The Brazilian Open Electric Market and the impact of solar PV growth

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Abstract

The Brazilian Electric Market is undergoing a structural change with more competition among Generators and Distribution Companies, leading toward an Open Electric Market. The literature has no agreement concerning how this market opening will influence renewable generation growth. This article aims to determine whether the opening of the Brazilian Electric Market influences the diffusion of solar PV. Our results show that market opening should contribute to solar PV installed capacity growth. In the most optimistic scenario, solar PV installed capacity will increase from 0,1 GW in 2010 to 64 GW in 2040. In all scenarios, the demand for solar generation in the Open Market exceeds that of the regulated one. Furthermore, the demand for solar PV is greater than the capacity available for sale. We conclude that market opening creates opportunities for new business models for solar PV technology, attracting investors and contributing to greater diversification of the electric grid and lower dependence on thermal and hydro plants.

Keywords: Electricity market, Liberalization, Renewable Energy, Photovoltaic energy, System Dynamics

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1. Introduction

Recent research has pointed out that opening the electricity market drives growth in renewable generation [15, 19, 14]. Public policy initiatives in an energy market can impact – and even accelerate – transitions to a more renewable mix [13]. However, more recent studies have shown that the greater the penetration of renewable energies in the mix, the greater the price volatility, as there is an increase in the supply curve that is not always accompanied by an increase in generation [5]. This is because renewable sources are mainly dependent on weather conditions. In parallel to the rise in supply, there is a price reduction in the short-term market, making them less profitable and impacting fewer investments in these generation technologies [12]. The supported hypothesis is that

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there is an incompatibility between market liberalization and renewable energy policy, considering the renewable energy policy paradox [5]. In addition, liberalized markets can reduce spending by the private sector and the government on energy R&D [29], directly impacting the associated technological development.

Brazil is an example of a country facing the total opening of its electricity market. Even having a mature market, it is permissible only to wholesale consumers. The indication of a proper opening of the electricity market to retail consumers makes the country an exciting object of study for the market versus renewable energy relationship. Despite having one of the most renewable matrices in the world, a large part of the national installed capacity refers to hydroelectric plants, and the sector's backup mechanisms are still based on thermal-electric generation. Thus, changes in hydrological cycles and water crises impact more expensive energy and significantly associated emission. For example, the water crisis faced in 2021 was the most severe in the last 90 years. As a result of this event, hydroelectric generation went from a share of 70% of electricity to just over 60%. In contrast, thermal-electric generation exceeded 20% of the energy demand in the year in question.

This scenario contributes to increased interest in exploring alternative renewable sources, with a view to a more diversified matrix [18]. The 2021 water crisis faced by Brazil indicated the need for investments to diversify the matrix, mainly increasing wind and solar generation capacity [11]. This matrix diversification is linked to developing and disseminating alternative renewable-generation technologies. The centralized solar photovoltaic generation, for example, is still embryonic in the Brazilian matrix, representing about 4% of the total installed capacity of the electrical system, less than 5 GW of installed power.

Therefore, this article aims to determine whether the opening of the Brazilian Electric Market influences the diffusion of solar PV. We build different scenarios based on a System Dynamics model to do so.

1.1. The Brazilian Electric Market

The Brazilian Electric Market is composed by two sub-markets, the first, the so-called Regulated Market (ACR in Portuguese) and the Open Market (ACL in Portuguese). In the Regulated Market, consumers are served only by local Power Distribution Companies (DC) in a sort of Natural Monopoly. DCs, on the other hand, buy power from Generators at National Bids organized by the Regulatory Agency. The National Bidding System helped increase the share of renewables, especially wind power over the last decade, helping in transitioning from a pure Hydro-Thermal grid towards a Hydro-Thermal-Wind one.

In contrast, the Open Market offers the possibility to direct purchase agreements between the consumer (wholesale consumers like Factories) and the Generators through Retailers that act as intermediaries. In this case, the DCs only deliver through their power lines.

Currently, the Regulated Market dominates the electric grid in Brazil since it was designed to offer stable energy prices in order to attract private capital, maintain grid expansion, and offer affordable prices and energy security.

However, following a worldwide trend, the Market in Brazil is shifting from a pure Monopoly-like market towards a more competitive - open - one [2, 23, 28]. One of the main criticisms of Regulated Market design is that it is based on the captive consumer through regulated long-term purchase bids (by the DCs) [6, 22]. Although this market design worked for some time, currently, it can be seen as inefficient, tending to run out [22].

As evidence, there is an increasing migration of consumers to the open market, representing around 34% of electricity consumption. In addition, with forthcoming changes in Legislation allowing more groups other than wholesale consumers to buy power from the Open Market, this migration will potentially increase. However, as the expansion of consumers in the Open Market continues, new problems arise, especially for the Regulated Market which has a goal to help in expanding the grid through the National Bidding System [22].

The changes to be faced by the Brazilian Electric Market are complex and long-term, with several interrelated and interdependent actors and institutions. The generation of dynamics, through feedback between the elements of the system, allows the provision of potential indications of a rebound effect, which can then help in decision-making [32]. Therefore, we chose System Dynamics modeling which models non-linear behaviors over time and is capable to accommodate feedback loops and time delays. These behaviors may reflect cumulative changes in the Electric Grid, as seen in [30] when considering the drastic change in the energy system from conventional to unconventional sources.

1.2. Structure of the paper

The paper is composed of five sections. First, we present the Introduction with the background and objective of the paper. Then we introduce the model-building stages. In the third section we show the main results, followed by discussions and policy implications. And finally, we delineate the most relevant conclusions of our study.

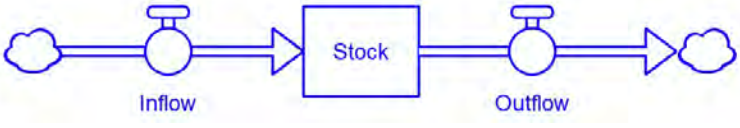
2. Model Development

The model was built using Stella Architect® and included factors for the centralized generation in an open market, such as the open market adoption rate, the intention rate per solar generation in the open Market, the participation of the solar source in regulated auctions, and the available share of the undertakings participating in the auctions. Furthermore, we consider including solar generation in the national electric matrix and the effect of learning on the price of the technology under study.

Since system dynamics modeling gives rise to a quantitative model that helps study the general behavior of complex socioeconomic systems, we considered the Brazilian electricity sector's feedback structure between decision variables. Further, we modeled decision rules, estimated parameters, behavioral relationships, and initial conditions, and defined business as usual (BAU).

The model was formulated as differential equations based on the representation of stocks and flows, as shown in Figure 1 and Equation 1. First, we defined the problem scope as well as the timeline of the model, considered between 2010 and 2040, to compare the model's response with the historical results and, even so, to understand the future dynamics of the variables involved. Then, we determined model boundaries and the endogenous and exogenous factors involved.

Figure 1: Stock and Flow Diagram



$$Stock(t) = Stock(t_0) + \int_{t_0}^{t} (Flow_{input}(s) - Flow_{output}(s))ds \tag{1}$$

Given the increase in the total Demand for electricity over the years, we model the diffusion of the Open Market, indicating the Supply from each market setting. Potentially free Demand is related to the permissiveness to the Open Market, represented in our model from different groups of consumers: Group A: consumers who receive electricity at high voltage (equal to or greater than 2.3 kV); Group B1: residential consumers; Group B1 Low Income: residential consumers receiving government subsidy; Group B2: rural class consumers; Group B3: industrial class consumers; and Group B4: Demand for public lighting. In the base scenario (BAU), only the Demand referring to Group A is potentially accessible to the Market. That is, only the consumers of this group can choose an open market.

We obtained the participation of each consumption group in the total annual Demand from historical observations [10]. We considered the yearly increase in total Demand from the government plans for developing the sector [8, 9]. We obtained the Demand to be met through the Open Market from the adoption rate of this market environment. This adoption rate follows the logic of [3] model, which considers the adoption of innovations from two streams, adopters who are not influenced by the environment - the innovators, and those who adopt the new product from communication in mass and interpersonal relationships - the imitators. In this process, imitators are responsible for increasing the speed of adoption based on the idea of contagion. Equation 2 illustrates the Bass diffusion model [3].

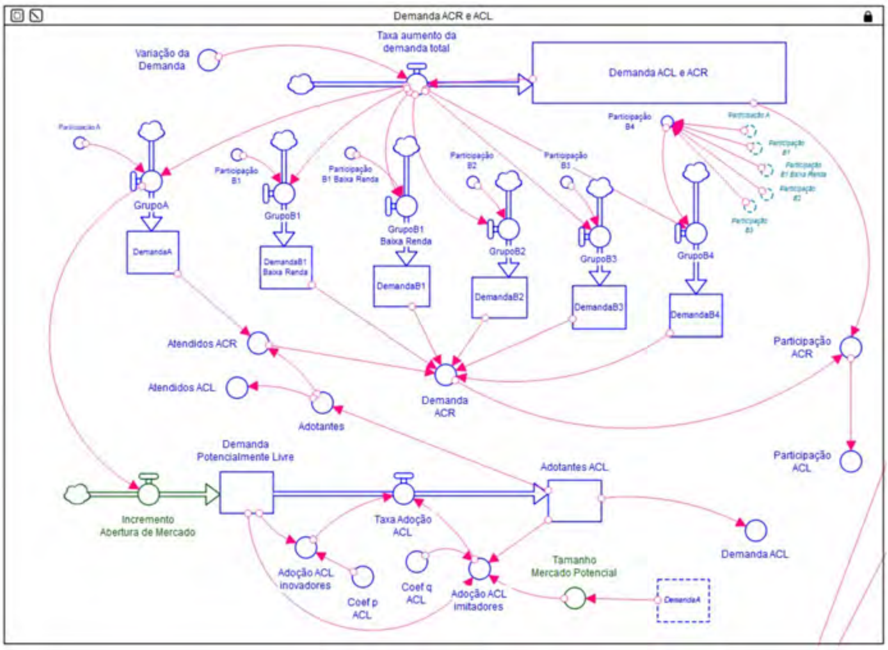
$$Z'(t) = p(m - z(t)) - q\frac{z(t)}{m}(m - z(t)) \tag{2}$$

Where:

- *Z'(t)* is the adoption rate;
- *z(t)* is the cumulative number of adopters;
- m is the potential market;
- p is the advertising effectiveness or innovation coefficient;
- q is the contact rate or imitation coefficient; and
- t is the time.

As the electricity market expands its opening, the potential free demand increases, represented by the Demand of the groups for which the open Market is permissible. Thus, based on the adoption rate, the greater the Demand to be met via the open Market must be. This logic makes up submodel 1, shown in Figure 2.

Figure 2: Submodel 1 - open market Broadcast



The Demand, whether from the regulated Market or the open Market, is supplied, in part, by energy generated from the photovoltaic solar source. At this point in the model, we highlight some issues. The first is that the model has a limit for inserting this generation of technology into the electrical matrix. This limit is due to operational factors associated with intermittent technologies. We consider here a limit of insertion of solar generation that reaches 15% of the total capacity of the electrical matrix, with growth between 2017 and 2040 from the behavior of the "S" curve.

We understand that in each market environment, there is a rate of intention for solar energy to supply the Demand. That is, the rate of solar intent in the Regulated Market considers the insertion of the solar source in the regulated market auctions, discounted from the portion of the capacity of the projects destined for the open Market. In an open market, this fee signals the insertion of the solar source in the Regulated Market auctions. However, the enterprises participating in these auctions do not usually sell 100% of their generation capacity in this environment, reserving part of their generation for contracts freely negotiated at an open market.

As for the open Market, we consider the Open electricity market reports, which demonstrate that around 20% of the energy traded in the Open Market comes from solar generation. Furthermore, as in the electricity market, consumers tend to choose cheaper energy. We also consider the effect of price learning on the solar intention rate in an open market. The learning effect on the price considers the accumulated experience of a given technology. The idea is that costs decrease as production increases, whether due to research / development (which leads to improvements in features, functionality, quality, and other attributes of the product's attractiveness) or even an increase in experience and consequent reduction of errors. It means that the learning rate increases in parallel with the increase in expertise with a given technology while, on the other hand, the costs associated with it decrease.

This relationship can be expressed from the learning curve, as observed in Equation 3. It generates a feedback loop as lower prices increase sales, increasing production. Thus, productivity increases, the learning curve increases, and the cost per unit decrease, allowing for lower prices.

$$P(t) = P(0)\left(\frac{C(t)}{C(c)}\right)^{li} \tag{3}$$

Where:

- *P(t)* is the price function;
- *P(0)* is the starting price;
- *C(t)* is the experience accumulated in time "t";
- *C(0)* is the initial experience; and
- *li* is the learning index, i.e., the strength of the learning curve.

For the price of the technology, we consider the CAPEX associated with photovoltaic solar generation, with an initial value of 1,500 U$$/MW. We contrasted the learning effect with the CAPEX associated with wind generation because the wind has the lowest generation costs among renewable sources. We considered Wind farm CAPEX to be 1,100 U$$/MW. Thus, we calculate the competitiveness factor of the solar source. So, the competitiveness factor is associated with the rate of intention by this source in the open Market.

For both market environments, we compare the Demand for solar energy against the generation capacity of the source. Following the same logic, the capacity building from the auctions is made available to the regulated Market. Whatever amount not sold in the regulated Market from the total solar generation capacity will be made available to the open Market. When the Demand for a specific market environment is greater than the generation capacity available, then there is a need to build the source specifically for that environment. In the model, the decision to build new plants must respect the limit of insertion of the given renewable energy in the matrix.

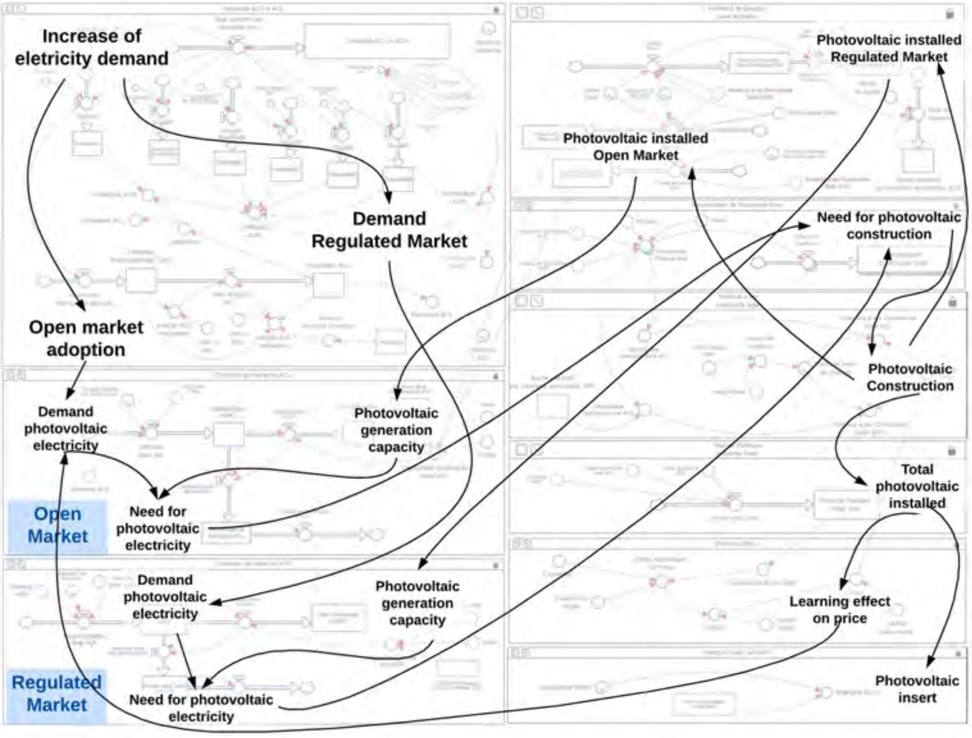
This logic establishes the increase in the installed capacity of photovoltaic solar generation over time, associated with both the regulated and open Market. Furthermore, as there is an increase in the installed capacity of this source in the matrix, the experience accumulated on the technology must be increased, impacting the learning effect on the price and, consequently, contributing to the increase of the source's competitiveness. Figure 3 allows observing the complete model, with the Submodels that compose it and the primary relationships highlighted.

The model uses some critical input parameters for simulating the reference mode. Notably, for the percentages related to each consumption group, together, to correspond to 100% of total Demand, the historical average share of Group B4 in Total Demand is obtained by reducing from the unit the values related to the historical average share of the other groups.

2.1. Model Validation

The model has been tested and verified for functionality. Among the various existing tests for validation of the simulation model, we adopted: (i) the comparison test with the reference mode - verifying if the model adequately reproduces the behavior of the problem according to its purpose [17, 4, 33], (ii) the robustness test under extreme conditions - checking if the model behaves as what would be expected when subjected to extreme situations [17, 4, 33, 21] and (iii) validation metrics of regression models [16, 31]. The metrics used were the coefficient of determination (or R^2), Mean Absolute Percentage Error (MAPE), Mean Absolute Deviation (MAD), and Root Mean Squared Error (RMSE), to analyze the accuracy of the simulated model with actual data in reference mode, for

Figure 3: System Dynamics Model for market opening X Diffusion of solar generation



error verification. The mathematical model must represent reality with a certain degree of reliability to be considered valid [25].

We realized the model validation from the standard scenario, called Business as Usual - BAU, which seeks to portray the dynamics of the expansion of photovoltaic solar generation as it currently occurs. This validation method is used as a way to examine the behavior standards of the system. The values that make up the behavior of the historical data involve the historical values of the total Demand between 2004 and 2020, as published by Energy Research Company [7]. We considered data from the Ten-year energy expansion plan between 2021 and 2030 for the reference scenario. After that period, since there were no annual demand projections by government agencies, linear growth was considered.

We also validated the model, considering the behavior of the open market demand. For this, we only consider the historical values of this variable between 2010 and 2020, as published annually by the Energy Research Company [7], since there is no forecast information for Demand by market environment made available by government agencies.

Figure 4 allows observing the behavior over time for the total simulated demand *versus*

Table 1: Model input parameters.

Parameter	Value	Unit
Total Demand (regulated market + open market)	415.667,76	GWh
Demand Group A	227.211,38	GWh
Demand Group B1	91.376,91	GWh
Demand Group B1 low-income	12.687,02	GWh
Demand Group B2	12.630,56	GWh
Demand Group B3	47.331,50	GWh
Demand Group B4	12.118,70	GWh
Average annual variation of Total Demand	2,73	%
Historical average share of Group A in Total Demand	51,41	%
Historical average share of Group B1 in Total Demand	25,27	%
Historical average share of Group B1 low-income in Total Demand	0,32	%
Historical average share of Group B2 in Total Demand	3,45	%
Historical average share of Group B3 in Total Demand	12,03	%

historical and projected (a), and the behavior for the Demand to be supplied from the simulated open market *versus* the observed historical values (b).

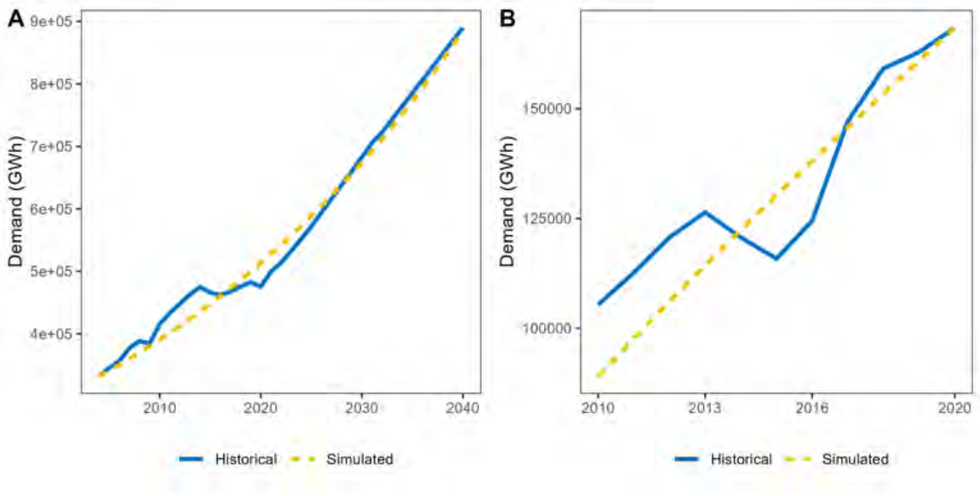
The adjustment for both variables is acceptable; the model responds to values very close to the real ones. We also calculated the metrics R^2, MAPE, MAD, and RMSE, for both variables, with the values obtained in Table 2.

Table 2: Model validation metrics based on total demand analysis.

Parameter	Value for Total Demand	Open Market Demand Aumont	Unit
R^2	97,5	83,7	%
MAPE	4	7	%
MAD	18.088,71	8.813,65	GWh
RMSE	69,78	58,04	GWh

It is possible to observe that the model explains in 97% the actual values, with only 4% error for the total Demand. Regarding this error, the observed values can be, on average, 18 thousand GWh away from the actual values. The model may be wrong by 69.78 GWh

Figure 4: Comparison of historical, projected, and simulated values.



for each simulated value, more or less. These values are considered low compared to the planned Demand of 274,617 GW for 2040.

Considering the Demand for the open Market, the model explains approximately 84% of the actual values, with only a 7% error. As for this error, the observed values may be, on average, 8 thousand GWh away from the actual values. The model may be wrong by 58.04 GWh for each simulated value, more or less.

We also perform sensitivity analyses to increase the understanding of the model dynamics and help to demonstrate the confidence levels of representation of the model's reality, supporting the effort of experimenting n situations that the model provides. For the sensitivity analysis, we considered 100 simulation runs, verifying the possible results of the model from the variation of certain model variables, whose assumed values are associated with a certain degree of uncertainty.

We consider the sensitivity analysis by changing the variable *coefficient p open market*, which implies adopting the open Market from consumers with an innovative profile, commonly known as *early adopters*, or those susceptible to experimentation. We also considered the change in the percentage of solar insertion in regulated auctions. The exponent li, which makes up the structure of the learning effect model on price, also had its value changed for sensitivity analysis. We chose Latin Hypercube sampling (LHS) to perform the sensitivity analysis.

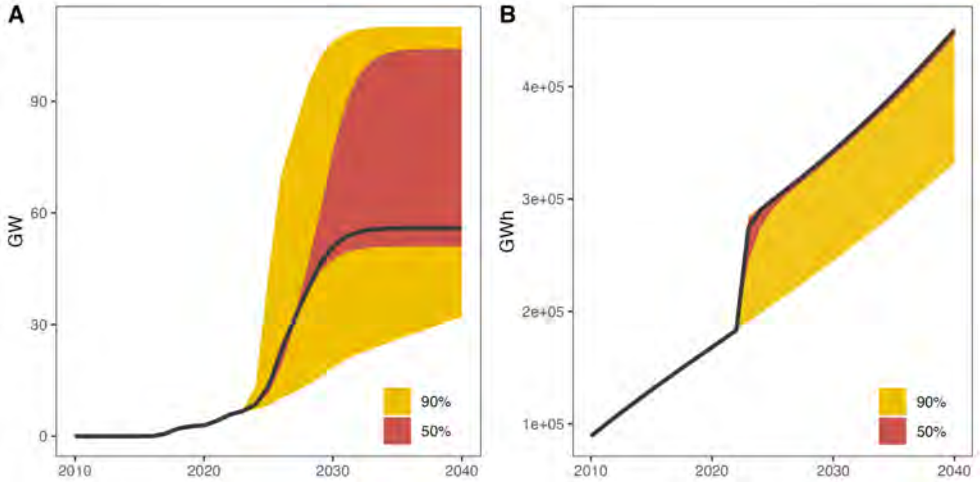
Table 3 presents the variables included in the sensitivity analysis and the range of variables considered for the sensitivity analysis. The sensitivity parameters considered were uniformly distributed for all variables, based on random sampling, with variation from 2022 onwards.

Table 3: Model Sensitivity Parameters.

Parameter	Minimum value	Maximum value
Coefficient p	0	1
Coefficient q	0	1
Insertion of the solar source in auctions	0,1	0,4
Exponent li of the learning curve	-0,3	0,01
Limit of insertion of the solar source in the matrix	0,1	0,4

The sensitivity graphs were expressed comparatively among the 100 simulated runs, presenting the results in confidence intervals of 50% and 90% of the values obtained. Figure 5 shows the graph of confidence values for the simulations carried out, both for the total installed power of solar generation (A), as for the adopters of open Market (B), that is, the Demand to be supplied in the open Market.

Figure 5: Confidence Interval for Solar Installed Power (A) and Open Market Adopters (B).



The total installed power expected at the end of the simulated period varies between 37 GW and 87 GW for a confidence interval of 90% (Image 5-A). On average, the analysis points to a total installed power of about 59 GW in the electricity matrix for the year 2040. Considering that the potential Market (Group A's Demand) is 457 GWh, even varying the uncertainty parameters of the model, the open Market would supply around 92% of all the Demand of Group A, since the average value obtained in the sensitivity analysis was approximately 420 GWh at the end of the simulation period (Image 5-B). Furthermore, it is worth mentioning that the maximum and minimum values for 90% of the values resulting from the sensitivity analysis are very close, indicating a certain robustness of the model, that is, low sensitivity to the variation of uncertain variables. Considering these variations, in 90% of the simulations, the free Market would be responsible for supplying between 42% and 51% of the total Demand, with an average percentage of 47%.

This process of varying parameters to analyze how the system's behavior changes are automated, but fundamentally, it is similar to an experimentation process. It is possible to verify how the results change by altering some parameters. Thus, this sensitivity analysis makes it possible to observe low model variations from the difference in variables associated with uncertainty, which indicates the model's robustness.

2.2. Formulation of Scenarios

We elaborated the scenarios according to the market opening: the permissiveness of different groups to the open Market, the increase in the insertion limit of photovoltaic solar generation on the regulated auctions, and the change in the adoption coefficients of the open Market from the increase in the insertion limit of photovoltaic solar generation on matrix and increase of technology's cost. The 4 table below presents the strategies addressed and the definition of simulated scenarios.

Table 4: Definition of Scenarios.

Scenario	Description
C1	Incremental opening of the electricity market.
C2	Market permissible only for Group A and increase in the insertion of solar source in regulat
C3	Total market opening and increased insertion of solar source in regulated auction
C4	Total market opening, increase in solar insertion limit, and increase in CAPEX.

Considering that migration to the open Market is only possible for some consumers, this research first investigates the reflection of a gradual opening of the electricity market in the diffusion of centralized solar photovoltaic generation. Thus, every two years, the open Market becomes permissible to a new group until it reaches whole opening in 2032, as follows:

- Groups A + B3 in the year 2024;
- Groups A + B3 + B1 in the year 2026;
- Groups A + B3 + B1 + B2 in the year 2028;
- Groups A + B3 + B1 + B2 + B1 Low Income in the year 2030;
- Total opening in the year 2032.

Scenario C2 allows the analysis of the system under study from the maintenance of the open Market permissible only to Group A, however, with an increase in the participation of the centralized solar photovoltaic generation source in the regulated auctions.

In this sense, we used the same idea of increasing the participation of solar sources in regulated auctions considered in the C3 scenario. However, we add the total opening of the electricity market. So, the C3 scenario combines the C1 + C2 scenarios. This scenario, therefore, involves a change in the behavior of both the regulated Market, regarding the profile of Demand for solar generation in this environment, and the open Market, considering the increase in potentially open Demand.

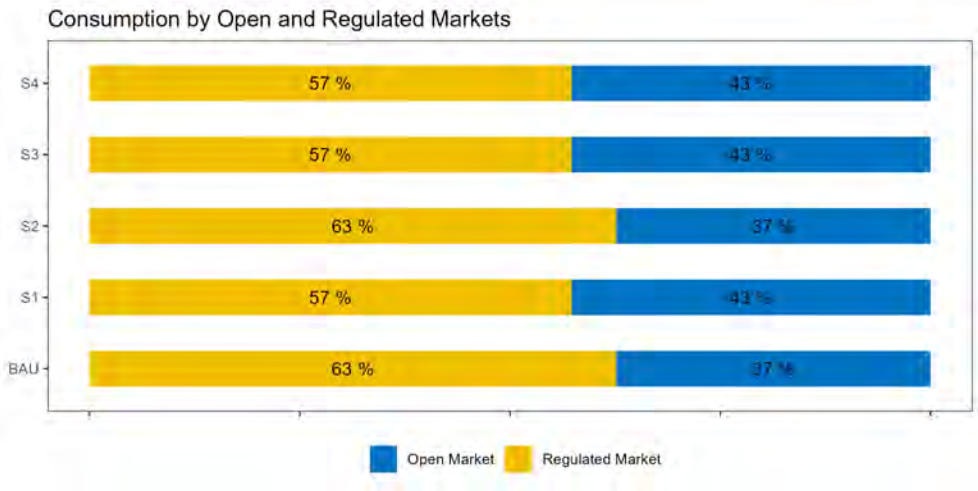
From the total opening of the Market, we investigate in the C3 scenario the possible reflexes for a centralized solar photovoltaic generation. So, we consider the increase of the limit of the insertion of this source in the matrix to 40%. This scenario simulates the development of technologies associated with the storage and growth of generation efficiency in solar panels and on the development of the technological system itself that involves electric vehicles, hybrid plants, community choice, microgrid, and smart grid, among others, that allow efficient operation of the Brazilian electricity sector with greater participation of intermittent sources, as in the case of solar.

We understood that these possible technological developments imply an increase in cost associated with the increase in the limit of insertion of solar generation in the matrix. Thus, the C4 scenario seeks to analyze the increase in the limit of insertion of the solar source in the matrix in a completely liberalized market environment, considering a range of CAPEX increases of this technology of 50%. We ran the sensitivity analysis for the variation of this variable, allowing the simulation results to be explored and examined.

3. Results

The simulated scenarios imply different results over the years. We observed the share of the Demand to be met from each market environment, the Demand for solar generation, the decision to build plants, and the reflection in the diffusion of the installed power generation of centralized solar photovoltaic. Regarding the participation of each market environment in the Supply of total Demand, the model resulted in two situations. When other consumer groups and Group A are allowed to access the open Market, this environment starts to answer for about 43% of the total Demand. When limited to Group A, the open Market accounts for 37%. We showed the results obtained for each scenario in Figure 6.

Figure 6: Percentage share of each market environment in final consumption in the 2040 year.

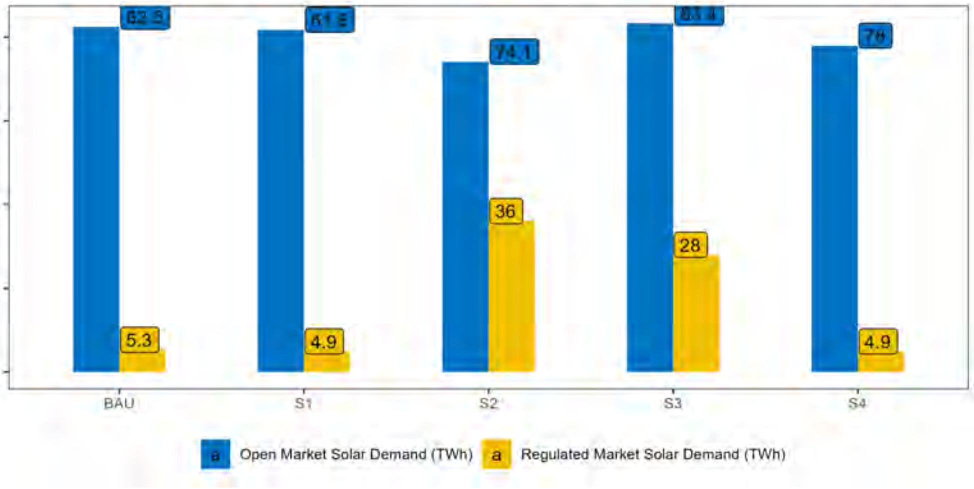


The BAU scenario shows that at the end of the simulated period, this percentage would be 37%, a timid growth, considering that currently around 34% of the total Demand is already supplied via the open Market. This growth is related to the development of total Demand (which reflects on the evolution of Demand in each consumption group) and to the adoption rate of potentially free consumers to the open Market, obtained from the parameters of 'adoption by innovation' and by 'adoption by imitation'. It means that almost 65% of the potentially free energy would be supplied, in 2040, by the open Market.

From the Demand to be supplied in each market environment, the model considers that photovoltaic solar generation must provide a share of Demand. Thus, in both market environments, part of the Demand not supplied by photovoltaic solar generation must be provided by other sources.

The model considers a limit to the insertion of solar generation in the matrix, and all generation sources, whether for the regulated market or the open market, come from the Total installed power of the technology. Figure 7 compares the absolute values of the demand to be supplied from solar generation in each market environment.

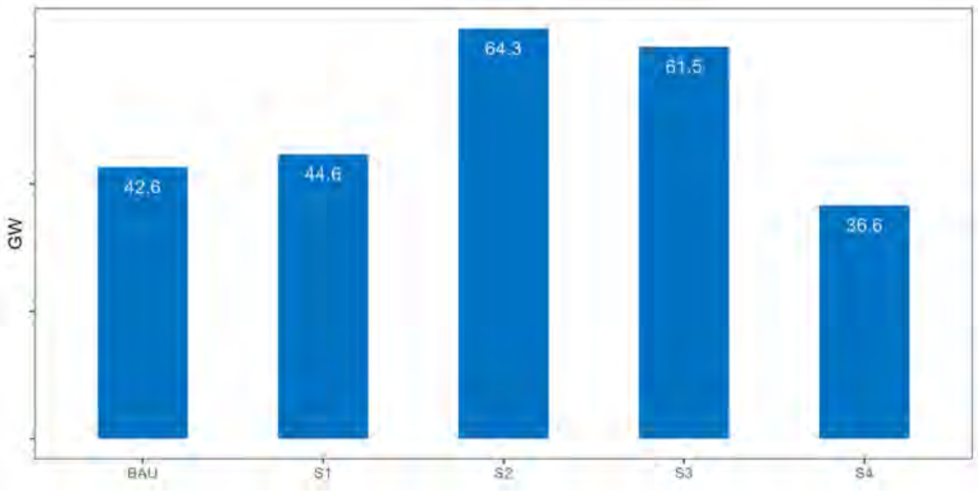
Figure 7: Demand for solar generation in each market environment in the 2040 year.



Scenario 3 reflected a greater demand for energy from solar sources in the open market in absolute values. We considered in this scenario the total opening of the market and the increase in the insertion of solar sources in regulated auctions. On the other hand, Scenario 2 had the highest demand for solar energy in the regulated market, a direct reflection of the increased participation of solar generation in regulated auctions. This result is interesting because it indicates that the opening of the market in parallel with the increase in the participation of solar sources in the auctions (Scenario 3) contributes more to the diffusion of solar in the open environment than the scenario that only considers the opening of the market (Scenario 1). Solar energy's demand in the open market also benefits from incentives for this source in the regulated market.

Demands for solar generation reflect the Total installed power of this source expected for 2040. Figure 8 shows that Scenario 2 is the one that results in a greater installed capacity of the solar source in the matrix for the year 2040, of 64.3 GW of photovoltaic solar generation. This result indicates that further intensifying the incentives for the solar source in the regulated environment reflects more significant benefits for the diffusion of this source in the matrix.

Figure 8: Total installed power of photovoltaic solar generation expected for 2040.



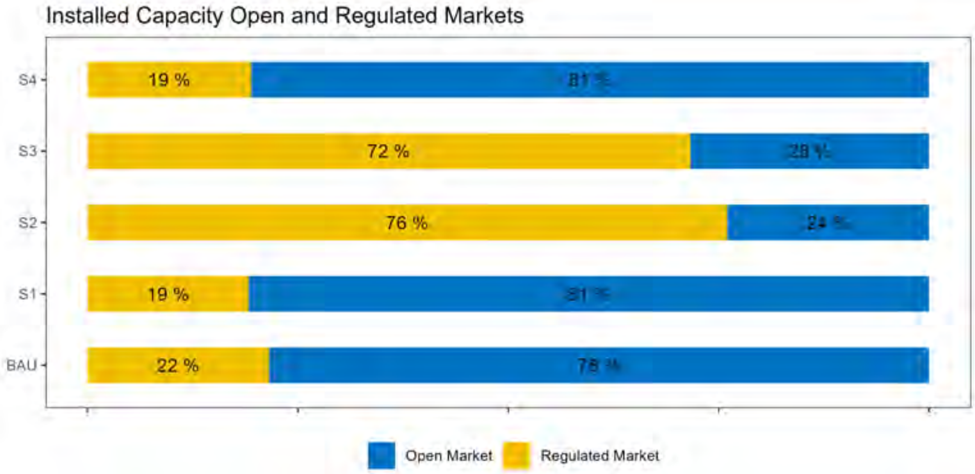
All scenarios presented different results. The most favorable outcome for the solar generation's diffusion in the matrix was Scenario 2, differing from the BAU only in terms of the more significant share of the source in the regulated auctions. Scenario 3 is also among the most expressive scenarios for the diffusion of centralized solar photovoltaic generation with about 5% less installed power compared to scenario 2.

The results obtained so far allow the following analysis: encouraging the solar source in the regulated environment, through its more significant insertion in auctions, contributes most to its diffusion in the matrix. Furthermore, this incentive, parallel to the opening of the market, contributes to the increase in the open market's demand for energy from the solar source. This dynamic reflects a reinforcing relationship between the opening of the electricity market and the incentive for solar in the regulated market with the solar generation's diffusion.

On the other hand, the scenario that least contributes to the increase in the installed power of the solar source is scenario 4, which involves increasing the insertion of the technology in the matrix. However, associated with an increase in CAPEX is associated with it. Furthermore, when we try to open the market, keeping the other parameters similar to the BAU (scenario 1), then, we observe a slight increase of about 2 GW of solar installed power in the matrix when compared to the installed capacity resulting from the BAU, of 44.6 GW.

It indicates that the market's opening needs to reflect a significant impact on the diffusion of the installed power of the photovoltaic solar source in the Brazilian matrix. However, two points are worth a more thorough consideration. First, we must consider that the model associates the construction of plants, that is, the increase in the installed power of the source, separately for the open and regulated markets. Considering the limit of insertion of the source in the matrix and the solar energy needs for each environment, the model defines the power to be built. Figure 9 shows how much of the total capacity is associated with the open market and how much is associated with regulated market in percentage terms.

Figure 9: Percentage of solar power associated with each marketing environment in the 2040 year.



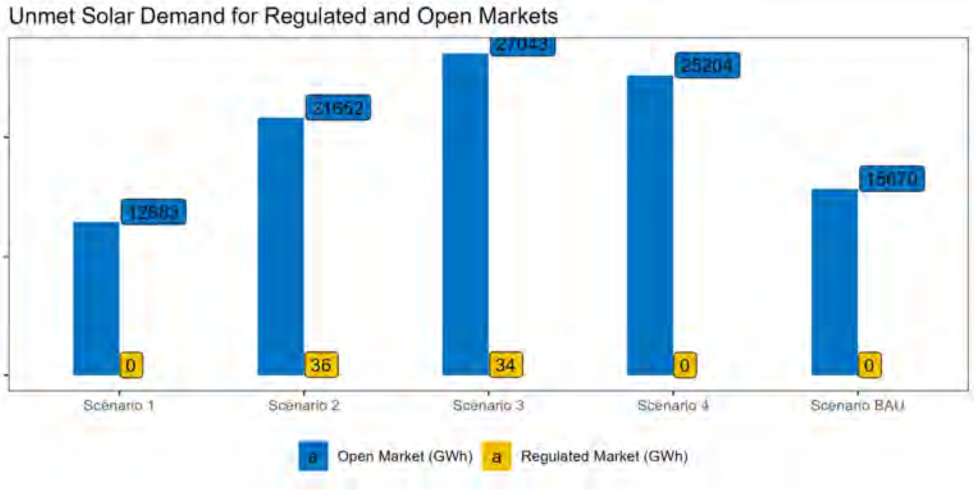
The auctions practiced in the regulated market are responsible for more than 70% of the photovoltaic's installed power during the simulated period, both in scenarios two and 3. Both these cases involve increasing the insertion of the solar source in the regulated auctions. However, Scenario 2 consists of the electricity market accessible only to Group A consumers, while Scenario 3 involves the total gradual opening of it.

For the other scenarios, which maintain the current participation of the solar source in the regulated auctions, more than 75% of the installed power of the solar source over the simulated years is associated with the open environment of electric energy contracting. We reinforce that, so far, the results indicate that the diffusion of the source under study is still associated with the regulated environment since when it increases its insertion in the auctions of this market environment, the results of installed power are more favorable (scenario 2).

However, as mentioned earlier, a second point deserves to be highlighted. Our model has a stock that indicates the need for generation from the solar source to meet the demand for this source in each market environment. This need is transformed into power to be built. This power is conditioned to the insertion limit of photovoltaic and considering the competitiveness of this technology.

There may be a need for solar energy that is not transformed into power to be built. In other words, in each market environment, demand for photovoltaic generation cannot be met due to the photovoltaic's limit of insertion in the matrix. Figure 10 shows the results of these values for each scenario.

Figure 10: Unmet demand for solar generation in the 2040 year.



The demand for unmet solar energy is observed in the regulated market only in scenario two and scenario 3; however, in shallow values. That is, even if there were an increase in the limit of insertion of the solar source in the matrix in these scenarios, the regulated environment would not contribute with a significant increase in the installed power of solar generation in the matrix than the values previously observed in Figure 8.

On the other hand, all scenarios showed significant values of unmet demand for solar energy for the open market, which indicates that this environment still has the potential to contribute more to the diffusion of solar generation in the Brazilian electricity matrix. In other words, if the technology were more competitive than the others or if a more significant insertion of solar generation into the matrix were operationally feasible - without changing CAPEX, then the open market could contribute more to the increase in the installed capacity of centralized solar photovoltaic generation. In this sense, scenario 3 deserves to be highlighted, as it could contribute to about 47 GW of installed power[1], considering the existing demand for generation from the solar source in the open market.

3.1. Summary of simulations

The simulated scenarios are based on changes in some parameters considered in the models. However, in all of them, we assumed a limit for the insertion of solar generation. The base scenario, for example, points to an insertion limit that, over the simulated years, reaches 15%, indicating for 2040 a total installed power of a photovoltaic generation of approximately 42 GW. In other words, this means that if (i) the patterns currently observed for the participation of solar in regulated auctions are maintained, (ii) the growth that has been observed by choice of generation from the solar source in the open market - reaching 20% in 2040, and (iii) respecting the insertion limit of 15% of insertion of the solar source in the matrix, then, solar generation tends to jump from an installed power of 1 MW observed in 2010 to 42 GW in 2040. Of this total, 78% must be associated with projects 100% destined for the open market.

We simulated the total opening of the electricity market in scenarios 1, 3, and 4, and only scenario one did not involve other parallel changes. Keeping the parameters established in the BAU scenario and only changing the size of the demand potentially open, scenario 1 indicates that the installed solar photovoltaic power for 2040 would be around 44.62 GW, while 81% of this power must be associated with projects 100% destined for the open market. Even with a total installed capacity slightly more expressive than in the BAU scenario, scenario 1 maintains the same relevance of the open market in the diffusion of photovoltaic solar generation as a BAU.

As pointed out by [27], targeted auctions are strategies to protect niche technologies. For scenario 3, in addition to the total opening of the market, an increase in the participation of solar sources in the auctions was considered. In other words, this scenario makes it possible to identify the reflections on the diffusion of solar generation from the increased source incentive actions in the regulated market. The prospective model allows us to observe that this measure positively impacts the Total installed power compared to the base scenario, which appears to be 64.32 GW, of which 72% are associated with projects that maintain PPAs with a regulated market. In other words, this measure could

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[1] We consider a capacity factor of 20% for solar generation

contribute more to the diffusion of centralized solar photovoltaic generation, keeping the regulated market as a source expansion engine in the matrix.

Scenario 4 was the one that presented a minor contribution to the diffusion of centralized solar photovoltaic generation in the national electricity matrix, indicating a total installed power of about 36 GW in 2040. This result shows almost 20% less than the power observed in the base scenario and about 45% less than scenario 2. In scenario 4, in addition to the total opening of the electricity market, an increase in the limit of insertion of solar generation in the matrix was considered, which reaches 40% in the year 2040. However, this increase in the insertion limit is parallel to a rise in the cost associated with the technology, mainly due to the cost of complementary equipment, such as batteries, for example, expanding the use of intermittent sources. Even associated with a more expressive price, the diffusion of centralized solar photovoltaic generation observed in scenario four is associated, in large part, with projects that exercise contracts exclusively in the open market, representing about 81% of the Total installed power in 2040.

Except for scenarios 2 and 3, which involve, in addition to the total opening of the electricity market, the strategy of protection and incentive of solar generation in the regulated market, all other scenarios, including the BAU, indicate the open market as a driver of the expansion of the photovoltaic solar centralized generation in the national electrical matrix. It is because, in the BAU, scenarios 1 and 4, the installed power reached in 2040 is associated mainly with freely negotiated contracts in the open market.

However, the results allow us to observe that scenario 2 is the one that most contribute to the diffusion of centralized solar photovoltaic generation in the Brazilian electrical matrix. This scenario is associated with the increase in the insertion of the solar source in regulated auctions, implying that 76% of the photovoltaic's installed power is associated with the contracts carried out in the open market. Similar results are achieved when we add to this strategy by increasing the insertion of the source in the auctions and the gradual total opening of the electric energy market (scenario 3).

The main difference between these two scenarios is the demand for unmet solar generation in each environment. In other words, if the electricity sector develops to the point of allowing a healthy operation, with values of the solar source still competitive and more significant insertion of this source in the mix, then the total opening of the market and the increase of solar insertion in the regulated auctions would together allow the Total installed power of the solar source to reach values close to 108 GW in 2040 (scenario 3). In this same idea, scenario 2, in turn, would result in values close to 101 GW based on the same considerations.

Considering that the BAU scenario and scenario 1 differ little regarding the Total installed power of the photovoltaic solar source for the year 2040, we assume that the liberalized environment is today the engine of expansion of the photovoltaic in the matrix. However, better results for the diffusion of photovoltaic solar generation in the Brazilian electricity matrix are associated with the increase in the participation of this source in the auctions practiced in the regulated environment. Even with the opening of the market and the diffusion in demand to be supplied from the open market, the more significant insertion of the solar source in the auctions results in more expressive values of the installed power photovoltaic's increase.

We understand that the development of centralized solar photovoltaic generation in the Brazilian electricity matrix is sustainable in the face of a total electricity market opening. That is, market protection mechanisms are no longer necessary for the source. If we did not consider, for example, the limit of insertion of the solar source in the matrix, this source could represent around 25% of the installed capacity in 2040, just with the market opening.

However, market protection mechanisms are still welcome and would allow for a more aggressive diffusion of the source. Making the same analogy, if the model did not consider the photovoltaic's limit of insertion in the mix, adopting the measures of increasing the insertion of the solar in the auctions and total opening of the market, the installed power of solar technology could represent in 2040 around 43% of the Total installed capacity of the Brazilian electricity sector.

4. Discussions and Policy implications

The path the Brazilian electricity sector took allowed the current direction to develop. Both reforms in 1998 and 2004 contributed to the reduction of price volatility. We proposed a generic model that presents the dynamics of the expansion of solar generation based on the choice of this source in the open market and its inclusion in auctions in the regulated market. The simulation results indicate that the photovoltaic's diffusion on the open market is nearly the competition of this source. In other words, if there is an increase in the costs of photovoltaic electricity (by ancillary technologies, for example), this renewable source can negatively reflect on the matrix. So, policymakers should be attentive to the develop future technologies in the long term and the possible impact on energy costs.

We considered a rate of choice for a photovoltaic generation that arrives in the year 2040 at 20% of the total demand of the open market. These values correspond to the values currently observed, where the vast majority of industrial consumers participate in this market [1]. Industrial consumers are associated with greater motivation to reduce CO2 emissions and greater attention to market price signals [14]. So, opening up the market to the retail consumer can reduce this rate of choice for solar generation. In this sense, we highlight the need to include knowledge from the social sciences in future studies to involve aspects of consumer choice.

This factor is particularly relevant when considering the energy policy objective of low tariffs. As much as liberalization has been associated with generalized efficiency gains, [26] showed, for example, that some consumer groups may face higher prices due to this movement. Electricity markets must rely on pricing schemes that balance economic efficiency, and social equity [20]. In other words, the open market is associated with the consumer's open choice, and knowledge about the market is inherent to the best options in terms of the price incurred. From the idea of universal access to electricity and tariff equality, in addition to the possible ways by the future developments to energy technologies, opening the market must be associated with policies to include knowledge diffusion about the market operation.

This research pointed to the hypothesis that there is a relationship between the opening of the electricity market and the diffusion of centralized solar photovoltaic generation. Given the assumptions made on the model, we understood that exist this relation, agreed with this hypothesis. The BAU scenario and scenario 1 (which indicates the gradual total opening of the market) have not shown significant differences for the photovoltaic's Total installed power to 2040 (45.01 KW in the base scenario versus 44.62 KW in scenario 1). However, the demand for solar in the open market is higher than in the regulated market. This result is likely associated with the fact that solar generation, like wind power, has a meager operating cost, contributing to this source's short-term decision.

The open market was associated with the unmet photovoltaic demand in all scenarios.

We assume that if it wasn't the insertion limit considered on the model (which is consistent with the operational reality of the matrix), this source could reach higher levels of installed power. So, we understood that the relationship between the opening market and photovoltaic diffusion is positive, suggesting that the market's opening contributes to the diffusion of centralized solar photovoltaic generation. However, these findings should be kept from other generation sources because, as discussed [24], photovoltaic is associated with unique characteristics, such as modularity and generation capillarity, and these characteristics may be related to investor choice. These characteristics can be positive highlights in new business models involving the decentralized generation and increase of prosumers, microgrids, Community Choice Aggregation, generation from hybrid power plants, and others [21, 33].

We increase the potential growth of capacity. The unmet solar electricity demand demonstrated in our simulations suggests many opportunities for this renewable source on the open market that can be developed. Thus, investments in Research and Development must be intensified to operationalize the Brazilian electricity sector with a more significant insertion of the solar source in the matrix, responding to the unmet demand for electricity from this source observed in the simulations. In this sense, opening up the market could also contribute to the diversification of the matrix and, consequently, to the reduction of hydrothermal dependence.

In addition, the unmet demand in the simulated scenarios allows us to observe that greater installed power of solar generation is kept at the end of the simulated period when we approach source support mechanisms in the regulated market. So, a more aggressive diffusion for photovoltaic electricity should be achieved through concordance between the opening market and policies to increase this source in a regulated market.

Even though we confirm the positive relationship between the opening market and photovoltaic diffusion, our model didn't involve the electricity price formation structure or even the logic of short-time market prices, so we don't have support to discuss the reflection of the opening electricity market in Brazil on the renewable energy policy paradox. However, we know that those hybrid regimes, with public coordination of the electricity system, can be favorable when compensating for externalities not considered by the market, such as decarbonization and energy security [19]. Furthermore, the renewable energy policy paradox isn't applicable to the centralized market [5], and additional research is necessary to explore the paradox in hybrid regimes.

Aligned with the positioning of [19] about the hybrid regimes, we understood that the auction mechanism would act as a result of a central planning strategy for expansion and diversification of the matrix, as protection not of the solar source but variable renewable energy sources. This strategy would encourage competition in the market through long-term contracts supporting investments. In contrast, the design of the total opening of the electricity market would contribute to the short-term optimization of the system. This mechanism is essential to consider construction cost and investment risk associated with generation plants from intermittent sources, such as solar and wind, this position, however, is regarding how these auctions take place in the current regulated market. In a market already experiencing maturity, as Brazilian case, considering the context's climatic and geographic conditions and the potential for the development of photovoltaic solar technology, our position is that such a source has the potential to increase on the matrix beyond the market protection measures, such as auctions. So, we understand that for auctions to contribute to competition in the market, they must be technology neutral, leaving aside the idea of a protection mechanism for a given technology, as occurs in the Brazilian sector. Each source must compete based on a combination of its attributes. In the understanding of [19], the challenge lies in developing this model. Review how the auctions occur, and we should value the attributes related to each technology without acting as a protection mechanism for specific technologies. Furthermore, this strategy can support the guarantee of the objectives of the Brazilian energy policy of energy doesn't apply universal access with reasonable tariffs.

5. Conclusions

This study offers an overly aggregated and simplified model of system dynamics in electricity involving different contracting environments. Our model should be seen as something other than finished but as a tool under construction, with possibilities for improvements and greater detail so that various analyzes can be carried out, helping policymakers. Using simulation models helps in testing strategic policies and analyzing long-term consequences without high costs.

Our results contribute to the studies on the opening of the electricity market, approaching a Latin country as an object of research and indicating that the Brazilian case experiences much more a moment of addition of technologies and marketing practices in the established regime than the energy transition itself. In this sense, we must use systems dynamics widely in the Brazilian electricity sector's political designs.

In the practical field, our results allow better decisions can do by policymakers, considering the systemic and global views on the possible reflexes of political and regulatory decisions are not must be left aside. For technology developers and energy professionals, these results support choices about where attractive business models can emerge. We hope that the results obtained will be helpful to both policymakers and planners, energy professionals, and researchers, contributing to discussions on energy markets and the decarbonization and diversification of electrical systems.

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