affecting investment decision-making.

Discount rates strongly depend on the maturity of the technology and the risks perceived in the investment cash flows. In that view, we will consider a higher discount rate for solar projects that for the construction of gas-fired power plants. In addition, one of the main determinants of the cash flow risk is the institutional setting. As shown in section 3.2, nowadays in Brazil, distributed generation faces a less attractive environment for investment, so we will consider (initially) a higher discount rate for distributed generation. Finally, the amount of generation defined by the niche market policy is introduced in the system. That is, we consider the niche market policy to ensure profitability of the corresponding investment.

4.4 Feedbacks (positive or negative)

There are three main feedbacks in our methodology, as shown in Figure 1. First, the simulation of the power system for the next year must take into account new generation capacity (either from solar or gas-fired power plants). Second, the amount of installed capacity for each technology, or equivalently its deployment, represents advancing in the experience curve. Consequently, the next step of the simulation, unit investment costs will be updated according to such experience. Third, we take into account the possibility that regulators and policy-makers observe the market results and modify policies accordingly. This will be done only in the case 3 considered in section 5.3. That will eventually result in the modification of the relevant discount rate, and hence it will critically affect investment decisions.

5. Analysis of the dynamics of the Brazilian power sector

In order to facilitate the exposition, we will limit the possibilities of investment in fossil-fuel-fired power plants to investment in gas-fired power plants. These investments will be compared to investment in new (and renewable) technology. As wind production has increased significantly in Brazil during the last decade, we will consider that the new technology entering the market is solar generation. Besides, we will differentiate between concentrated solar and distributed solar generation. Hence, investors in our model will choose among one of those three technologies. In that context, investors consider only whether a unit investment is profitable under the previous conditions. The size of the power plant to be built is defined exogenously.

5.1 Case 1

We first analyzed the case where there is no technology policy in place. In this case, we assume the evaluation criteria for policy makers to decide to maintain or change the rules is just the electricity price. From that point of view, this case will confirm that, in order to achieve the introduction of solar technologies in the power system, some kind of policy is required. This will confirm the analysis developed in the first sections of the paper. In that view, this case will serve as a test of the model parameters. This first simple case can be summarized by considering that investment takes place under the following conditions:

- Gas-fired power plants have a minimum size of 7000 MW the first 5 years of the time scope. This represents higher needs of investment associated with large increases of demand. Those investments are valued at a discount of 15%. Besides, as gas-fired power plants are CO2 emitters, they are penalized with a carbon tax, which results in a decrease of 15% of power plant income streams
- Solar power plants are built with a minimum size of 50 MW, and are valued at a discount of 20%

No additional features are added in this case, In particular, it does not include niche markets, and regulators and policy-makers do not react to observed outcomes of the market. In this scenario, Figure 6 depicts the investment in gas-fired power plants at each node of the system.

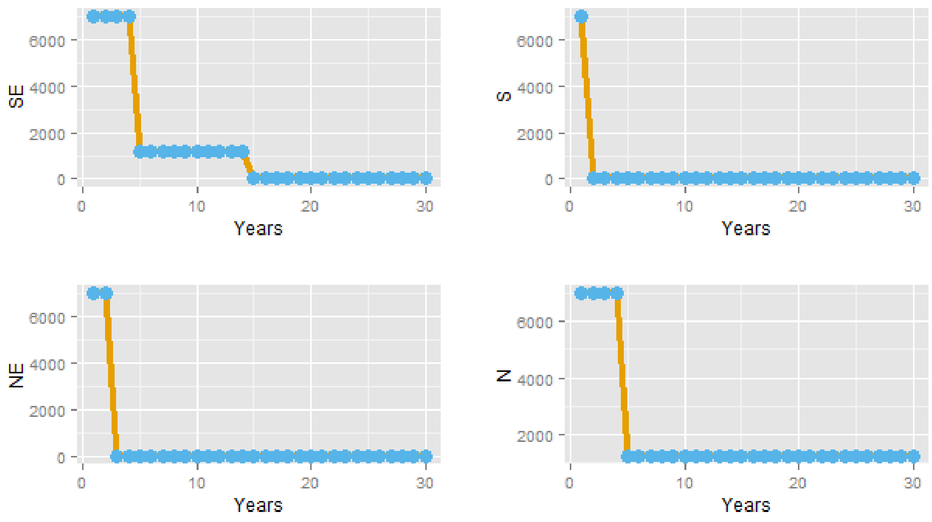

Figure 6. Investment in gas-fired power plants over the complete time scope. Note that for the N node, investment never reaches zero.

In addition, we observe that solar power plants never enter the market, as shown in Figure 7, which considers together concentrated solar and distributed solar. Except for an isolated investment in one of the first years at the SE, no investment in solar plants is achieved.

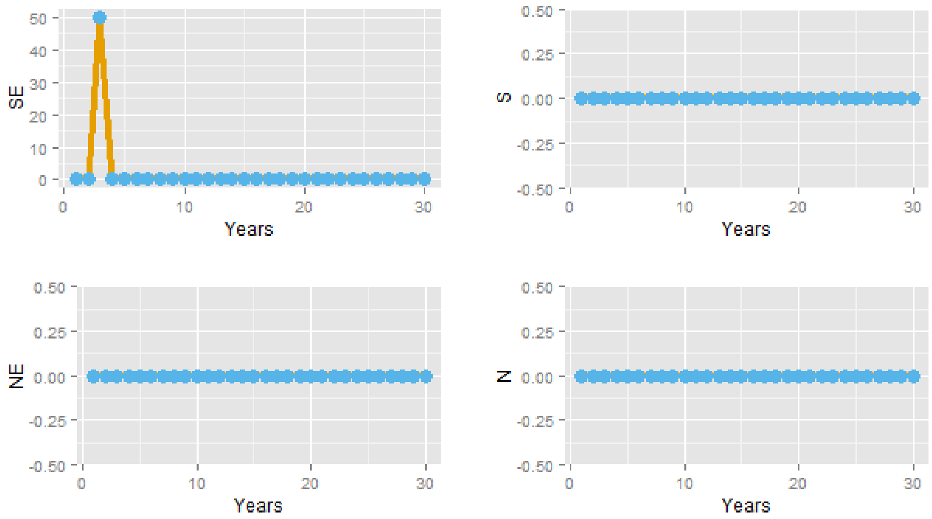

Figure 7. Investment in solar power plants (considered concentrated solar and distributed PV together).

In summary, this case shows that, in absence of some policy to facilitate the insertion of new technology, the high unit costs of the new solar technology will preclude its penetration in the Brazilian power system. Next cases will introduce such policies.

5.2 Case 2

In the second case, we analyze whether the introduction of a solar policy can modify the previous results. The evaluation criteria in this case is the increase of the capacity of solar generation. The basic characteristics of the previous case are reproduced here:

- Gas-fired power plants have a minimum size of 7000 MW the first 5 years of the time scope. This represents higher needs of investment associated with large increases of demand. Those investments are valued at a discount of 15%. Besides, as gas-fired power plants are CO2 emitters, they are penalized with a carbon tax, which results in a decrease of 15% of power plant income streams
- Concentrated solar power plants are built with a minimum size of 50 MW, and are valued at a discount of 20%
- Distributed solar generation, as shown in 3.2, faces a less favorable environment, so they are valued at a discount rate of 25%

By contrast, in this case we introduce a niche market policy. This represents well the current policy solutions implemented in Brazil, and the ones put in place for the introduction of wind power. The Brazilian system is carrying out dedicated auctions for solar technology (as it did previously for wind technology), which is in fact a niche market policy: the auction represents a firm long-term contract, which consequently lock-in demand to develop the technology. The representation of such policy in our methodology is as follows:

- There are niche markets in place during the first 6 years of the simulation scope. They are represented by an investment in concentrated solar plants of 100 MW without cost

Consequently, we investigate in this case whether the policy dedicated to concentrated solar, which will reduce unit costs of both technologies (both technologies share the same experience curve), is enough to allow the introduction of distributed generation (at less favorable discount rates).

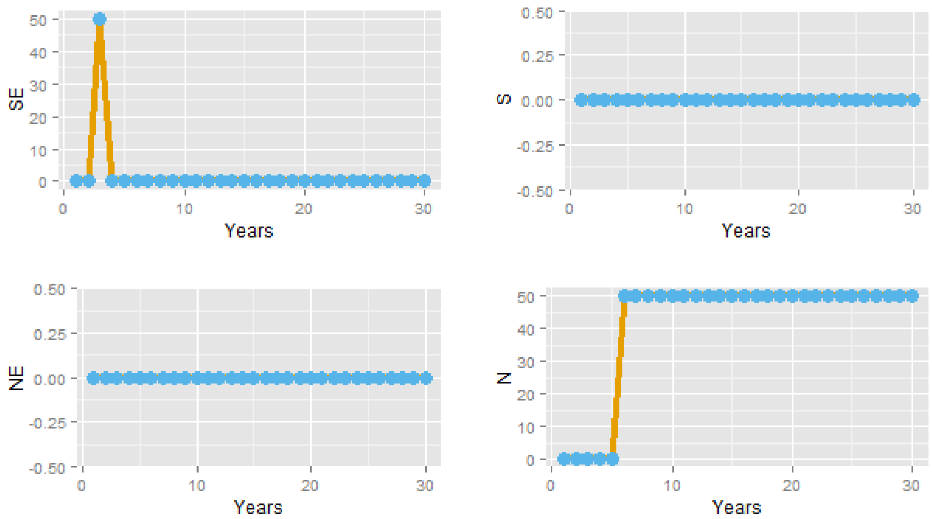

Figure 8. Investment in concentrated solar over the time scope.

Figure 8 shows the concentrated solar capacity installed over the simulation scope. We observe that concentrated solar is introduced consistently at the N node (North).

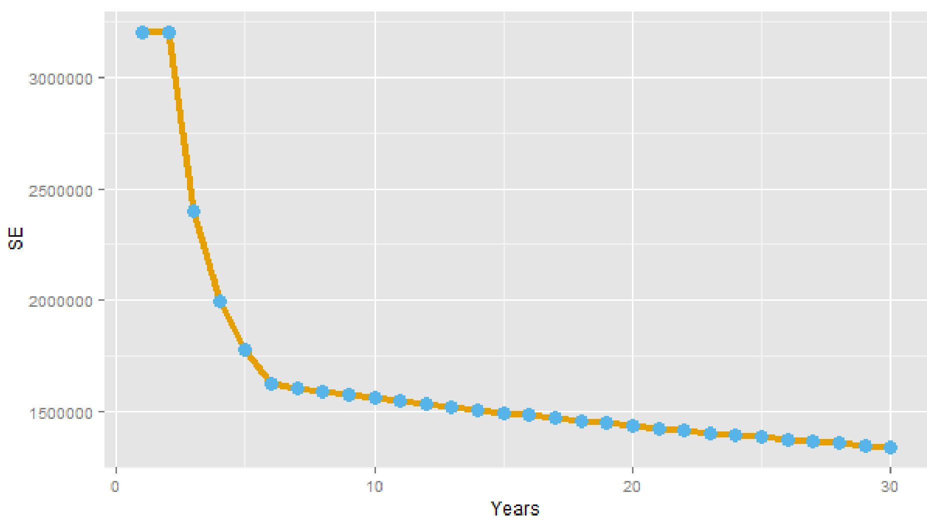

Figure 9. Fixed cost for solar technology over the time scope. The decay shows the effects of the learning process.

In addition, Figure 9 shows the effects of the niche market policy on the experience curve of solar technology. The steep decrease of the first years of the simulation is associated with the niche market policy (it lasted 6 years). After that, concentrated solar plants are introduced in the market competitively. It is worth to note that this result has an analogue in the evolution of wind power in Brazil, where the previous dynamic was actually observed in the market (several dedicated long-term auctions followed by several competitive auction where wind power plants won the contracts). The rationale behind the Brazilian approach is to mimic those results with solar power plants.

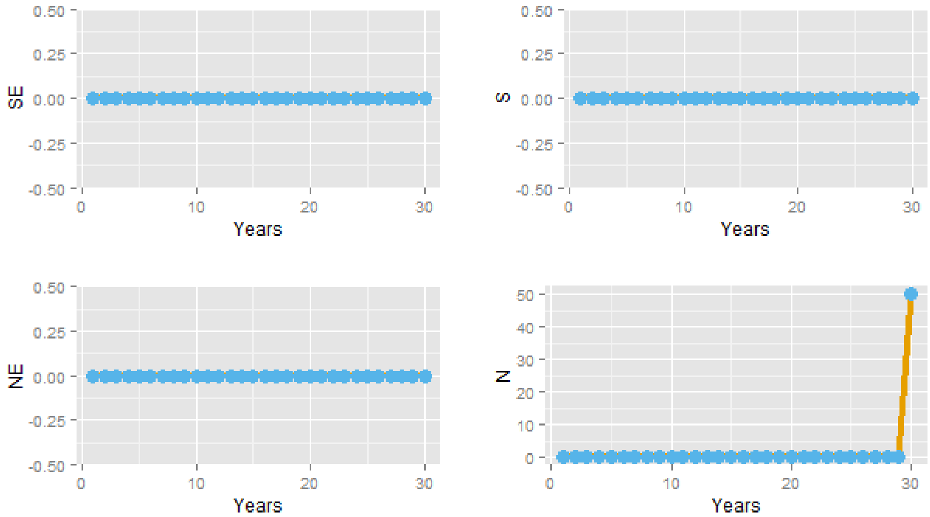

Figure 10. Investment in solar PV (distributed technology).

However, Figure 10 shows the results for distributed generation. Except for an isolated investment the last year of the simulation, the technology is never introduced. This was one of the main points raised in section 3.2: the difficulties faced by distributed generation precludes its introduction in the market, even if it benefits from the niche market policy.

5.3 Case 3

In this last case, we show the main contribution of this paper: the need for institutional adaptation. The idea behind this case is to show that, frequently, the problem institutions were supposed to solve when they were designed changes over time. In particular, we will model the response of regulators and policy makers to the fact that the policy designed to promote solar generation introduced in fact become a barrier for one of the possible solar technologies. In this case the evaluation criteria of policy makers of the outcome is not just the introduction of solar (capacity) but also the coherence between the market design rules and the technical characteristics of the new technology.

The starting point is the case described above: there a niche market in place that reduces unit costs of both technologies; but the first one (concentrated solar plants), which enjoys favorable conditions associated with the institutional setting, is valued at a discount rate of 20%; the other one (distributed solar photovoltaic installations), with less favorable conditions, faces a discount rate of 25%.

In this situation, policy makers can observe market investment in solar technologies to assess whether the policy is successful. If the amount of concentrated solar is higher than double the amount of solar photovoltaic, they establish a discount of 20% (representing that they eliminate barriers to distributed generation). Note that we do not assume that distributed generation is cheaper than concentrated solar plants.

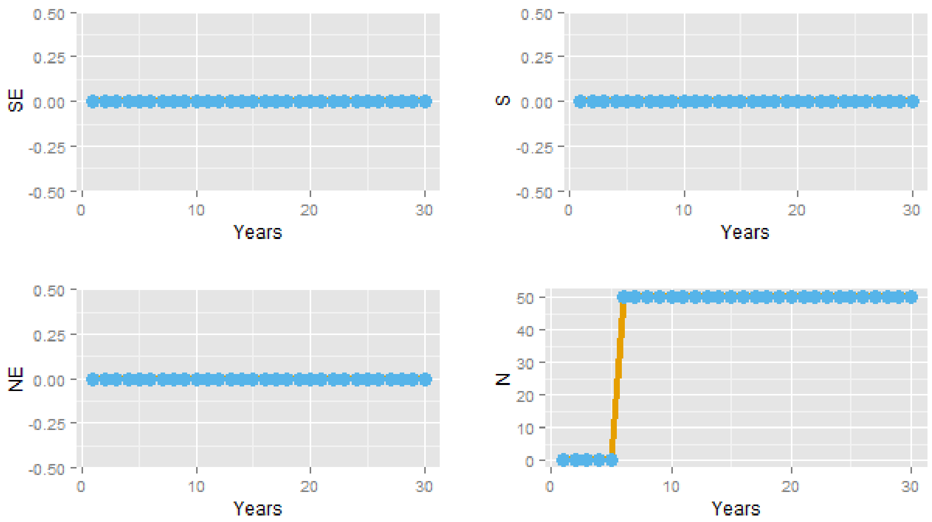

Figure 11. Investment in distributed solar generation.

Figure 11 shows that, when regulators and policy makers respond to observed conditions, distributed solar generation is introduced in the system competitively. It shows that the technology is consistently introduced at N, as investment levels are maintained years after the niche market policy disappears.

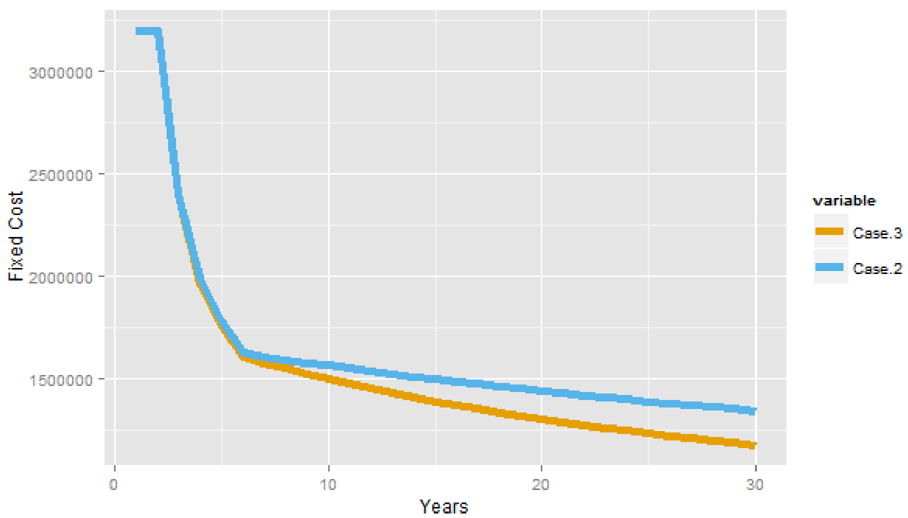

Figure 12. Comparison between the learning processes in cases 2 and 3.

Finally, Figure 12 compares the cost reduction (through experience curves) obtained in cases 2 and 3. It can be observed that the introduction of distributed solar improves the learning process and hence reduces costs. Consequently, if regulators and policy makers respond to the observed difficulty of distributed generation to enter the market, it finally enters and obtains a larger amount of installed solar megawatts.

6. Conclusion and policy implications

In this paper, we first showed that understanding the interrelation between the evolution of technology and institutions is crucial in a strongly uncertain environment. In particular, we have shown that, when considering regulators with bounded rationality making decisions in a complex environment, rules are the consequence of a set of beliefs about how the system works. Regulation then emerges as a combination of the regulators' beliefs and the feedback they obtain observing system outcomes, which makes them adapt the regulatory framework. We operationalize this idea using the Institutional Analysis and Development framework. In particular, the study of level-shifting strategies developed within the framework allows generalizing the dynamics of rules evolution. We have shown that one of the main drivers for rule evolution is the evaluative criteria, as these criteria defines the way in which rules adapt.

In order to show this, we have developed a new model of the decision-making process in the Brazilian power system to analyze quantitatively the effects of institutional adaptation. In the simulation of a stylized Brazilian system, we have shown that the current institutional setting impacts on the technological dynamics of the industry. Therefore, when facing large technological uncertainty (and hence the need for adaptation is very likely), if evaluative criteria are myopic there will be potential technological pathways. In this sense, we show that the use of the myopic criteria to evaluate outcomes is a relevant piece of the lock-in mechanism. We have studied the effects of considering three different criteria: i) regulators observe only whether electricity is produced by the cheapest available technology nowadays; ii) they observe whether new technology is introduced by niche markets; and iii) they observe whether adapting regulation is necessary to avoid technological lock-in. We observe that only the third criterion avoids barriers to distributed PV in Brazil.

From a policy-making point of view, our simplified study points at the importance of considering the way in which regulators evaluate the industry outcomes. Most of studies consider regulation as a static set of rules defined exogenously to the system. We introduce a framework where regulators interact dynamically with the industry resulting in the joint evolution of regulation and industry characteristics. In particular, we propose a way to operationalize it by considering the primitive of study is not regulators' decisions but their evaluative criteria. Regulation, in that sense, would be an emergent property of a complex system. On the other hand, we have considered an extremely simplified transformation of evaluations into actions. That is, we have considered an abstract set of solutions for each evaluative criteria (represented by modifications of the perceived discount factor), which is perfectly defined in each case. Obviously, a more detailed representation is required to describe real-world systems. In that context, our case study should be interpreted as a first step in the operationalization of studies of regulatory learning processes. Future research must pay attention to the way in which evaluative criteria are formed, and how those criteria are transformed into regulatory actions.

Acknowledgement

We thank Ronaldo Bicalho for fruitful discussions that helped shaping the ideas developed herein. We also benefited from participants at the 2015 ISNIE Conference and at the Workshop "Challenges Of The Power Industry: Policies, Goals And Implementation" at the Fluminense Federal University. This research has been partly funded by CAPES/BRASIL through the Science without Borders post-doctoral program.

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7. Appendix

7.1 Demand, wind production and hydro power inflows

Besides the data defining generation capacity, our modeling approach considers fundamental drives to define system marginal costs. The fundamental drivers considered in this paper are: (i) demand, (ii) wind production, (iii) inflows to hydro plants, which will be ultimately transformed into capacity of their reservoir, and (iv) fuel prices. This subsection deals with the first three drivers, and we leave the fourth driver for the next subsection. Our approach to model them is based on considering them as functional data. In order to model those functions and estimate them from historical data, we will rely on non-parametric techniques. Modeling functional data often relies on linear regression. Although linear models are relatively easy to describe and implement, it is often unlikely that the true function is actually linear.

Our goal will be to find a useful approximation $\hat{f}(x)$ to the true function $f(x)$, where $f(x)$ denotes each of our fundamental drivers. In order to find that approximation, consider that our input is a real-valued random variable, $X \in \mathcal{R}$, and our output is also a random variable $Y \in \mathcal{R}$. We will find a function $f(X)$ that predicts Y. To that end, we will use that the regression function $f(x) = E[Y/X]$ minimizes the squared error.

The first step in our methodology is to consider the following problem: among all functions $f(x)$ with two continuous derivatives, find one that minimizes the penalized residual sum of squares (RSS), which is given by

$$RSS = \sum_{i=1}^{N} \left(y_i - f(x_i)\right)^2 + \gamma \int \left(f''(t)\right)^2 dt$$

where x_i and y_i are each of the N points of our data, and γ is the smoothing parameter. We observe that the RSS is made up of two terms: the first one measures how close to the original y_i data our estimation $f(x_i)$ is; the second term represents a penalty on the curvature of our estimation. The smoothing parameter γ represents the trade-off between both. Consequently, if the smoothing parameter is zero, the curvature penalty will be ignored. On the other hand, is the smoothing parameter is infinite, the closeness criterion will be ignored. It can be shown that the minimizer of the previous definition of RSS is a natural cubic spline.

The second step is to represent multidimensional data. To that end, we will use Generalized Additive Models. Our setting now considers that our input is a random variable with several dimensions, $X \in \mathcal{R}^p$. Consequently, the regression function can be expressed now by $f(x) = E\left[Y/X_1, \dots, X_p\right]$. In this regression setting, the generalized additive model is represented by

$$E\left[Y/X_1, \dots, X_p\right] = f_1(X_1) + \cdots + f_p\left(X_p\right)$$

That is, we transform the multi-dimensional regression problem into the sum of several one-dimensional regression problems. In that view, Y is the outcome and each of the f_j is a smooth regression function. Consequently, we use a smoothing approach analogous to the one-dimensional problem, combined with an algorithm that simultaneously estimates all p functions.

Hence, we need to define the RSS for the generalized additive model, which is now given by the following expression:

$$RSS = \sum_{i=1}^{N} \left(y_i - \sum_{j=1}^{p} f_j(x_{ij}) \right)^2 + \sum_{j=1}^{p} \gamma_j \int \left(f_j''(t_j) \right)^2 dt_j$$

where γ_j are the smoothing parameters. Analogously to the one-dimensional case, it can be shown that the minimizer of the previous expression is an additive cubic spline model. We use the backfitting algorithm to find the fit.

In order to apply the previous methodology to the fundamental drivers of the electricity marginal costs in Brazil, we consider each of the variables (demand, wind production and water inflows) as functional data. That is, each observation will be considered as part of function that describes the variation of the variable over one year. In that view, each point in the sample will depend on two variables: year and month. Consequently, our generalized additive model will be expressed by the following model:

$$E[Y/Year, Month] = f_{year}(Year) + f_{month}(Month)$$

Besides, each of the components will be modeled by a smoothing spline. Next, we show examples of the fits obtained by the previous procedure.

■Wind Production at NE (North East) – Wind production in the North Eastern region in Brazil has grown markedly in the last decade, as can be observed in the left panel of Figure 13. In it, we represent the smooth component relating wind production and yearly evolution.

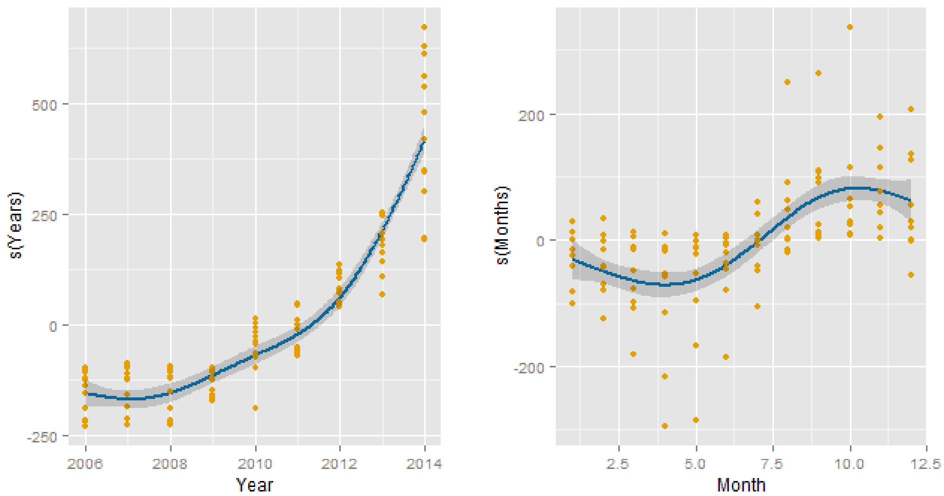

Figure 13. Smooth components of the GAM for the wind production at NE.

■ Inflows – As before, we fit a Generalized Additive Model, based on smoothing splines, to represent inflows at hydro plants. Figure 14 depicts the model for the NE node (North East).

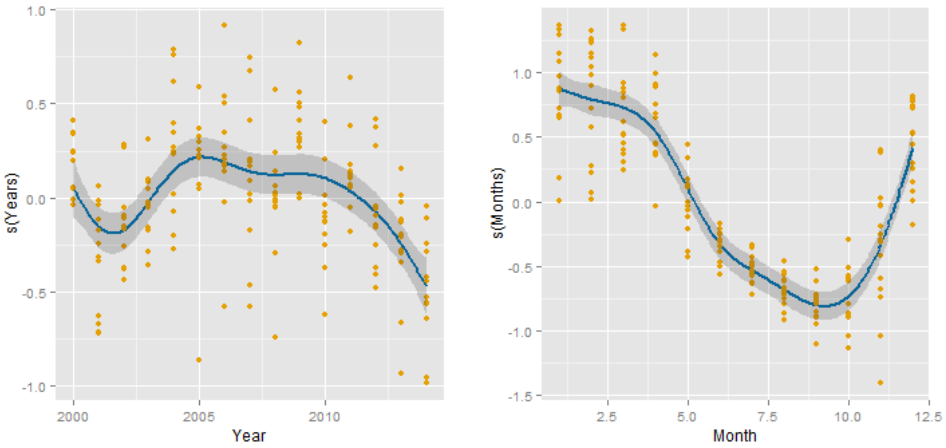

Figure 14. Smooth components of the GAM for inflows at NE.

■Demand – Finally, we fit a Generalized Additive Model, based on smoothing splines, to represent the demand for electricity at each node. Figure 15 depicts the smooth components for the S node (South).

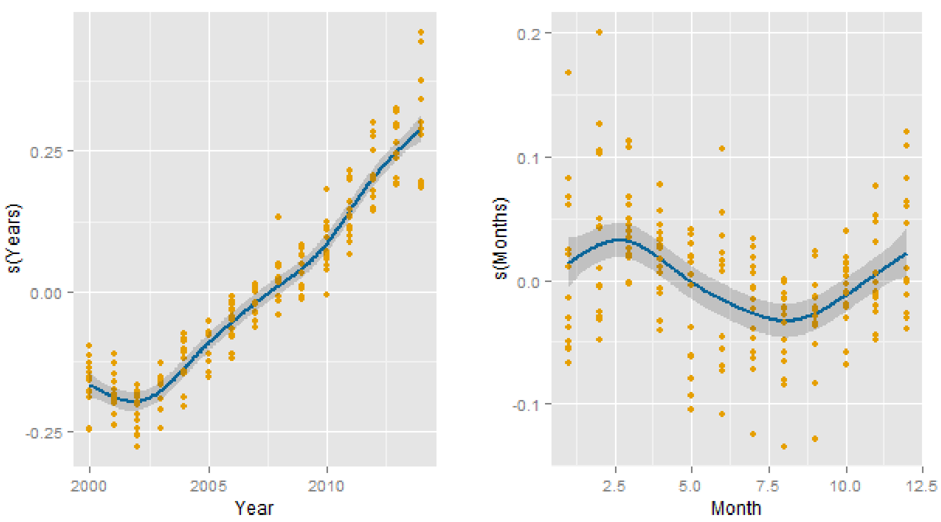

Figure 15. Smooth components of the GAM for demand at S.

7.2 Representing financial data on fuel prices

The model proposed in this paper to represent the dynamics of the power sector is built on the representation of its fundamental drivers. Among them, the prices of the fuels used to fire power plants play a central role. To represent the dynamics of those prices, we consider that the amount of forward trades in fuel markets is relatively large. This results in a relatively large set of market prices, which can be used to obtain market information.

To that end, we will model the dynamics of forward curves. The general idea behind this is to describe the forward curve as a continuous function, made up of the forward prices, which evolves over time. That is, the problem is not the analysis of the evolution of a random variable, but rather the evolution of a curve. Consider the following model, proposed in (Black, 1976):

$$\frac{dF_{t,T}}{F_{t,T}} = \sigma dW_t$$

In this model, the dynamics of forward contracts, represented by $F_{t,T}$ (where t is quotation time and T is expiration date of the contract) are governed by a zero-drift Geometric Brownian Motion W_t with volatilityσ. However, the applicability of such process is limited, because it describes the evolution of forward prices independently –i.e. without taking into account how the contract price interrelates with prices of other forward contracts. When dealing with energy markets, on the contrary, one typically needs representing the whole term structure of forward prices at a given date. Consider for example the valuation of gas storage facilities. Natural gas tends to have high prices in the winter and low prices in the summer. Thus, optimizing the injection and withdrawal schedules of the storage facility would imply to define the evolution of the whole term structure, as the storage value depends on the spreads between contracts along the curve.

This leads to the use of the methodology developed in (Heath et al., 1992) to analyze the evolution of interest rates, which can be expressed by the following equation:

$$\frac{dF_{t,T}}{F_{t,T}} = \sum_{z} \sigma_{t,T}^{z} dW_t^z$$

In this model, each of the z random shocks is defined by a deterministic function $\sigma_{t,T}^{z}$. Each of these functions in turn are multiplied by a Gaussian factor dW_t^z, and these factors are not correlated. In practice, a simpler version is typically used. These techniques are applied, among many others, in (Koekebakker and Ollmar, 2005), where the forward curve of the NordPool is in studied, or in (Clewlow and Strickland, 1999), where the forward curves in the NYMEX gas and oil markets are analyzed. The main results are given by the following model:

$$\frac{dF_{t,t+s}}{F_{t,t+s}} = \sum_{z} \sigma_{s}^{z} dW_t^z$$

where the subscript $s = T - t$ denotes the time to expiration of the forward contract. Thus, we will consider the random shocks governing the dynamics of the forward curve as functions only of the time-to-expiration time, i.e. independent of the quotation date t.

The most used method to estimate the functions σ_s^z is using Principal Component Analysis (PCA). The basic idea behind that approach is that frequently a small number of principal components suffice to explain most of the variability in the forward curves. However, the complex characteristics of energy forward curves make difficult to use linear methods as PCA. Hence, we will estimate the functions using non-linear techniques.

To that end, we will use a Generalized Additive Model (GAM) approach, along the lines of the models used for the rest of fundamental drivers. The idea is to extend the multiple linear regression context by using nonlinear functions instead. When applied to estimating forward curves, we will use the following regression problem as estimator of the forward curve:

$$E[Y/X] = f_{year}(Year) + f_{month}(Month) + f_{exp}(Expiration)$$

The variable 'Expiration' represents the time to expiration of each of the contracts that conform the forward curve. Along the lines of the models for the other fundamental drivers, each $f_i(X_i)$ will be a smoothing spline, fit by means of the backfitting algorithm. Consequently, each component $f_i(X_i)$ will represent one of the functions driving the evolution of the forward curve, $F_{t,t+s}$.

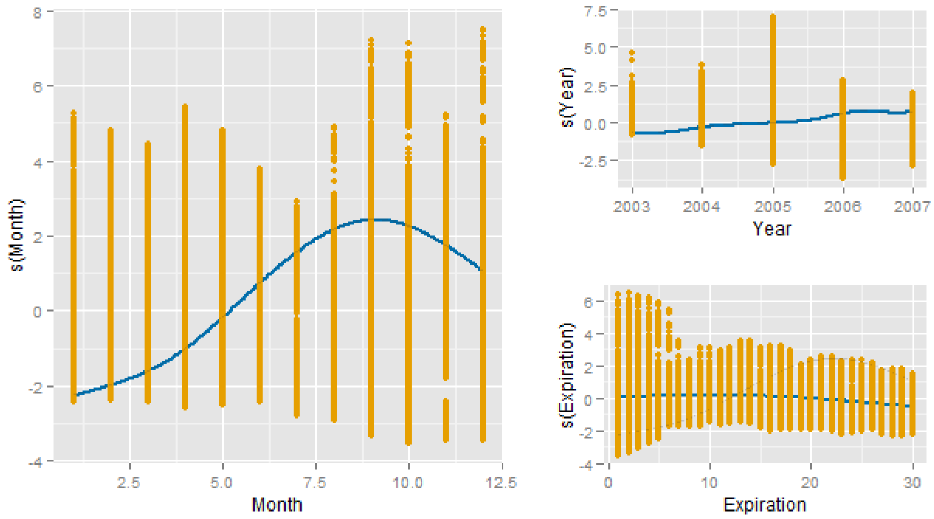

Figure 16. Smooth components of the Generalized Additive Model used to represent gas forward curves.

7.3 A model to optimize the Brazilian power system operation

Many of the models aimed at representing the short-term market in power systems are defined by the solution of a static, non-cooperative game. The idea behind that approach is to define a game by means of the interaction of the firms involved in the market, each of whom solves a profit-maximizing problem taking into account that their decisions can effectively modify the market price. To complete the game, the market operator clears the market and calculates the price. Such approach, although may be not approximate enough in the case of the Brazilian market, will be useful to motivate our representation. We will consider, as a first step in the development of our methodology, the basic model for a short-term power market (see for instance (Borenstein and Bushnell, 1999) for a description of the rationale behind the approach). Let us define:

- q_i is the total output of firm i
- $C_i\ (q_i\ )$ is the generation cost of firm i.
- q_i^{max} is the maximum output of firm i
- ρ_i^{min} and ρ_i^{max} are the Lagrange multiplier corresponding to minimum and maximum output constraints, respectively
- π is the equilibrium price

Each firm solves the following problem:

$$\begin{aligned} max \quad & \pi(q_i\ )q_i\ - C_i\ (q_i\ ) \\ s.t. \quad & 0 \le q_i\ \le q_i^{max} \qquad : \rho_i^{min}, \rho_i^{max} \end{aligned}$$

We assume that the curves $C_i\ (q_i\ )$ are convex ones, in order to ensure that there is just one Nash equilibrium. Besides, in order to solve the Nash game we need equations that explain the behavior of the market operator. In this case, we will consider that the operator's clearing process is represented just by imposing that demand is equal to supply. This implies that we are considering an inelastic demand. Formally, $\sum_i q_i = D$. The set of equations that describe the Nash equilibrium are:

- Each firm's optimality with respect to output decisions (one optimality per firm)

$$\pi(q_i) + \frac{\partial \pi}{\partial q_i} q_i - \frac{\partial C_i (q_i)}{\partial q_i} - \rho_i^{max} + \rho_i^{min}$$

- Each firm's maximum output constraint

$$0 \leq q_i \leq q_i^{max}$$

- Each firm's complementarity conditions ($A \perp B$ denotes that A and B are complementary)

$$(q_i - q_i^{max}) \perp \rho_i^{max}$$

$$(0 - q_i) \perp \rho_i^{min}$$

The equilibrium point, hence, has to fulfill the set of equations defined by the optimality conditions of every market participant, plus the market clearing equation $\sum_i q_i = D$. In order to solve the problem, we assume that the cost curve is known, so that $\frac{\partial C_i (q_i)}{\partial q_i}$ is known as well. We also assume that $\frac{\partial \pi}{\partial q_i}$ is a known parameter of the problem. We will also define $\theta_i = -\frac{\partial \pi}{\partial q_i}$.

Our approach to solve this equilibrium problem builds on the analysis developed in (Hashimoto, 1985). The central idea behind that work is that it is possible to use a single optimization program as a representation of the strategic interaction, because the optimality conditions of the appropriate optimization problem are the same as the equilibrium conditions of the previous game. The main advantage is that the optimization problem is easier to solve. It is easy to check that the equilibrium conditions defined above, when $\theta_i = -\frac{\partial \pi}{\partial q_i}$, are the same as the first-order optimality conditions of the following quadratic program:

$$\begin{array}{lll} min & \sum_i \theta_i \, q_i^2 + C \ (q_i) & \\ s.t. & 0 \leq q_i \leq q_i^{max} & : \rho_i^{min}, \rho_i^{max} \\ & \sum_i q_i = D & : \pi \end{array}$$

This basic model allows us present the reasoning applied to the Brazilian system. As shown in section 3.1, the institutional setting in Brazil defines that, once all energy is procured through the long-term auctions (and hence commercial agreements are formalized through long-term Power Purchase Agreements), the ONS (national system operator) takes control of the system. Such situation can be understood as a model where no market player have market power, and hence $\theta_i = 0$. Consequently, our model for the short-term operation will be a system optimization, taking into account generation costs and technical constraints.

In power systems, technical constraints play a major role in the definition of the system marginal cost. In order to represent such technical constraints, we develop a multi-nodal version of the model described above. To do so, we consider the following extension, see (Barquín and Vazquez, 2008) for details:

$$\begin{aligned}
\min \quad & \sum_{t,i,n} C_{t,i,n}(q_{t,i,n}) - U(D_{t,n}) & \\
s.t. \quad & D_{t,n} + \sum_{j} m_{n,j} f_{t,j} = \sum_{i} q_{t,i,n} & : \pi_{t,n} \\
& 0 \leq q_{t,i,n} \leq q_{i,n}^{max} & : \rho_{t,i,n}^{min}, \rho_{t,i,n}^{max} \\
& f_{t,j} = y_j \ (\varphi_{t,n} - \varphi_{t,n'}) & : \rho_{t,j}^{DC} \\
& f_j^{min} \leq f_{t,j} \leq f_j^{max} & \rho_{t,j}^{Fmin}, \rho_{t,j}^{Fmax}
\end{aligned}$$

There are two major differences with respect to the former model. On the one hand, we have added the parameter t, in order to represent the time evolution of the relevant variables. On the other hand, we have also added the parameter n, in order to represent the node with which the variable is associated. We assume we have $n = \{1, \dots, N\}$ nodes. Besides those two differences, we have new variables representing the power lines connecting the nodes, which will be indexed by $j = \{1, \dots, J\}$. In the model above, the first constraint represents the balance equation in power networks: at each node, demand must be equal to supply plus the electricity flows leaving the node (either positive or negative). The last constraint represents the thermal limits of power lines, i.e. the maximum and minimum flows that it can transport. The second and third constraints represents the simplified physical characteristics of the power flow (this representation is often called 'DC power flow'). The above model can be written in vector form, in order to make clearer its relationship with the single-node model, by defining the following notation:

- $\boldsymbol{q}_{t,i}$ is the vector of total outputs of firm i at time t: $\boldsymbol{q}_{t,i} = \begin{bmatrix} q_{t,i,1} \\ \vdots \\ q_{t,i,N} \end{bmatrix}$

- $\boldsymbol{C}_{t,i}(\boldsymbol{q}_{t,i})$ is the generation cost of firm i at time t:

$$\boldsymbol{C}_{t,i}(\boldsymbol{q}_{t,i}) = \begin{bmatrix} C_{t,i,1}(q_{t,i,1}) \\ \vdots \\ C_{t,i,N}(q_{t,i,N}) \end{bmatrix}$$

- $\boldsymbol{q}_i^{max}$ is the maximum output of firm i

$$\boldsymbol{q}_i^{max} = \begin{bmatrix} q_{i,1}^{max} \\ \vdots \\ q_{i,N}^{max} \end{bmatrix}$$

- $\boldsymbol{\rho}_{t,i}^{min}$ and $\boldsymbol{\rho}_{t,i}^{max}$ are the Lagrange multipliers corresponding to minimum and maximum output constraints, respectively, at time t:

$$\boldsymbol{\rho}_{t,i}^{min} = \begin{bmatrix} \rho_{t,i,1}^{min} \\ \vdots \\ \rho_{t,i,N}^{min} \end{bmatrix}, \boldsymbol{\rho}_{t,i}^{max} = \begin{bmatrix} \rho_{t,i,1}^{max} \\ \vdots \\ \rho_{t,i,N}^{max} \end{bmatrix}$$

- $\boldsymbol{\pi}_t$ is the market price at time t:

$$\boldsymbol{\pi}_t = \begin{bmatrix} \pi_{t,1} \\ \vdots \\ \pi_{t,N} \end{bmatrix}$$

- $\boldsymbol{f}_t$ is the flow through the lines at time t:

$$\boldsymbol{f}_t = \begin{bmatrix} f_{t,1} \\ \vdots \\ f_{t,J} \end{bmatrix}$$

- $\boldsymbol{f}^{min}$ and $\boldsymbol{f}^{max}$ contains the limits for the flows

$$\boldsymbol{f}^{min} = \begin{bmatrix} f_1^{min} \\ \vdots \\ f_J^{min} \end{bmatrix}, \boldsymbol{f}^{max} = \begin{bmatrix} f_1^{max} \\ \vdots \\ f_J^{max} \end{bmatrix}$$

- $\mathcal{M}$ represents the nodes-lines incidence matrix, whose element $\mathcal{M}_{n,j}$ is 1 if the line j is leaving the node n, -1 if the line is arriving at node n and 0 otherwise

- $\boldsymbol{\varphi}_t$ is a vector containing the voltage phases at every bus, but the bus 1 whose phase is set to zero

$$\boldsymbol{\varphi}_t = \begin{bmatrix} 0 \\ \varphi_{t,2} \\ \vdots \\ \varphi_{t,N} \end{bmatrix}$$

- $\mathcal{F}$ is the matrix, obtained from the admittance data, relating flows and voltage phases

- $\mathcal{T}_i$ is a 0-1 matrix, which maps firms into buses. That is, $\mathcal{T}_i(n,i) = 1$ means that firm i is placed at bus n

The above notation allows representing the equilibrium problem as

$$\begin{aligned}
\min_{q_{t,i}, D_{t,n}, f_{t,j}, \varphi_{t,n}} \quad & \sum_{t,i} \boldsymbol{C}_{t,i}(\boldsymbol{q}_{t,i}) - U(\boldsymbol{D}_t) \\
s.t. \quad & \boldsymbol{D}_t + \mathcal{M}\boldsymbol{f}_t = \sum_i \mathcal{T}_i \; \boldsymbol{q}_{t,i} && : \boldsymbol{\pi}_t \\
& 0 \leq \boldsymbol{q}_{t,i} \leq \boldsymbol{q}_i^{max} && : \boldsymbol{\rho}_{t,i}^{min}, \boldsymbol{\rho}_{t,i}^{max} \\
& 0 \leq \boldsymbol{q}_{a,i}^{h} \leq \boldsymbol{E}_i^{max} && : \boldsymbol{\rho}_{a,i}^{hmax} \\
& \boldsymbol{f}_t = \mathcal{F}\boldsymbol{\varphi}_t && : \boldsymbol{\rho}_t^{DC} \\
& \boldsymbol{f}^{min} \leq \boldsymbol{f}_t \leq \boldsymbol{f}^{max} && : \boldsymbol{\rho}_t^{Fmin}, \boldsymbol{\rho}_t^{Fmax}
\end{aligned}$$

In summary, each system operation scenario in our study will be formed by using fundamental driver scenarios in this model. Consequently, we will obtain, for each combination of fundamental drivers, at each point in time, the value of system marginal costs: they will be given by the (vector-valued) dual variable $\boldsymbol{\pi}_t$. Nonetheless, in order to understand the dynamics of the power system, it is not only necessary to obtain marginal costs at each point in time, but, more importantly, the incentives to invest in each technology.