Diffusion Dynamics of Wind Energy Technology in Brazil

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Abstract

Renewable energy sources hold great promise to offer a solution to on-going energy scarcity worldwide and to reduce CO2 emissions. Brazil now is the country with the 9th largest installed wind capacity in the world. However, the same auction-based policies that boosted wind energy technology development in Brazil, might be threatening its future development: in the last 3 years, wind energy suffered from a decrease in purchase agreements until reaching zero contracted energy in 2016. This article aims to analyze policy alternatives for increasing the diffusion of wind energy technology in the country, through the modeling of the wind energy market based on innovation diffusion theory. For policy testing, seven scenarios are developed, four related to tax incentives and three related to new auction programs in 2019 onwards. The results show that tax incentive policies effectively decrease the price of energy sold but have little effect in the increase of wind installed capacity. On the other hand, policies aimed at continuing auction programs in the long run provided higher positive variations of wind installed capacity with respect to the base case scenario.

Keywords: wind energy; innovation diffusion; renewable energy; system dynamics

1. INTRODUCTION

Renewable energy sources hold great promise to offer a solution to on-going energy scarcity worldwide and to reduce CO2 emissions (Jacobsson & Johnson, 2000; Negro, Alkemade, & Hekkert, 2012). The diffusion of these technologies in innovation systems are very important to ensure wide uptake of these technologies but has proved to be slow – especially in developing countries (Negro et al., 2012).

Recent literature has acknowledged the potential of modeling approaches as 'iterative' tools to improve understanding of complex real systems, such as renewable energy technologies (Hamarat, Kwakkel, & Pruyt, 2013). It is then, within the perspective of complex systems that system dynamics modeling has a long tradition of application in energy policy and management (Ford, 1997; Musango, Brent, Amigun, Pretorius, & Muller, 2012). A recent trend has also shown that this could be useful for exploring the hitherto poorly understood process of the diffusion of renewable technologies in developing countries (Cardenas, Franco, & Dyner, 2016; Jimenez, Franco, & Dyner, 2016; Musango et al., 2012; Radomes Jr & Arango, 2015).

Of particular interest in this article, we focus on the diffusion of wind energy technology (Dykes & Sterman, 2010; Mejía et al., 2006) in Brazil, identified as one of the key renewable energy sources in the near future (IEA, 2014).

Brazil, with its privileged geographical location and territorial extensions, has excellent natural resources available for energy production. In the power sector, the country uses mainly water resources for generation. In 2016, out of the 150 GW total power generation of installed capacity in the country, 64.7% is from hydropower, 27.3% from thermal power, 6.7% from wind and then, 1.3% nuclear (ANEEL, 2017).

Despite hydropower generation having environmental benefits in relation to fossil fuels, it makes the country highly dependent on hydrological regimes, in particular rainy seasons. In drought years, water resources are drastically reduced, leading to blackouts, as seen in 2001 and 2002 (R. C. da Silva, de Marchi Neto, & Seifert, 2016; Juárez, Araújo, Rohatgi, & de Oliveira Filho, 2014), or to a substantial increase in thermal power costs and environmental impacts, as seen in 2014 and 2015 (Prado et al., 2016).

In this respect, wind generation presents itself as an excellent alternative to balance the Brazilian energy grid. Firstly, in drought seasons winds are more favorable to this type of generation, reducing Brazilian vulnerability (Prado et al., 2016; Schmidt, Cancella, & Junior, 2016). Secondly, wind power generation is considered more environmentally friendly than large and medium-sized hydropower dams, as large areas of land is flooded for creating reservoirs. Although reservoirs reduce dependence on rain, this also leads to the situation that expansion of this infrastructure is difficult as there are few locations that are suitable for this to be developed (Prado et al., 2016). Finally, wind generation is already the second cheapest option in Brazil, and by 2025 it is forecasted that this source will have lower costs than those of water generation, which currently has the lowest prices (EPE).

Although there are several studies analyzing the importance of wind energy and its diffusion in Brazil (N. F. da Silva, Rosa, & Araújo, 2005; N. F. da Silva, Rosa, Freitas, & Pereira, 2013; Dalbem, Brandão, & Gomes, 2014; Dutra & Szklo, 2008; Filgueiras, 2003; Juárez et al., 2014; Schmidt et al., 2016), no work has been found that considers the Brazilian auction system and the decision-making processes of the actors in the ecosystem.

Given the Brazilian Regulated Contracting Environment complexity and the importance of adequate policies to assist in wind energy development in Brazil, this article aims to analyze policy alternatives for increasing the diffusion of wind energy technology in the country. In order to do so, a system dynamics model is built to model the Brazilian Regulated Contracting Environment.

2. WIND ENERGY DIFUSSION IN BRAZIL

As mentioned in the introduction section, Brazilian wind power installed capacity went from 27 MW to 10092 MW over the 2004 to 2016 period. Despite the low cost of wind power generation and their strategic benefits for the country (as stated above), the share of wind installed capacity, in Brazil, in relation to total installed capacity was around 6.7% in 2016. Countries like China or the US, for instance, already have 145 GW (9.6% of total installed capacity) and 74GW (6,9% of total installed capacity) of wind installed capacity, respectively (GWEC, 2016), highlighting Brazil is on the right track, when it comes to wind energy. Figure 1 shows the evolution of wind installed capacity in selected countries, note that China, the US and Germany move beyond the chart.

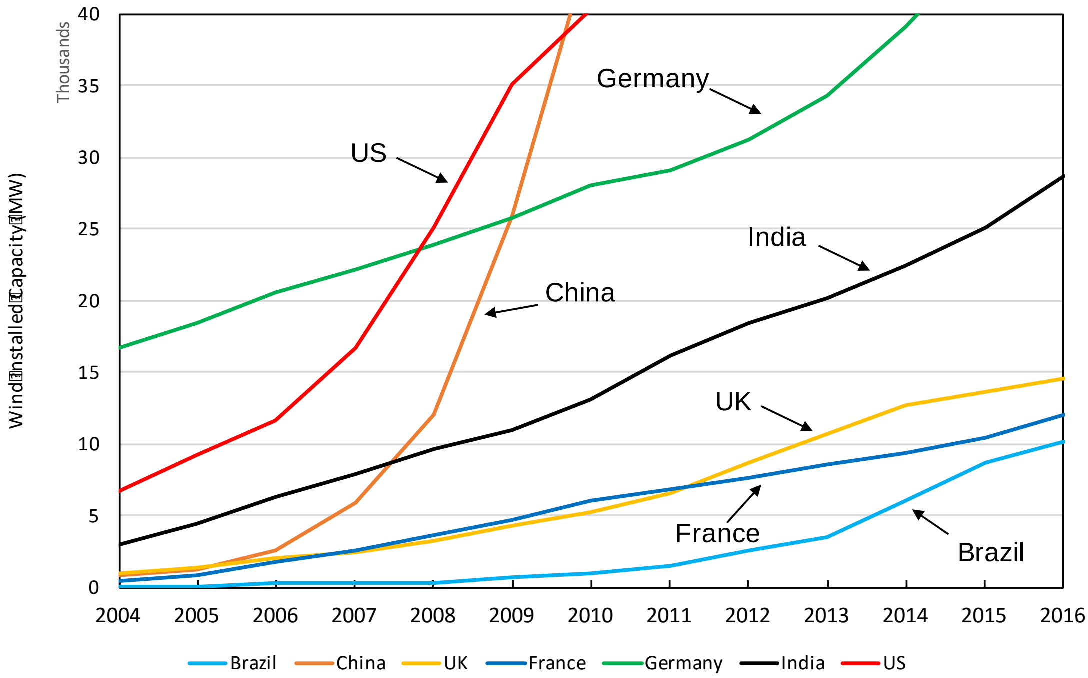

Figure 1. Cumulative installed wind capacity in selected countries. Source: Adapted from GWEC (2016)

In light of the dependence on hydropower and of the benefits from wind power generation, in 2001 the Brazilian government instituted a program to encourage wind energy generation called PROEÓLICA (Emergency Wind Energy Program), aiming to install 1050 MW of wind capacity in the country (BRASIL, 2001). However, the program failed due to a lack of tax incentives for the industry (Filgueiras, 2003).

A new incentive program was launched in 2003 through the Alternative Energy Sources Incentive Program (PROINFA), which sought to encourage alternative energies from wind, small hydropower and biomass sources (BRASIL, 2002). This program was better designed than PROEÓLICA as it offered tax incentives, through the Brazilian Development Bank (BNDES), for companies, if they met a minimum ratio of manufactured parts and equipment, of domestic origin, for the construction of wind farms, in addition to 20-year energy sales contracts. Although targeted to encourage three different generation sources, PROINFA was particularly successful in developing wind power generation, which has experienced exponential growth (Juárez et al., 2014). The PROINFA programme is now seen as one of the main initial drivers of wind industry development in Brazil.

From the above, the importance of public policies for developing the wind energy industry is evident. However, despite the exponential growth seen over the last decade, the remaining potential for installed capacity is still enormous. Where the currently installed capacity for wind generation is 10.1 GW the upper limit is estimated at 400 GW with turbines up to 120 meters in height (GWEC, 2016). The Brazilian government goal is that by 2024, a target of 24 GW of installed power will be reached amounting to around 11% share of total installed capacity.

However, recent events in the sector raised doubts about whether these targets will be achieved. Over the past years, wind power purchase agreements, through auctions or bids, has fallen, from 4.7 GW in 2013 to 2.2 and 1.2 GW in 2014 and 2015 respectively, reaching zero in 2016 (CCEE, 2017).

In order to understand this decrease in contracting, it is necessary to analyze the Brazilian Regulated Contracting Environment (ACR), responsible for 75% of installed capacity building programmes. Created in 2004 (BRASIL, 2004), after the Brazilian electricity market was split into two submarkets: i) the Free Contracting Environment (ACL) and ii) Regulated Contracting Environment (ACR). ACR currently has 1572 agents, distributed as traders, importers, independent producers, generators, self-producers and distributors (ANEEL, 2016). These agents are responsible for the generation, distribution and sale of electric power in the country, contracted through energy auctions or bids. These auctions, in turn, can be divided into 9 modalities, ranging from auctions aimed specially at buying energy from renewable sources all the way to auctions to adjust energy contracts by distributors, for example.

Such purchase agreements may involve short-term trades of 2-3 years and long-term trades of 20, 30 or 50 years, and different delivery dates to reach full operation, ranging from a few months up to 5 years. Each auction has its own guidelines, even within the same modality, with an extensive legislative framework to regulate this market.

3. METHOD

Based on technology diffusion model theory, the authors developed a theoretical framework based on the Bass Diffusion model (Mahajan, Muller, & Bass, 1990) and adapted it to the case of wind energy technology by drawing on established system dynamics model formulations (Milling & Maier, 2009; Sterman, 2000). We use data from secondary sources, related to the current installed capacity of wind energy in MW and in the number of wind farms, the number of new wind farms in construction, as well as the key relevant policies.

System Dynamics uses feedback loops and stock and flow diagrams to model complex systems behavior over time. In this approach, stocks are mathematically calculated by integral equations, while flows are differential equations (Sterman, 2000) . SD models are continuous, in which the system behavior is the result of decisions and policies and the feedback produced by it.

4. CAUSAL LOOP DIAGRAM (CLD)

Considering previous SD formulations of the Bass Model and the incentive programs (PROINFA) to expand the installed wind power generation capacity in Brazil, we defined early adopters of the system as the enterprises contracted under the incentive auctions and bidding processes. To this end we have formulated the causal loop diagram (CLD) shown in Figure 2 below, which sought to identify the important feedback loops for the growth of wind installed capacity generation in Brazil.

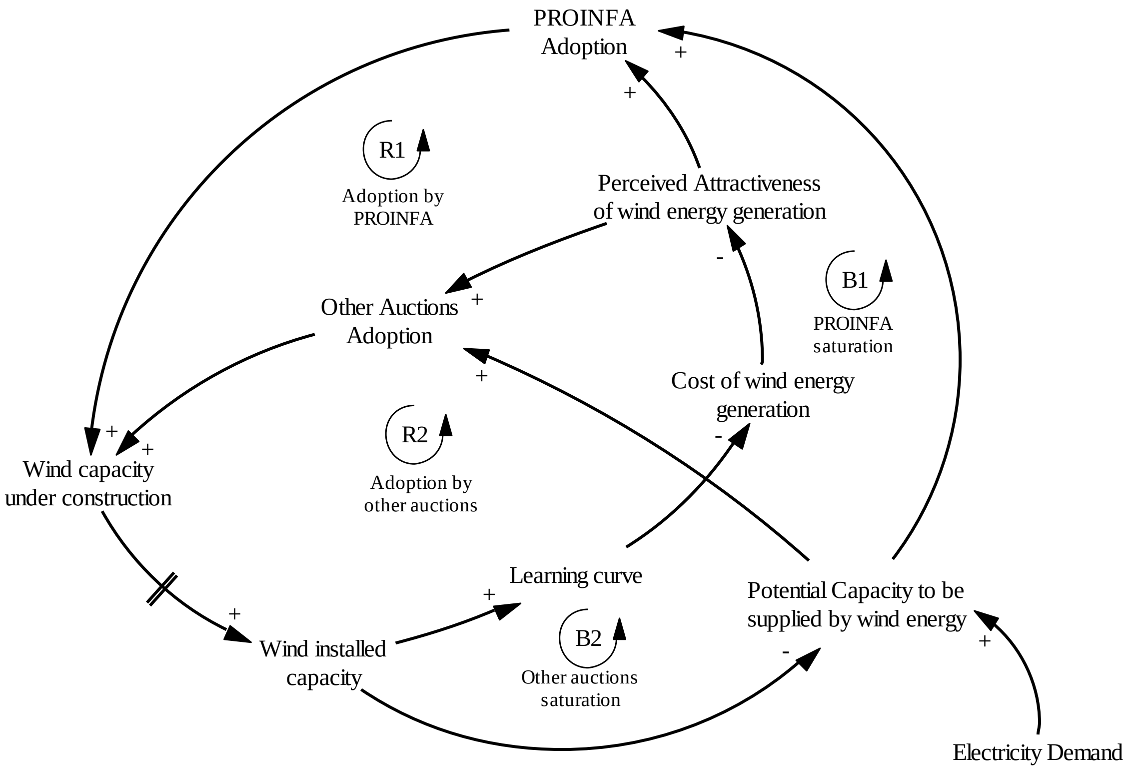

Figure 2. Causal loop diagram for wind energy diffusion in Brazil.

The dynamic hypotheses shown in Figure 2 describes two important reinforcing loops namely: R1 (adoption by PROINFA) and R2 (Adoption by other auctions). The first loop, R1, the 'innovator adoption' process is modelled based on typical diffusion models, in that it postulates an early adoption behavior, driven through the PROINFA program. The second loop, R2, in turn, postulates the 'imitator adoption' of typical diffusion models. Both the feedback loops are influenced by current 'wind installed capacity' and the growing attractiveness of wind power generation, as result from the learning curve (or learning experience curve) which reduces its generation costs. Alternatively, two balancing feedback loops were identified (B1 and B2), which relate to the saturation effect of both adoption behaviors, due to the depletion of the 'potential capacity to be supplied by wind energy', which decreases as 'wind installed capacity' increases reaching 'electricity demand'.

The causal loop diagram was the basis for the development of the stock and flow diagram. The main characteristic is that in Brazil, power capacity is divided by regions, which are under the responsibility of power distribution companies. Like before, the main assumption is that all future wind energy farms are sold in government-led auctions. These auctions are divided into 4 types when it comes to commissioning new wind farms. For the stock and flow model, it is assumed that the only difference between them, is the time needed for the farms to be in full commercial operation (the time-to-operation), as shown in Table 1.

Table 1: Time-to-operation – several auction types

Auction type	TTO (years)
A3	3
A5	5
LER	2.33
PROINFA	2.33

5. STOCK AND FLOW MODEL

The model is based on the Bass Diffusion Model, as proposed by Sterman (2000), which has extensive applications in the literature, including the field of renewable energies, see for instance, Radomes Jr and Arango (2015) and Jimenez et al. (2016). The model structure is based on the dynamic hypotheses previously described. The two main adoption mechanisms, in this model, are 'adoption by PROINFA', which models the PROINFA effect on wind energy generation growth and 'adoption by other auctions', which models the remaining auctions (LER, A3 and A5).

Innovator and imitator adoption rates are calculated using equations (1) and (2), respectively.

PROINFA Adoption = PROINFA Effectiveness * Capacity to be supplied by wind energy   Eq. 1

Other Auctions Adoption= CI * (Installed Wind Capacity)/(Electric Capacity Auctioned)   Eq. 2

Where "CI" is the coefficient of influence of entrepreneurs who have already adopted wind power to build their own wind farms and "PROINFA Effectiveness" represents the influence of PROINFA's incentive actions on entrepreneurs.

"Capacity to be supplied by wind energy" represents the potential market for wind energy generation, that is, the totality of entrepreneurs who would be willing to build a wind farm, is given by equation (3).

Capacity to be supplied by wind energy = Electric Capacity Auctioned * Effect of price on Wind Diffusion   Eq. 3

Thus, as generating wind energy becomes cheaper and more competitive, the greater the number of entrepreneurs that are willing to adopt it (i.e. entering the auctions). This variable depends on the wind energy generation costs over time, which is presented as in equation (4).

Effect of price on Wind Diffusion = Initial wind power price * Effect of learning on price   Eq. 4

Finally, "Effect of learning on price" is the result of the learning curve gains considered, which estimates the reduction rate in production costs that can be attributed to efficiency gains from the accumulated production experiences (Argote & Epple, 1990;

Desroches, Garbesi, Kantner, Van Buskirk, & Yang, 2013). This rate, fed by the wind power source adoption flow, is given below in equation (5).

$$\text{Effect of learning on price} = (\text{Accumulated Wind Experience} / \text{Initial Wind Experience})^{C} \quad \text{Eq. 5}$$

The parameter "C" is a typical negative exponent that determines how steep the learning curve is and was calibrated for the variable "price" to fit the historical price curve, resulting in a value of -0.11.

Figures 3 and 4 show the two sectors in the stock and flow model. Figure 3 shows the structure of power generation of wind sources and the cumulative installed wind capacity.

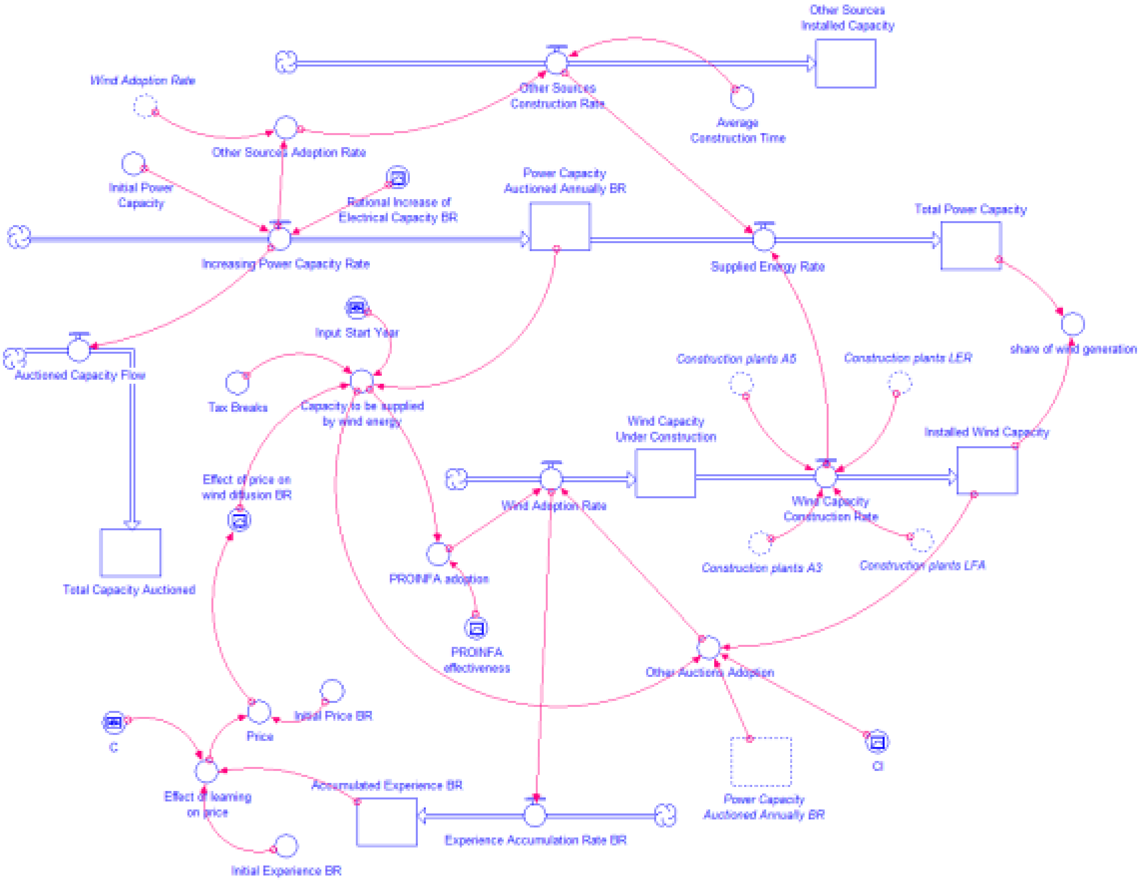

Figure 3. Stock and Flow model for wind power generation.

Figure 4, on the other hand, shows the structure of commissioning new wind power through the different types of auctions. In detail, Figure 4 presents one stock of cumulative wind power for each one of the four auction types described above.

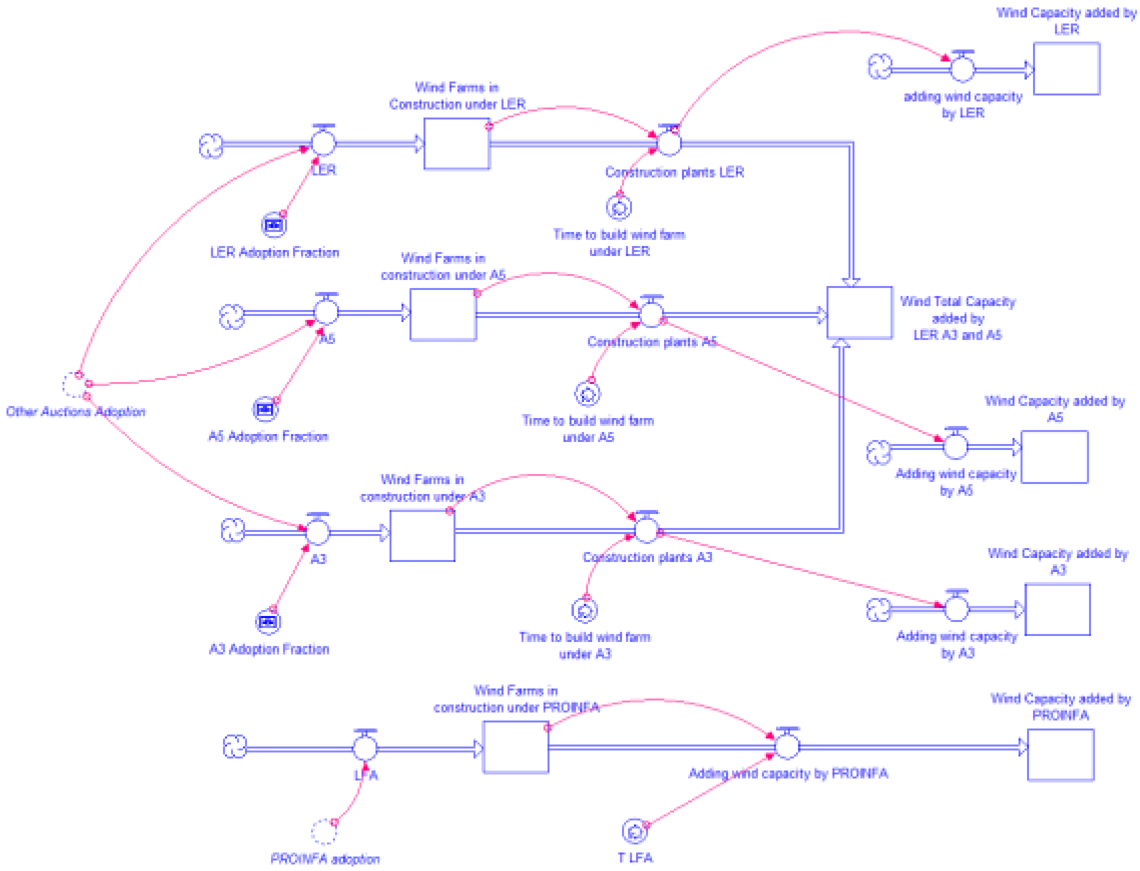

Figure 4. Stock and Flow model for the wind power capacity building.

6. RESULTS AND DISCUSSION

6.1 Base case scenario

The model was calibrated by using the historical data of CCEE, for the period of 2004-2016 (CCEE, 2017). From 2016 onwards the model generates simulated data, based on the assumption of business-as-usual until 2030. Figure 5 shows the growth of wind power installed capacity in Brazil up to 2023, as well as the historical trend up to the year 2015.

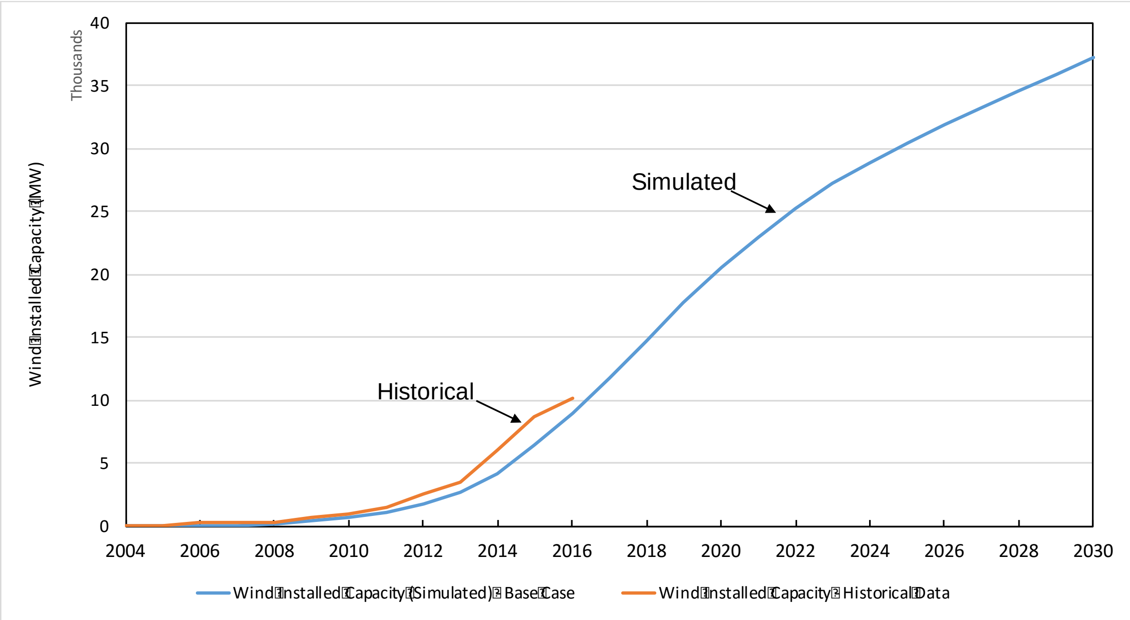

Figure 5. Base case for the cumulative installed wind capacity in Brazil.

As shown in Figure 5, the baseline scenario shows an S-shaped growth over time, with a steep growth until 2020, approximately, and then an ever decreasing growth (due to the balancing feedbacks shown earlier) until 2030. Table 2 shows the simulated values for the wind installed capacity in selected years as well as the share of wind on the total installed capacity of the country.

Table 2: Simulated values for the base case scenario

Year	WIC	SWC
2004	29	0
2015	6,358.34	4
2020	20,507.99	11
2025	30,417.60	13
2030	37,152.43	13

WIC: Wind Installed Capacity (in MW)
SWC: Share of Wind Capacity (in %)

Wind power prices were also simulated for the period between 2004 and 2030, in the base case scenario without the adoption of incentive guidelines. Figure 6 shows the simulated results.

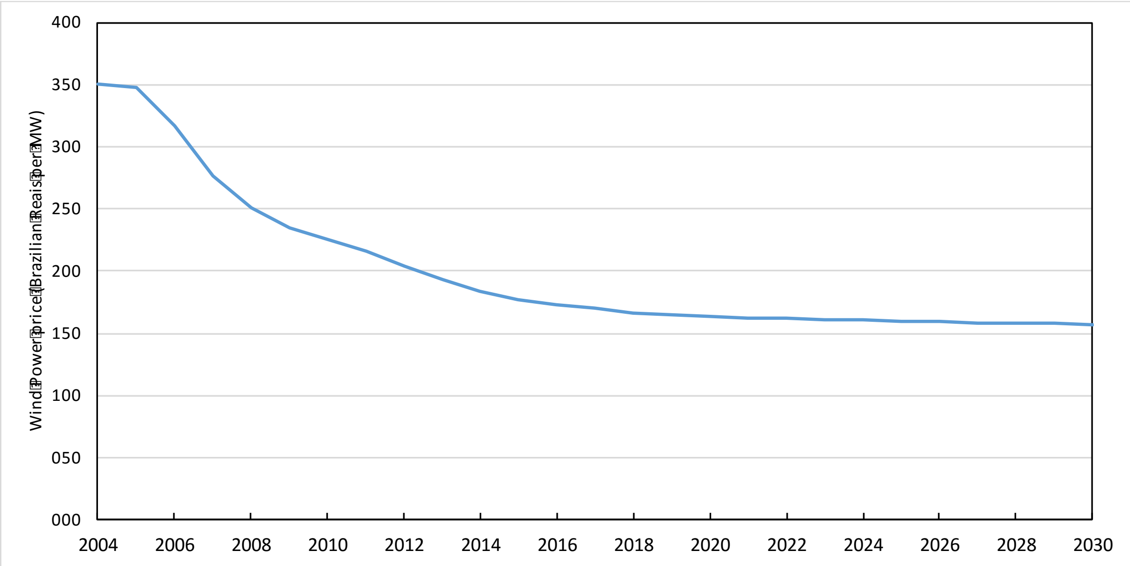

Figure 6. Base case for the wind power price in Brazil

Compared with (EPE, 2017) estimates of 155.98 R$/MWh for wind power costs in 2025, for example, our model obtained an estimate of 160 R$/MWh for the same year. Figure 6 also shows the price stabilizing over the last years of the simulation, signaling that the price may not cross the 150 R$/MWh lower limit.

Next, Figure 7 shows the share of wind installed capacity against the total installed capacity of the country, evidencing, as well, an S-shaped curve, due to the saturation of auction-based growth by 2030.

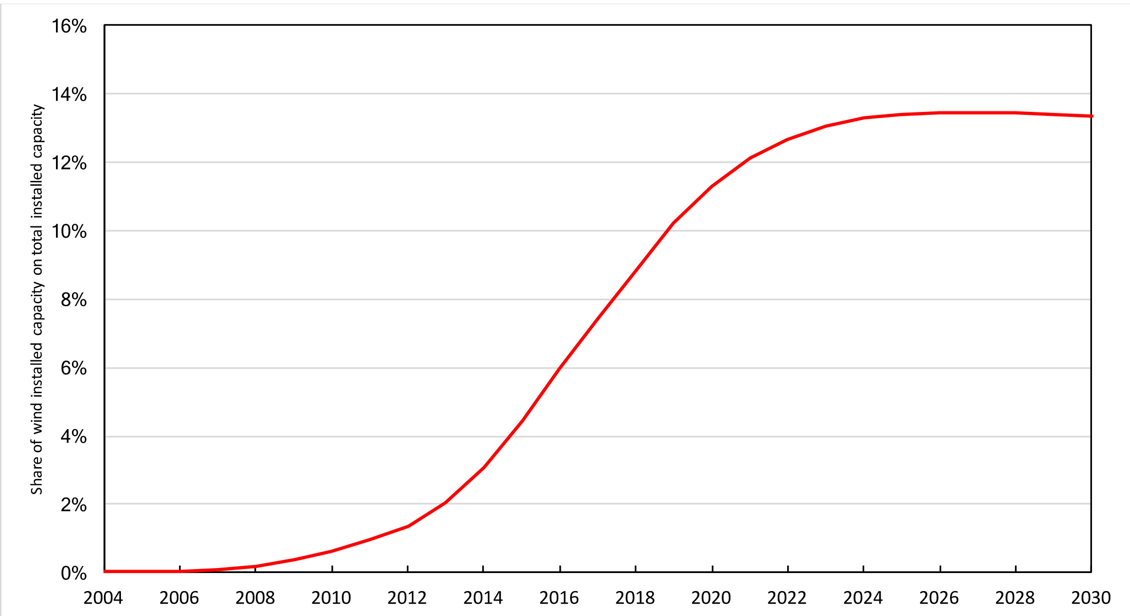

Figure 7. Share of wind power generation in relation to total power generation

6.2 Policy Testing

The authors commence policy testing through running various scenario by introducing several shocks to the model, which will be presented in two groups:

- Policy testing scenarios 1: Introduction of tax incentives: which are modeled by reducing the price of wind energy at different rates (18%, 33%, 50% and -22%); and
- Policy testing scenarios 2: New auction programs, similar to the ones introduced before in the country (PROINFA, LER, A3 and A5).

6.2.1 Introduction of tax incentives

Tax incentives can help in reducing the price of wind power generation and thus, it can help in increasing the growth of installed capacity in the country. In the model, the introduction of tax incentives is represented by forcing the price curve to change its trajectory. In this sense, four different scenarios are developed, three of them simulating the reduction of price (at different rates) and the fourth, simulating an increase in price (See Table 3).

Table 3: Simulated values for the tax incentive scenarios

Scenario	Decrease/ increase in price	Price in 2030 (R$ per MWh)	WIC	VBC	SWC
Base Case	0%	157.16	37152.43	-	13.4
Scenario 1	-18%	125.49	38537.74	3.7	13.9
Scenario 2	-33%	99.70	40405.80	8.8	14.5
Scenario 3	-50%	73.28	42353.05	14.0	15.2
Scenario 4	+22%	195.80	36624.74	-1.4	13.2

WIC: Wind Installed Capacity in 2030 (in MW)
VBC: Variation from Base Case with respect to WIC (in %)
SWC: Share of Wind Capacity in 2030 (in %)

The logic of introducing tax incentives is that at some point in the future, tax incentives will produce a shock to the system by drastically reducing the price of wind power generation onwards. In the scenarios run on the model we introduce the shock on price the year 2019. Figures 8 and 9 show the effect of these incentives on wind installed capacity and the price of wind generation over time.

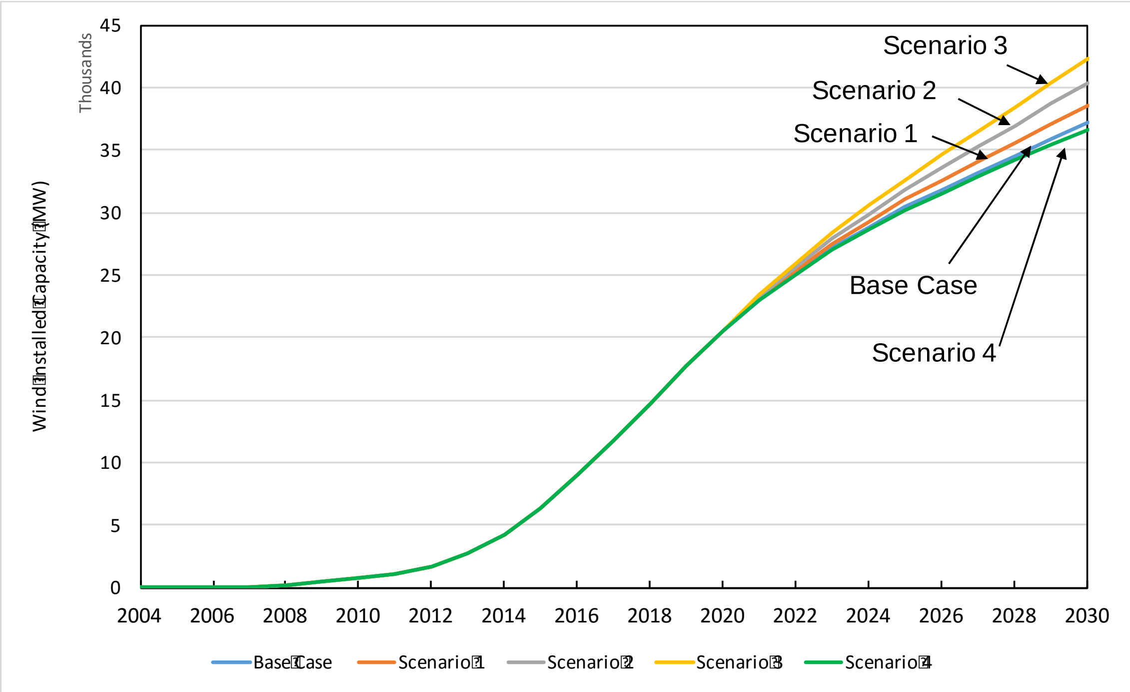

Figure 8. Response of the cumulative wind installed capacity in Brazil to tax incentives

Figure 8 shows the response of wind power installed capacity to different rates of tax incentives. Although the tax incentive policy is meant to be in operation in 2019, Figure 8 shows a delay in the response of the system of approximately two years before the curves begin to separate from each other. Even though there are four distinctive curves at the end of the simulation, additional data from Table 3 helps in concluding the only scenario which yielded a significant increase, was scenario 3, which, by reducing the price by 50%, enables an additional growth of 14% in wind installed capacity.

Figure 9, shows significant decreases in the price of power generated by wind sources, effective in 2019 onwards, as outcome of the shocks given to the model.

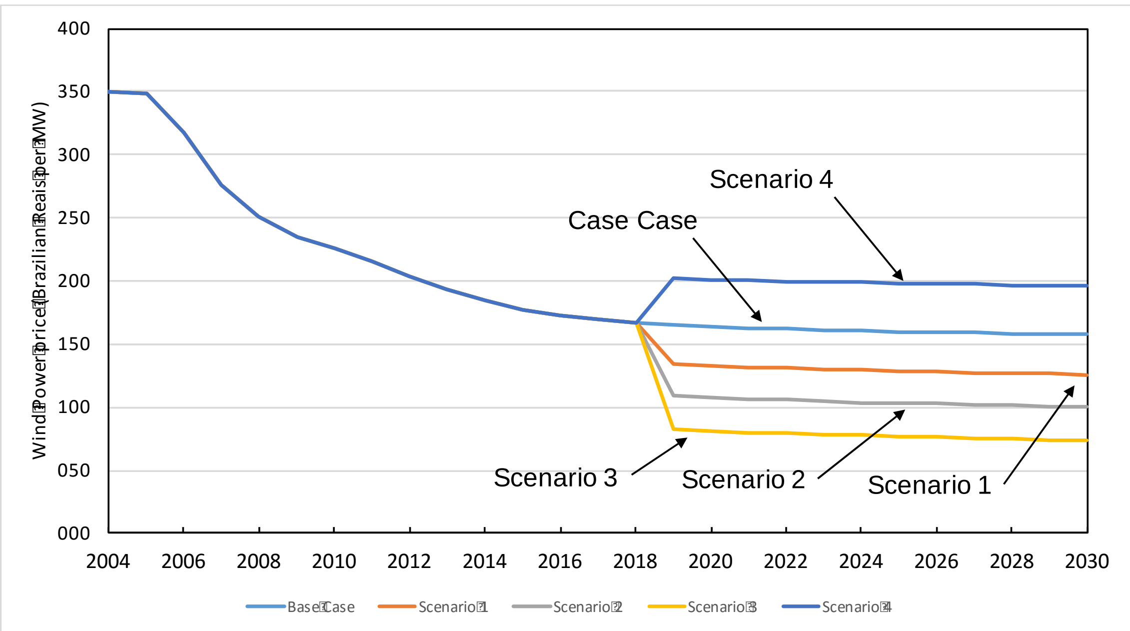

Figure 9. Response of wind power generation price to tax incentives

6.2.2 New auction programs

The second group of policies and scenario tested on the model relate to new auction programs, similar to the previous PROINFA and other auctions led by the government. Historical data suggests the number of auctions for wind power contracts has been decreasing, reaching a value of zero megawatts in 2016. The aim of this set of policies is to test whether such auction programs may lead to a larger growth in wind installed capacity than the one presented in the base case.

As an assumption, such programs have as start year, 2019 and are different in the sense of how each policy is developed onwards: scenario 5 refers to an aggressive auction program, which is modeled as a steep shock to the CI coefficient, which influences the adoption rate; scenario 6 refers to a moderate auction program (a milder shock to the CI coefficient) and scenario 7 refers to a conservative auction program (a small shock above the base case).

As shown in Figure 10, the various scenarios have a quite large impact on simulated model outputs. Scenario 5 which is also the most aggressive of the auction program scenarios have the biggest impact on the installed capacity. Similarly, Figure 11 shows the effect of scenarios 5, 6 and 7 on price, evidencing very little decrease from the base case. Finally, Table 4 synthesizes some of the key indicators, such as wind installed capacity growth and price, confirming the higher installed capacity growth, with respect to the previous policy, and the small change in price.

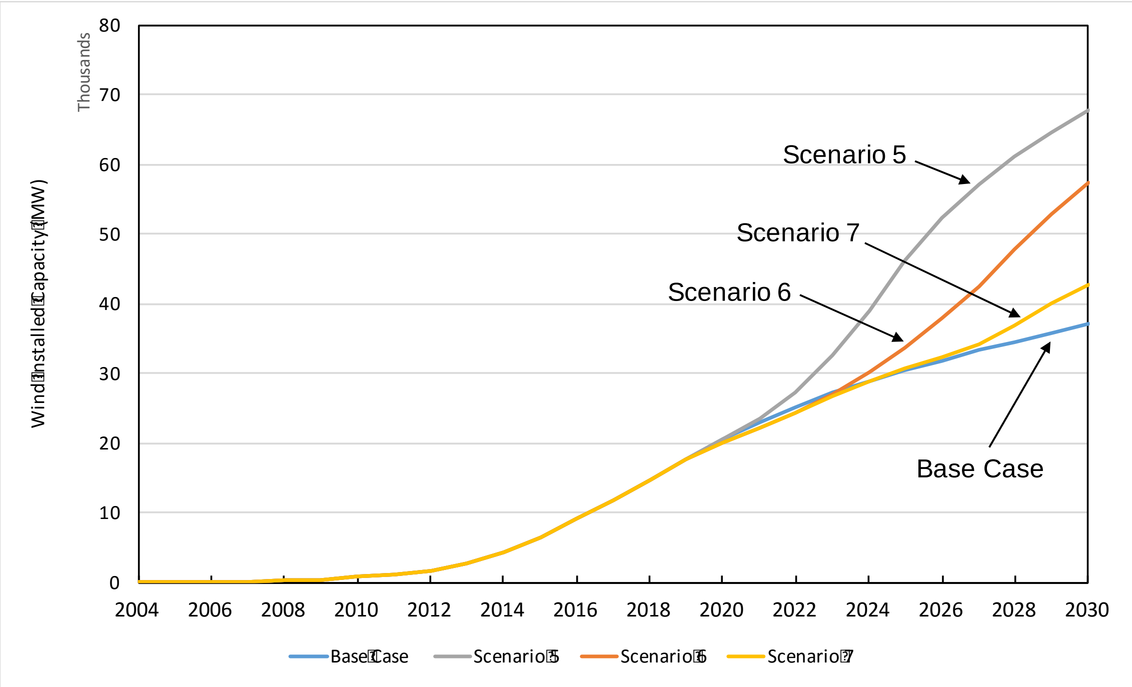

Figure 10. Response of the cumulative wind installed capacity in Brazil to new auctions

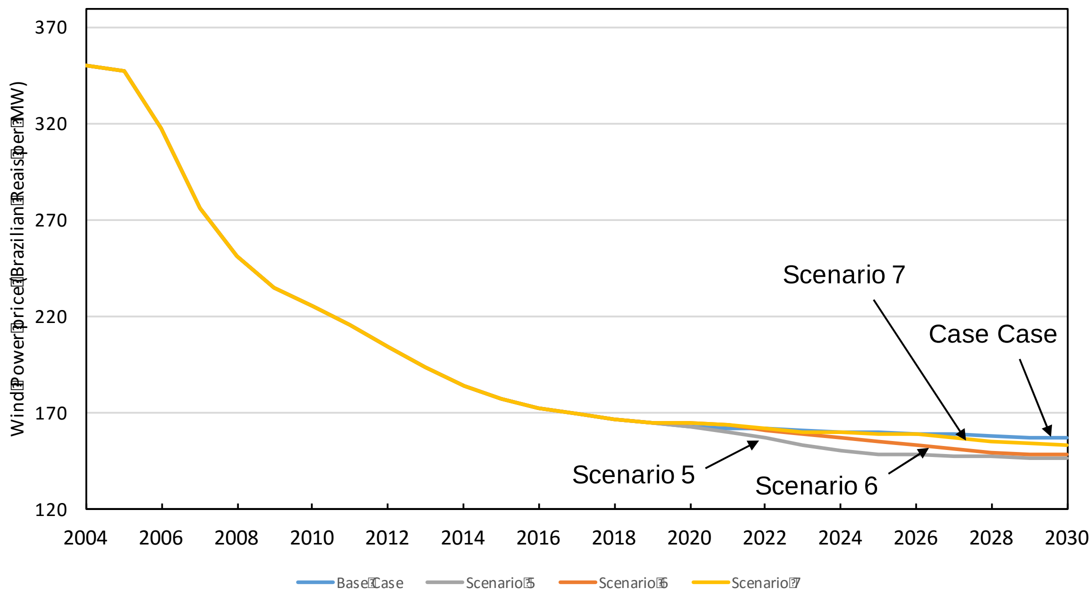

Figure 11. Response of wind power generation price to new auctions

Table 4: Simulated values for the new auction programs scenarios

Scenario	Decrease/ increase in price	Price in 2030 (R$ per MWh)	WIC	VBC	SWC
Base Case	0.00%	157.16	37152.43	-	13.4
Scenario 5	-0.03%	146.68	67647.65	82.1	24.3
Scenario 6	-0.02%	148.33	57252.12	54.1	20.6
Scenario 7	-0.01%	153.71	42681.66	14.9	15.3

WIC: Wind Installed Capacity in 2030 (in MW)
VBC: Variation from Base Case (in %)
SWC: Share of Wind Capacity in 2030 (in %)

6.3 Discussion

Reflecting on the usefulness of the model developed, the authors have modelled various scenarios for tax incentives as well as the policy the auction programs and their projects and their effects on build programs as well as the price of installing wind power in Brazil. This has contributed insight into decision around the implementation of these mechanisms towards stimulating the wind energy sector in the country.

Below we, in summary format, present the results of the simulation runs of the scenarios tested (Table 5). When comparing all seven scenarios it is clear that continuing auctions or bid programs is the most efficient policy towards increasing the wind installed capacity in Brazil, reaching up to 24% in the most aggressive auction program scenario.

Table 5: Simulated values for the tax incentive scenarios

Scenario	Decrease/ increase in price	Price in 2030 (R$ per MWh)	WIC	VBC	SWC
Base Case	0%	157.16	37152.43	-	13.4
Scenario 1	-18%	125.49	38537.74	3.7	13.9
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WIC: Wind Installed Capacity in 2030 (in MW)
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SWC: Share of Wind Capacity in 2030 (in %)

The main explanation of the success of the auction program policy is that it stimulates the adoption reinforcing feedback loop much faster, increasing through time, the reliability of the auction programs and the confidence of market agents with respect to the continuous execution of auctions in the long run. Surprisingly, on the other hand, the auction program policies showed small reductions in the price of wind energy in such auctions, suggesting in a sense, investors and entrepreneurs may not be too sensitive to price changes as long as the auctions keep coming in an orderly fashion.

With respect to tax incentives, directed towards reducing the price of energy sold, the model showed even steep decreases, such as 50%, would not have positive variation rates in wind installed capacity as high as the ones from the auction program policies. One task remains though, which is to develop scenarios in which both policies are mixed to test whether such may bring even better results.

6. CONCLUSIONS

This paper had as main aim to analyze policy alternatives for increasing the diffusion of wind energy technology in the country. In particular, we focused on two policy types: tax incentives aiming at reducing the price of energy sold and auction programs, aiming at continuing wind power sales in the long run. The model showed that the most successful policy, for the case of Brazil, is the continuing support of auction programs for wind power.

In order to be able to better understand such decision making, this model may be expanded in future to allow for improved ability to consider trade-offs between policies and also between generation technologies on the larger system and the grid. As further expansion of the model that also may be useful will link the issue of infrastructure expansion e.g. grid connections and distribution infrastructure requirements to these scenarios. Also, the integration with other theoretical approaches might also be a future path to expand the model presented in the paper, in particular, the approaches from the sustainability transitions literature, such as the functions of technological innovation systems (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Hekkert & Negro,

2009) and the multilevel perspective (Verbong & Geels, 2007) , which incorporate other agents and behavioral explanations beyond what is traditionally accounted for in energy policy literature.

Finally, with respect to the Brazilian grid, besides the complementarity relations between hydropower and wind power and the prospects that the latter will become the country's cheapest source option to generate electricity, regulators and stakeholders are up to decide whether it is worthwhile to jeopardize the wind power development in Brazil by encouraging other power sources instead of wind in the future energy auctions.

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