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Developing Brazil's Market for Distributed Solar Generation

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Abstract

We show the availability of solar resources is a poor predictor of the penetration of distributed photovoltaic (PV) generation in Brazil. Analyzing data from 5,563 municipalities in Brazil, we show that demand-side factors such as population, GDP, and electricity tariffs prevail as key determinants of PV undertake. Solar radiation only appears as positively correlated with PV adoption when comparing municipalities within the same influence area of electricity providers. Public policies should target frictions on the demand for electricity to promote PV. In addition, estimates of the potential of renewable sources to mitigate climate change are upward biased if demand-side factors are not taken into account.

Keywords

distributed generation, solar photovoltaic, radiation

Jel codes

Q01, Q40, Q41

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1. Introduction

Renewable technologies are seen as a key instrument in combatting greenhouse gas emissions and climate change, and the availability of renewable natural resources is regarded as the main requirement for a nation's ability to reduce climate risk (IPCC, 2014). However, the development of the renewable energy sector occurs not only through determinants of supply, i.e., the availability of natural resources, but also through aspects of demand.

We examine the penetration of distributed solar photovoltaic (PV) generation in Brazil to assess the relative importance of supply and demand factors, pointing to possible implications for policy design. Brazil is an interesting case study. Despite the country's remarkable solar potential[1], supply-side resources are concentrated in less populated areas. This is a favorable configuration to disentangle the relative importance of supply and demand factors as predictors of PV adoption.

Our study uses a unique dataset built entirely from publicly available information, comprising data from different sources, and covering 5,563 municipalities in Brazil. We combine solar radiation data from the recently launched second edition of the Brazilian Solar Energy Atlas (INPE, 2017), geolocation of consumer units with photovoltaic distributed generation obtained from the Brazilian Electricity Regulatory Agency (ANEEL), and demand-side factors such as municipal Gross Domestic Product (GDP), population, and electricity tariffs.

Results show that demand factors prevail as determinants of PV penetration. This effect is so relevant that municipalities with lower annual solar radiation have, on average, more consumer units with distributed solar photovoltaic generation. Demand factors such as income, population, and electricity tariff positively affect the number of PV units in Brazil. The analysis also takes into account the characteristics of electricity distribution companies, considering their specific incentive policies. Only when comparing municipalities within the same concession area, and thus the commercial policies of those companies, are we able to show that higher radiation is associated with a higher number of PV units.

These results have important policy implications. First, the design of renewables policies aimed at climate risk mitigation should target demand-side factors in addition to

[1] The average annual horizontal radiation is more than 1,800 kWh/m^2 throughout most of Brazil (IEA, 2016). The average annual irradiation in Brazil varies between 1,200 and 2,400 kWh/m^2/year, which is higher than in Germany (between 900 and 1,250 kWh/m^2/year) (EPE, 2012).

supply-side availability of natural resources. In particular, frictions caused within the system of tariffs might have important consequences for the penetration of PV. For example, electricity tariffs are relatively low in the Northeast region due to sector's subsidy policy, preventing greater penetration of distributed generation in the highest solar potential region in Brazil. Second, the promotion of renewable energy sources in places where physical potential is far greater than demand would require specific strategies based on the capacity of electricity to foster development as documented by Lipscomb et al. (2013).

The remainder of this paper is organized as follows. Section 2 presents the literature review and Section 3 describes the institutional context regarding distributed generation in Brazil. Section 4 introduces the data and descriptive statistics. Section 5 presents and discusses results and Section 6 concludes.

2. Literature Review

Several studies have assessed the main factors underlying the success of solar photovoltaic generation. Lang et al. (2015), for example, have reviewed global economic attractiveness of rooftop PV for residential buildings under combinations of geographic, technological, and economic factors. They find that irradiation, electricity prices, investment costs, and the achievable share of self-consumption (i.e., the use of locally-produced PV power to meet own power demand) are among the most important influence factors when assessing rooftop PV's economic prospects in an area. In many regions, rooftop PV can already today be an attractive investment, even in the absence of subsidies. According to their analysis, Brazil is one of the countries with high investment attractiveness.

As the authors point out, however, no regional factor alone can ensure or impede PV's economic performance. The physiographic potential, therefore, cannot uniquely determine the effectiveness of this source. This goes in line with evidence presented by Celik et al. (2009) for European countries. Even though the deployment of PV systems is strongly influenced by solar radiation, the authors show that other factors, such as GDP per capita and government incentives, play a major role in the evolution of photovoltaic markets.

For that reason, even in regions with high solar potential, the location of PV units can be suboptimal. According to Rogers and Sexton (2014), this was the case of solar panels installed under the California Solar Initiative. The authors argue that the program – which consisted of a US$2 billion subsidy towards investments in distributed solar generation, implemented in California in 2006 – would have been more cost-effective if the government had invested directly in utility-scale projects located in areas with higher solar radiation.

The role of the electricity tariff in the expansion of PV systems is discussed by different authors. According to Lang et al. (2016), for residential and commercial distributed generation, one should consider the electricity retail prices when assessing the profitability of solar energy. This is mainly because the competitiveness of PV systems is greatly influenced by high electricity prices. Bernal-Agustín and Dufo-López (2006) demonstrate that, in the context of the Spanish market, the higher the energy tariff, the shorter the investment's return time, and, therefore, the more attractive it is to invest in PV installations.

This relationship is also presented by Borestein (2008) when studying the expansion of residential PV systems in California. As the average price of electricity in the state is relatively high, and the rates are designed to increase with the amount of energy consumed, the author demonstrates that incentives to install solar panels are disproportionately distributed towards wealthier and higher electricity users.

Finally, the population size and resulting roof area is another factor determining the distribution of PV units in a country. According to the Energy Research Office (2014), for Brazil, the roof area available for PV installation, in addition to solar radiation, will directly determine the capacity for energy generation in a certain area. Regions with higher populations have greater generation potential since they have more households and, therefore, more roof area. The study shows that in most municipalities in Brazil the population size offsets lower radiation levels.

3. Distributed Generation in Brazil

3.1. Brazilian Power Matrix

In the Brazilian Power Sector, which is a centralized hydro-thermal system, thermal power plants should operate in a complementary manner. Thermoelectric plants are only triggered when reservoir water levels are low. From 2012 to 2015, however, the thermoelectric plants were continuously activated. The increase in the use of natural gas for thermoelectric power generation boosted the number of non-renewable sources in the Brazilian energy matrix. Currently, there is an effort to expand the participation of alternative renewable sources (solar, wind, biomass, and small hydro plant) in the energy matrix.

As stated by Joskow (2011), however, those renewable generating technologies are inherently intermittent, and therefore, cannot be supplied in a dispatchable sense. The main barrier to the reliance on these energy sources is their unpredictable output, which can vary according to climatic and technologic conditions. For that reason, system operators should combine the use of dispatchable and intermittent generating technologies in order to balance supply and demand. With that in mind, distributed generation comes as a complementing alternative for the centralized energy generation system, reducing the need for the construction of large central power plants and transmission lines.

Table 1 presents the number of units and capacity by generation type in Brazil′s centralized and decentralized energy systems. The centralized system includes both renewable and non-renewable sources. The photovoltaic solar expansion is still in its early stages representing only 0.1% of total capacity of the centralized generation. On the other hand, there is great potential for the integration of solar photovoltaic in the decentralized system. Photovoltaic solar source represents 69% of total capacity and 99% of the total number of units. Currently, however, the total number of consumer units generating electricity is extremely low and represents only 0.014% of total consumers in Brazil. There is, therefore, a low penetration of solar energy in Brazil, both in a centralized and decentralized way.

Table 1 – Brazil´s Renewable and Nonrenewable Power Supply – Units and Capacity by Type

	Centralized			Decentralized		
Generation Type	**# Plants**	**Power (kW)**	**%**	**# Units**	**Power (kW)**	**%**
Hydroelectric	219	93,216,340	61.1%	-	-	-
Thermal	2,926	41,021,055	26.9%	51	19,187	14.6%
Wind	439	10,701,743	7.0%	52	10,183	7.7%
Small Hydro Plant	434	4,976,230	3.2%	-	-	-
Thermonuclear	2	1,990,000	1.3%	-	-	-
Super Small Hydro Plant	613	546,491	0.4%	15	11,253	8.5%
Solar Photovoltaic	50	144,214	0.1%	11,365	91,038	69.2%
Total	**4,683**	**152,596,073**	**100.0%**	**11,483**	**131,661**	**100.0%**

Notes: The table reports the number of plants and the capacity in kW by generation type in the centralized system and the percentage of each type of generation in the total capacity of the centralized system. This information was extracted on 30 June 2017 in the Generation Database on ANEEL's website. The table also reports the number of consumer units with distributed generation, the capacity in kW by source and the percentage of each source in the total capacity of the decentralized system. This information was extracted on 30 June 2017 on ANEEL's website.

3.2. Technological Characteristics

The use of sunlight as a source for electricity generation has been adopted in many countries for more than fifty years, initially in batteries and isolated systems, and, more recently, for grid connected systems. As solar energy is abundant all around the world, photovoltaic generation has long been acknowledged for its great technological and economic potential, becoming very competitive among renewables.

Until very recently, photovoltaic technology was not such an attractive investment, given its high upfront capital costs. Bazilian et al. (2013) point out, however, to the dramatic changes suffered by the PV industry regarding cost reductions. Investments in PV systems comprise the costs for the modules and for the hard and soft balance of system (BOS). The second component (BOS) refers to all the parts of a photovoltaic system other than the modules[2]. Module costs depend on global market trends, while the BOS prices may change according to local characteristics, such as wage and industry structures.

The costs of PV are fundamentally measured as the modules' price-per-watt (Bazilian et al., 2013). Since the second half of 2008, modules prices have declined

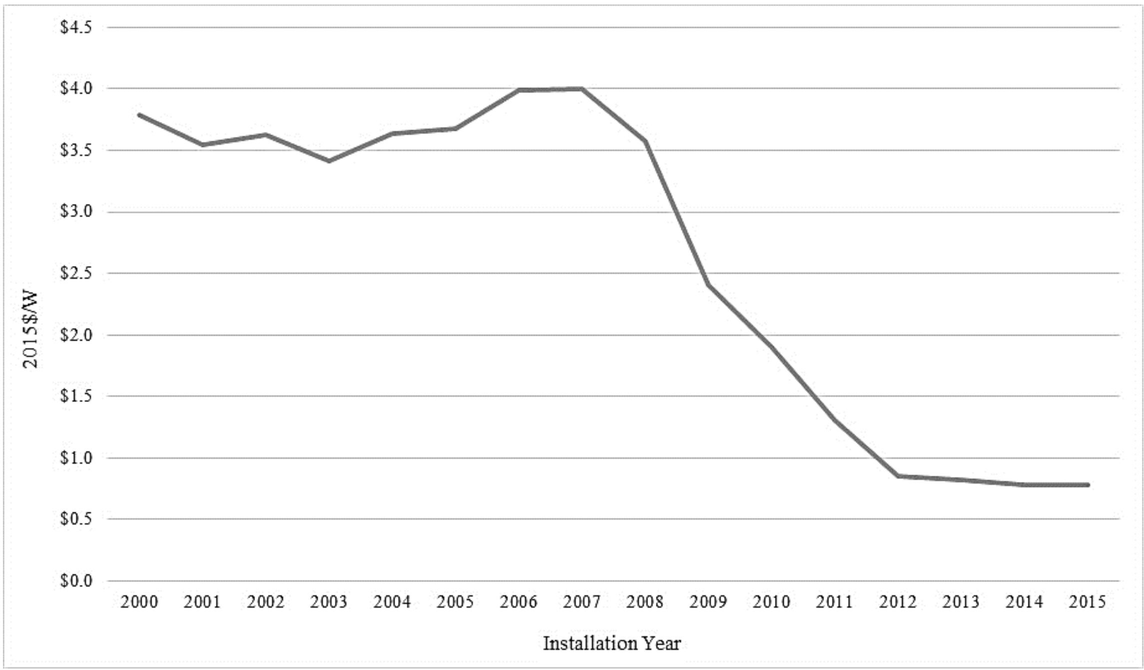
[2] The hardware part of the BOS comprises inverters, mounting systems, electrical cabling etc., while the software includes all installation-labor costs.

extraordinarily. In Figure 1, the graph shows the descending trend of PV module costs, which were reduced approximately 4 times in 15 years.

Another crucial factor for this expansion were public subsidies, which were initially more common in European countries. The implementation of distributed generation, in combination with incentives such as the feed-in-tariff and the net metering system, increased demand, contributing to the cost reduction of solar panels.

Even though in 2014, solar energy represented only 1% of the total electricity generation in the world, it had increased from 3.7 GWp in 2004 to 177 GWp ten years later (EPE, 2016). As to the Brazilian context, the expansion of the solar energy market is also on course. Most of the installation costs of residential photovoltaic systems (43%)[3] come from the price of the modules, which have only started to be produced in Brazil. Since PV modules are mostly imported goods, its price follows the trends from the international market. Therefore, we can conclude that, even if lagged behind, the costs of PV systems in the Brazilian territory tend to fall in the short run.

Figure 1 - Module Price Index over Time for Residential PV Systems



Notes: The Module Price Index is the U.S. module price index published by SPV Market Research.
Source: Barbose & Darghouth, 2016

[3] EPE, 2016.

3.3. Institutional Characteristics

The incentives for distributed generation are justified by the promising benefits that it can provide to the electrical system. Distributed generation, in addition to diversifying the energy matrix, has the potential to reduce investments in the expansion of transmission and distribution systems, lower environmental impacts, reduce load networks, and diminish transportation losses.

Distributed generation is a counterpoint to the current centralized generation model, in which the energy is generated in large sources, such as hydroelectric and thermoelectric plants, and transmitted over long distances until reaching the final consumer. Even with technological developments, cost remains one of the main bottlenecks to the expansion of distributed generation in Brazil.

In order to encourage the penetration of small distributed generation, on April 17, 2012, the Normative Resolution No. 482/2012 was approved. The resolution establishes the general conditions of access of micro- and mini-[4] distributed generation to the distribution network and the conditions for the power compensation system. The Brazilian consumer can generate their own electricity from renewable sources (hydro, solar, biomass, wind) or from qualified cogeneration and provide the surplus to the distribution network at their location.

The compensation system is defined as an arrangement in which the active energy injected by consumer units with distributed generation is transferred to the local distributor. The consumer is then subsequently compensated through their consumption of active electricity. In the net metering system, a consumer of electricity installs small generators in their consumer unit and the energy generated is used to reduce the electricity consumption of the unit.

In practice, if in a given billing cycle the power injected into the network by a micro- or mini- generator is greater than the consumption, the consumer will receive a credit on energy (in kWh) in their next bill. Otherwise, consumers pay only the difference between the energy consumed and generated.

The consumers should analyze the cost/benefit ratio for installation of generators, based on several variables: power supply type, technology equipment, size of the consumer unit and the generating plant, location (rural or urban), electricity tariff where

[4] Micro- installed power up to 75 kilowatts (kW). Mini - installed power above 75 kW and less than or equal to 5 MW.

the consumer unit is submitted, payment terms, and the existence of other consumer units that can make use of credits from electric power compensation system.

To encourage the advancement of the sector, in 2015 the government exempted PIS / PASEP and COFINS[5] on distributed generation. In the same year, the ICMS[6] Convention 16/15 was instituted by the National Finance Policy Council, authorizing states to exempt consumers from paying the tax on the value of the energy they consume from the distributor if it corresponds to the number of energy credits they obtained through the net metering system. In other words, the consumer will only be charged the ICMS on the electric power that exceeds the amount previously injected by the unit on the distribution system. Until June 2017, the only states that did not join the ICMS Convention were Espírito Santo, Amazonas, Paraná, and Santa Catarina.

In 2015, the Brazilian Electricity Regulatory Agency (ANEEL) published Normative Resolution No. 687/2015 reviewing the Normative Resolution No. 482/2012 in order to promote the use of distributed generation in the country. The highlights of the revised regulation are the following:

- Reduction of the network connection costs and the time for the distributor to connect the plant.
- Increased target audience (the installed power is less than or equal to 5 MW and not 1 MW as before).
- Increased expiration time of the electricity credits (60 months instead of 36).
- There is the possibility for the consumer to use those credits toward other previously registered units in the same concession area. These are characterized as remote self-consumption, shared generation, or multiple consumer units (condominiums).
    - Remote self-consumption - credits of a consumer unit can also be used to reduce the consumption of consumer units placed in another location by the same owner;
    - Shared generation - consumers united in a consortium or a cooperative install a micro or mini distributed generation and use the energy generated to reduce bills of consortium members;

[5] PIS – Social Integration Program; PASEP – Training Program of the Civil Servants; COFINS – Contribution to Social Security Financing.
[6] ICMS - Tax on goods and services.

- Multiple consumer units (condominiums) - the energy generated can be shared among the joint owners in percentages defined by the consumers themselves.

All of the aforementioned measures seem to have reached the goal of encouraging the expansion of distributed generation in Brazil, since in the last year the number of units tripled to more than 11 thousand by June 2017.

3.4. Electricity Tariff in Brazil

In Brazil, the public electricity distribution service is carried out by 63 concessionaires and 38 permissionaires[7]. Distributors cannot set their own prices as they are regulated by the government through ANEEL.

The regulatory agency's goals are to ensure a fair price to consumers as well as access to a continuous quality service, and to confirm that distribution companies are economically and financially viable to fulfill their contracts.

In Brazil, the electricity tariff is fixed per distributor and considers the characteristics of each concession area, such as number of consumers, market density (amount of energy distributed from a particular infrastructure), distribution network length in kilometers, and the cost of purchased electrical power.

A concession area is a territory where each distributor performs. When the concession area coincides with the extension of a state, the electricity tariff is unique in that Federal Unit. Otherwise, different tariffs may be applied in the same state, or even in the same municipality. In most states, especially in the North and Northeast regions, the concession area corresponds to the state geographical boundaries; in others, mainly São Paulo, Santa Catarina, and Rio Grande do Sul, there are distribution companies with much smaller coverage areas than the boundaries of the state.

The following costs are taken into account by ANEEL to calculate the tariff of each distributor: energy generation, transportation to the consumer unit (transmission and distribution), and sector charges. In addition to the tariff regulated by ANEEL, federal, state, and municipal governments charge PIS /COFINS, ICMS, and Contribution to Public Lighting (CIP) in the electricity bills, respectively.

[7] According to article 2nd of the Concessions Law (Law 8987/95), Concessions and Permissions are public service delegations made by the government under a bidding process. The difference between concession and permission is regarding the contract's stability. Concessions are more secure since the services they refer to require more upfront investment.

$$Electricity\ Tariff = \left\{\frac{Regulated\ Tariff\ by\ ANEEL}{1-(PIS+COFINS+ICMS)}\right\} + CIP$$

As the tariff fixed by ANEEL, taxes and public lighting rates may vary in all states and municipalities. The tariff ensure that distributors receive sufficient revenue to cover operational costs and investments required to expand capacity, as well as to ensure service compliance.

4. Data and Descriptive Statistics

Our empirical analysis is based on a cross-section of 5,563 municipalities entirely built from publicly available data and combining information from three sources: geolocation of consumer units with photovoltaic distributed generation and electricity tariff obtained from ANEEL; solar radiation from INPE (National Institute for Space Research), Laboratory of Modeling and Studies of Renewable Energy Resources (LABREN) and the Earth System Science Center (CCST); data for 2012 municipal Gross Domestic Product (in R$ 1,000) and population taken from Brazilian Institute for Geography and Statists (IBGE). Missing data for seven[8] municipalities impose a sample restriction, in 2017 there were 5,570 municipalities in the country total.

4.1. Photovoltaic Units and Electricity Tariff

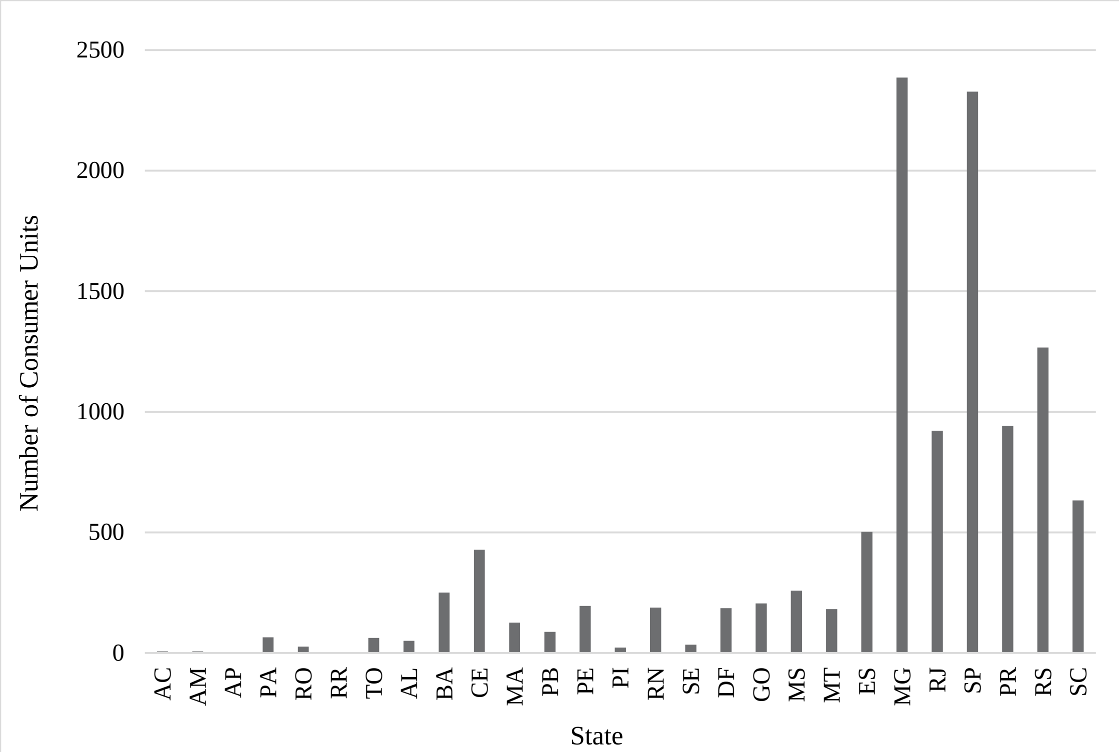
Information about all consumer units with distributed generation is available at the Superintendent of Generation Concessions and Authorizations from ANEEL. The data includes the owner's name, the class of consumption, the unit's location, and the energy source. This study refers to the information extracted on 30 June 2017. As of that date, only 1% of all units are not photovoltaic, i.e. wind, biomass and small hydro. From the photovoltaic consumers, 80% are residential and 15% are commercial units[9].

The number of consumer units with photovoltaic distributed generation varies considerably between states and municipalities. Only 1,478 have at least one unit, while the maximum number of units in the same municipality is 436 in Rio de Janeiro. Figure

[8] The municipalities removed from our database are Fernando de Noronha, Nazária, Pescaria Brava, Balneário Rincão, Mojuí dos Campos, Pinto Bandeira and Paraíso das Águas.
[9] The other 5% corresponds to public lighting, industry, rural and public service.

2 shows the number of PV units by state in June 2017 and most units are concentrated in states of South and Southeast regions, such as Minas Gerais (MG), São Paulo (SP) and Rio Grande do Sul (RS).

Figure 2 – Number of Consumer Units with Distributed Solar Photovoltaic Generation by State



Notes: Authors' elaboration based on data extracted on 30 June 2017 from ANEEL's website.

As stated before, electricity tariffs are regulated by ANEEL, who sets the price each distribution company may charge consumers in their concession areas. By looking at all ANEEL's tariff resolutions for each distributor, we concluded that, until that date, residential consumers (group B – low voltage – subgroup B1) were charged the same electricity price as consumers in the commercial class (subgroup B3). In this case, as 95% of our sample corresponds to those two subgroups, we based our analysis on the residential tariff.

We consider the distributor's average tariff, which corresponds to the distributor's total revenue obtained from energy supply divided by the total residential consumption in MWh. The average tariff including taxes (PIS, COFINS, and ICMS) – for March 2017 – was taken from ANEEL's Decision Support System. Since information about the electricity tariff applied in each municipality is not available, it was necessary to identify to which distributor's concession area a particular municipality belongs to and, based on that, obtain its corresponding tariff.

Information about the electricity distributors in each municipality was taken from ANEEL's Geographic Information System for the Electricity Sector (SIGEL) corresponding to the year of 2014. Since a distributor's concession area does not necessarily correspond to the municipality's limits, there may be more than one distributor in the same municipality. For this reason, SIGEL's dataset does not include three of the 63 concessionaires: Energisa Nova Friburgo Distribuidora de Energia S.A., Força e Luz Coronel Vivida Ltda., and Empresa de Força e Luz João Cesa Ltda. The concession areas of these companies are only part of a certain municipality.

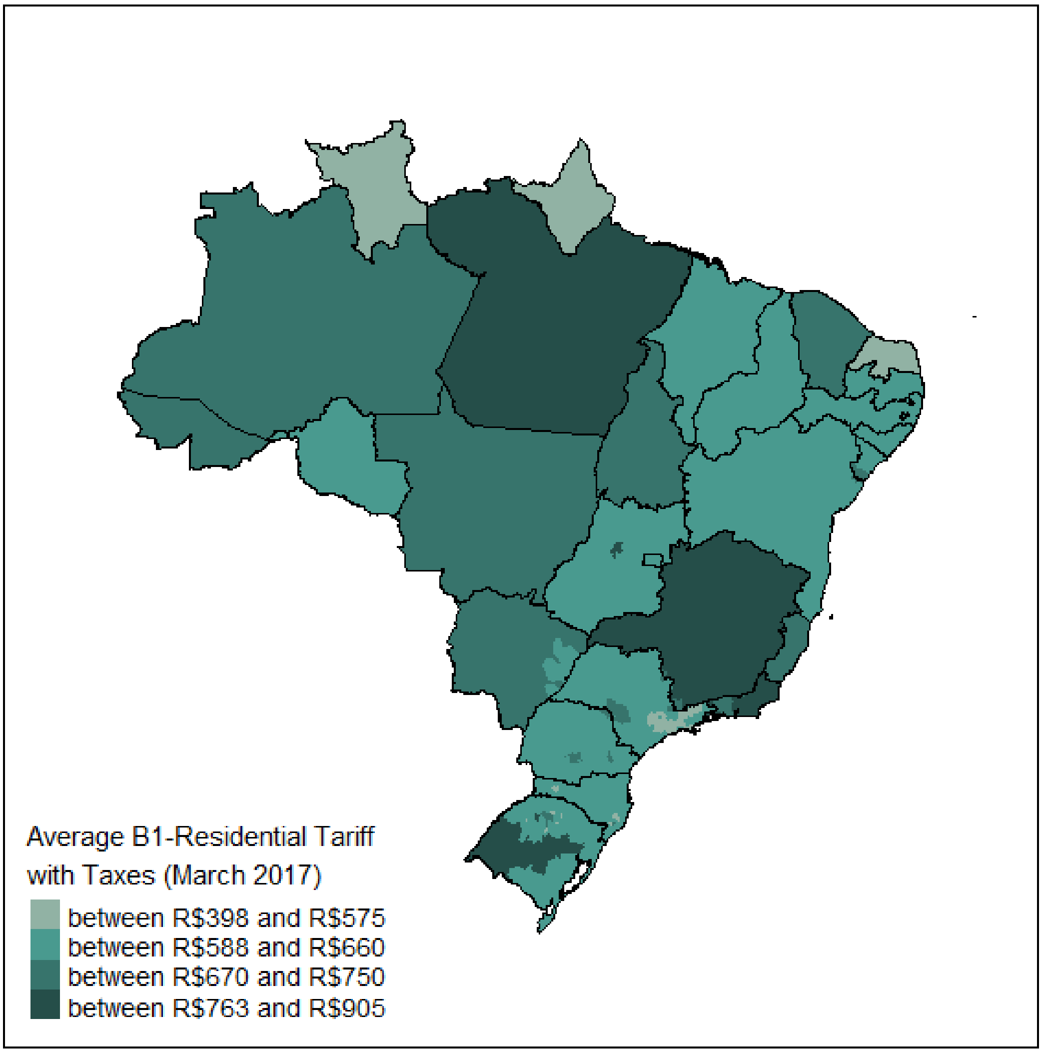
Also, the SIGEL´s database does not list the name of permissionaires. In 39 municipalities from the states of São Paulo, Santa Catarina, and Rio Grande do Sul, the distributors' names were not specified. The information for these municipalities was taken from ANEEL´s Performance Panel of the Electric Power Distributors by Municipality, which is an interactive tool that allows the consumer to verify the electricity supply in the municipality.

In total, the database has 70 distributors, of which 60 are concessionaires and 10 permissionaires (see Annex 1 for the list of distributors). The number of permissionaires included is lower than the total of 38 since their concession areas are usually smaller than the municipality's limits. In 17 Brazilian states there is only one distributor, in seven states there are two or three, and in São Paulo, Santa Catarina, and Rio Grande do Sul, there are several distribution companies.

Finally, since Companhia Energética de Roraima lost its concession area to Boa Vista Energia S.A. through ANEEL's Normative Resolution No.748, in November 2016, the electricity tariff in all Roraima's municipalities corresponds to Boa Vista Energia's.

Figure 3 shows the electricity tariff by municipality. The Northeast region has the lowest average tariffs, with the exception of Ceará, and a small part of Sergipe. On the other hand, municipalities facing the highest tariffs are located in the state of Rio Grande do Sul, followed by those in Minas Gerais, Rio de Janeiro, and Pará.

Figure 3 – Residential Electricity Tariff by Municipality



Notes: The map shows the average electricity tariff – total revenue in R$ divided by the total consumption in MWh – with taxes for residential consumers, subgroup B1, charged by the distributor in each municipality in Brazil during March 2017.
Source: ANEEL's Decision Support System and ANEEL's Geographic Information System for the Electricity Sector (SIGEL).

Part of this price variation is a result of public subsidies, which reduce the electricity tariff by discounting certain sectoral charges. This policy is applied in such a way that the sectorial charges in the Southeast region are larger than those in the Northeast. Consequently, consumers in these upper states pay electricity tariffs that are artificially lower, which, in its turn, reduces their incentives to invest in solar energy. Therefore, this policy is preventing the market for photovoltaic distributed generation to evolve in the Northeast states, which have great potential to reap its benefits.

4.2. Radiation

There are many factors that may influence a consumer's decision to adopt solar energy as a source of energy generation. When it comes to geographic characteristics, solar radiation is a major determinant of power output in PV systems, which are more efficient and have higher energy yields in areas with higher sunlight levels, representing a promising and clean alternative to the energy generation of countries with great solar resources (Makrides et al., 2010). For that reason, the municipality's solar potential must be considered when analyzing consumer decisions to install photovoltaic panels.

The analysis used the 2005-2015 data for Brazil's annual global horizontal solar radiation from the Laboratory of Modeling and Studies of Renewable Energy Resources (LABREN), the Earth System Science Center (CCST) and the National Institute for Space Research (INPE) – Brazil. The georeferenced data are measured in Wh/m^2/day – which were converted to kWh/m^2/day – and organized into cells with approximately 10km x 10km accuracy. In order to find the annual average radiation level in each municipality, that dataset was combined with a second georeferenced database for municipal perimeters in Brazil in 2007 available at IBGE. This allowed for the estimation of the solar radiation within the limits of each municipality and for the calculation of the mean value inside that area. The average annual solar radiation for the period of 2005 to 2015 in the country was 5.03 kWh/m^2/day, with the lowest value of 3.82 kWh/m^2/day found in Garuva, Santa Catarina and the highest of 6.04 kWh/m^2/day found in São José da Lagoa Tapada, Paraíba.

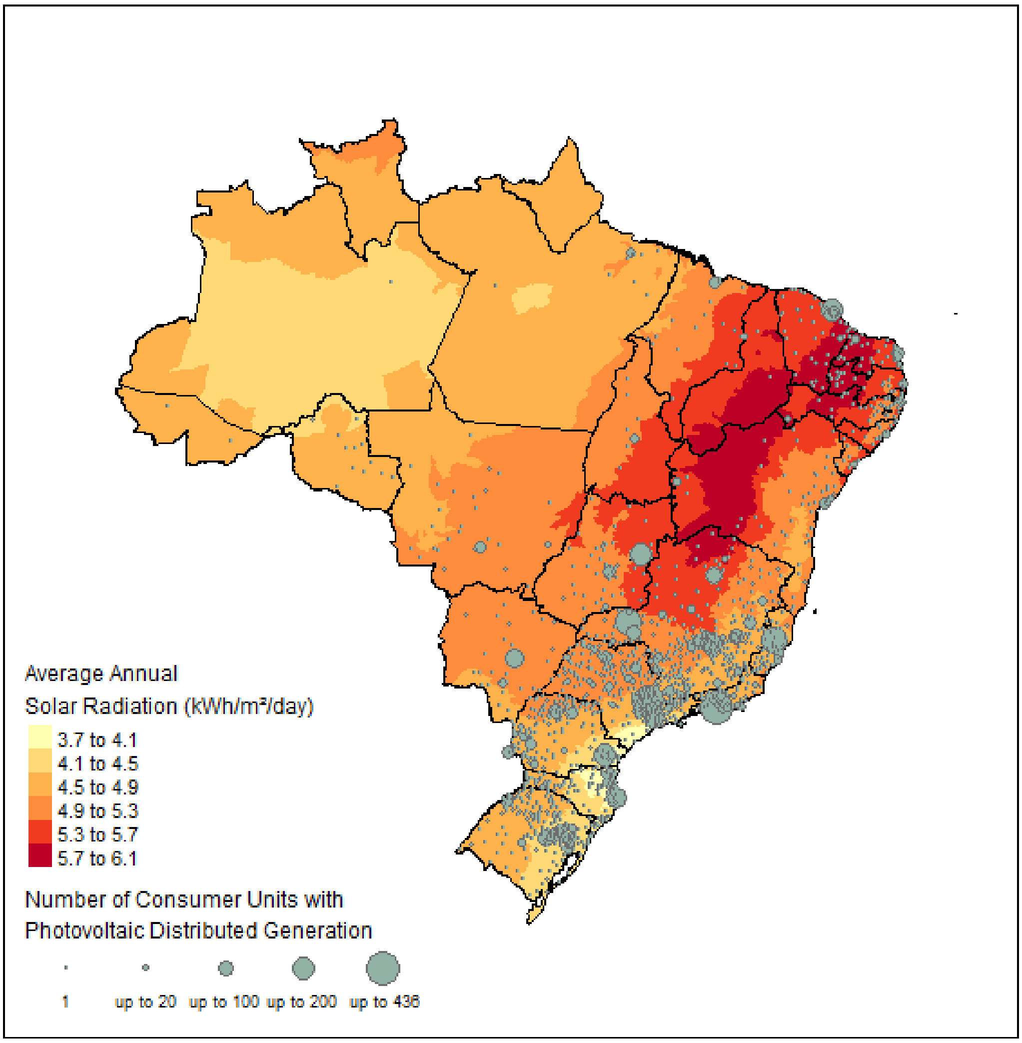
In the map of Figure 4, we plotted the municipal average annual solar radiation combined with the number of consumers with photovoltaic generation in each municipality.

At first, we can see that the areas with the greatest numbers of consumer units with distributed generation are not necessarily those with the highest levels of solar radiation. On the contrary, the map shows that PV units are mainly concentrated on the Southeast and South, in states such as Rio de Janeiro, São Paulo, Minas Gerais and Paraná. These are areas with minor solar potential when compared to the Center and Northeast regions, where most municipalities don't have consumer units with solar distributed generation.

This result indicates that, in Brazil, the supply of sunlight has a negative correlation with the number of consumer units with photovoltaic generation. The distribution of the number of consumer units with distributed PV generation seems to be related to aspects of demand and not only to the solar potential.

In the following sections, we examine the penetration of distributed solar photovoltaic generation in Brazil to assess the relative importance of supply and demand factors.

Figure 4 – Average Annual Solar Radiation and Consumer Units with Photovoltaic Distributed Generation per Municipality in Brazil



Notes: The map shows the number of consumer units with distributed solar photovoltaic generation per municipality in 30 June 2017, combined with the average annual solar radiation ($kWh/m^2/day$) in the municipality for the period of 2005-2015.
Data source: Superintendent of Generation Concessions and Authorizations (ANEEL); Laboratory of Modeling and Studies of Renewable Energy Resources (LABREN); Earth System Science Center (CCST); National Institute for Space Research (INPE) – Brazil.

4.3. Descriptive Statistics

Table 2 presents the averages, standard deviations, minimum and maximum of the variables used in the empirical analysis, which provide some important insights.

First, the mean number of consumer units with PV panels per municipality is about 2, with a significantly high standard deviation of 12.87 units. The occurrence of distributed generation throughout the territory is uneven since almost 80% of PV units are located in the South and Southeast Region. Secondly, there is a major variation in terms of municipal GDP, since the highest value corresponds to R$ 533 billion, while the lowest goes down to R$ 8,983,000. The same is true for the population size and annual average solar radiation. The average electricity tariff also changes considerably depending on the distribution company in each municipality.

Table 2 - Descriptive Statistics

Variable	Obs	Mean	Std.Dev	Min	Max
Number of PV units	5,563	2.04	12.87	0	436.00
Tariff	5,563	674.86	86.22	398.76	904.51
Radiation	5,563	5.03	0.45	3.82	6.04
GDP	5,563	863,894	8,798,431	8,983	533,000,000
Population	5,563	34,863	205,824	807	11,400,000

Notes: The table reports municipality-level means, standard deviations, minimum and maximum for the variables used in the empirical analysis. Units and sources: number of PV units (total number, ANEEL); Tariff (R$/MWh, ANEEL); Radiation (kWh/m^2/day, INPE and IBGE); GDP (R$ 1,000, IBGE); Population (total number, IBGE).

5. Main Results

5.1. Solar Radiation, Demand Factors, and PV Units

The impact of supply and demand factors on the number of consumer units with PV distributed generation is estimated in a given municipality. Since the outcome variable is a count variable, a log transformation of the dependent variable is not sufficient to overcome the major limitations of the linear model; in 73% of the municipalities, there is no installation of photovoltaic distributed generation.

Therefore, to accommodate the occurrence of zero values in the dependent variable, the inverse hyperbolic sine (IHS) transformation is applied. This symmetric function is linear around the origin and approximates the logarithm in its right tail. Specifically, the following IHS transformation is applied:

$Y_i = \sinh^{-1}(D_i) = \ln(D_i + \sqrt{(D_i{}^2 + 1)})$

where D_i is a count of consumers with photovoltaic generation in municipality i.

The estimation equation is given by regression:

$$Y_i = \alpha_1 + \beta_1\, lnRadiation_i + \beta_2\, lnGDP_i + \beta_3\, lnPOP_i + \beta_4\, lnTariff_i + \epsilon_i \quad (1)$$

where $lnRadiation_i$ is the log-transformation of the annual average solar radiation (kWh/m^2/day) in municipality i, $lnGDP_i$ is the logarithm of the Gross Domestic Product level (R$ 1,000) in municipality i, $lnPOP_i$ is the logarithm of the population of municipality i and $lnTariff_i$ is the logarithm of average tariff (R$/MWh) of the distributor operating in municipality i .

Everything else held constant, if solar radiation is augmented by 1%, the number of consumers increases by approximately $\beta_1\%$ in a given municipality according to equation 1.

Table 3 presents OLS coefficients for specifications that gradually include variables as follows: column 1 reports results for the regression including only the supply factor (solar radiation); column 2 adds GDP and population; and column 3 adds electricity tariffs. The table´s key result is captured in the progression of the R-squared along columns 1 and 2. The R-squared value for column 2, as well as for column 3 are relatively high, suggesting that the number of PV units is also explained by demand factors. In specifications of columns 2 and 3, an increase in the municipality-level solar radiation does not significantly affect the number of PV units. Results show that demand factors prevail as determinants of PV penetration. This effect is so relevant that municipalities with lower annual solar radiation have, on average, more consumer units with distributed solar photovoltaic generation.

Both population and GDP positively affect the number of PV units in municipalities. The larger the population in the municipality, the larger the number of consumer units and thus, the larger the number of consumer units with photovoltaic panels. The higher the income of municipalities, the larger the number of consumers with resources to invest in the installation of panels and then, the larger the number of units with distributed generation. The tariff coefficient is positive and significant at a 1%

significance level. The higher the electricity tariff in the municipality, the greater the incentive to invest in photovoltaic panels to generate power. Thus, demand factors such as income, population, and electricity tariff positively affect the number of PV units in Brazil.

Table 3 − OLS Regressions: Effect of Supply and Demand Factors on Number of Consumer Units with Distributed Solar Photovoltaic Generation

	IHS transformation of the number of PV units			
	(1)	(2)	(3)	(4)
lnRadiation	-1.868***	-0.0802	-0.0329	0.897***
	(0.141)	(0.123)	(0.123)	(0.202)
lnPOP		0.0453**	0.0404**	0.308***
		(0.0203)	(0.0204)	(0.0288)
lnGDP		0.439***	0.445***	0.275***
		(0.0186)	(0.0188)	(0.0233)
lnTariff			0.703***	
			(0.0822)	
Observations	5,563	5,563	5,563	5,563
R-squared	0.030	0.476	0.484	0.558
Distributor fixed effect	No	No	No	Yes
Number of distributors				70

Notes: Coefficients are estimated using a cross section of 5,563 municipalities. The dependent variable is the IHS transformation of the number of PV units at the municipal level. Column 1 presents OLS coefficients for a specification including only the solar radiation as independent variable; column 2 adds the logarithm of the Gross Domestic Product level and the logarithm of the population; and column 3 adds the logarithm of the average tariff. Column 4 includes the distributor fixed effect. Robust standard errors in parenthesis; constant omitted. Significance: *** p<0.01, ** p<0.05, * p<0.10.

5.2. Solar Radiation and PV Units inside the Distributor´s Area

The proliferation of distributed generation transforms the delivery of electricity services and the use and management of distribution systems in many jurisdictions. Distributed generation introduces bidirectional power flows and, at significant penetration levels, entails profound changes to the real-time operation of distribution systems. Distribution companies may need to make substantial investments to accommodate increased penetration of distributed generation. These investments enhance the benefits of distributed generation such as optimizing resources, increasing efficiency, and bringing new possibilities for services to be made available to the consumer.

In Brazil, some distributors stimulate distributed generation in their concession area and already have the perspective of changing the role of the electricity distribution company. Contrarily, other companies do not stimulate the proliferation of PV units since this will lead to a reduction in the volume of energy consumed, decreasing their revenue.

Therefore, distributors affect the number of consumer units with distributed generation not only via the electricity tariff. To capture this relationship, the impact of solar radiation on PV units within the distributor area in a given municipality is estimated.

The estimation equation is given by regression:

$$Y_i = \alpha_2 + \beta_5 \, lnRadiation_i + \beta_6 \, lnGDP_i + \beta_7 \, lnPOP_i + \beta_8 \, \gamma_c + \varepsilon_i \quad (2)$$

where Y_i is the IHS transformation of the number of consumers with photovoltaic generation in municipality i; $lnRadiation_i$ is the log-transformation of the annual average solar radiation (kWh/m^2/day) in municipality i, $lnGDP_i$ is the logarithm of the Gross Domestic Product level (R$ 1,000) in municipality i, $lnPOP_i$ is the logarithm of the population of municipality i, and γ_c is a distributor fixed effect.

Everything held constant, if solar radiation is augmented by 1%, the number of consumers increases by approximately $\beta_5\%$ in a given municipality within the distributor area according to equation 2.

Column 4 of Table 3 presents the estimated results for equation 2. The inclusion of distributors′ fixed effects mitigates differences across their incentive policies. The result shows that higher solar radiation will significantly increase the number of consumer units with photovoltaic distributed generation in a certain municipality within the distributor area. A 10% increase in the annual average radiation level increases the number of PV units by approximately 9%.

The results indicate that, when the characteristics of electricity distribution companies are considered, and thus the commercial policies of those companies, the radiation positively affects the number of consumers in the municipality.

5.3. Counterfactual Simulation

The adoption of photovoltaic distributed generation reflects differences in tariffs along the Brazilian territory. To better understand the tariff effect in the number of PV units, a counterfactual simulation was conducted to estimate the total number of consumer units with photovoltaic distributed generation per municipality in a hypothetical scenario where all municipalities have the same tariff, equal to the Brazilian average tariff.

Equation 3 calculates the difference between the estimated number of consumers with photovoltaic generation in municipality i and the estimated number of PV units considering the same tariff in all municipalities.

$$\widehat{D}_i - \widehat{D}_i' = sinh\left(\widehat{Y}_i\right) - sinh(\widehat{Y_i'}) \quad (3)$$

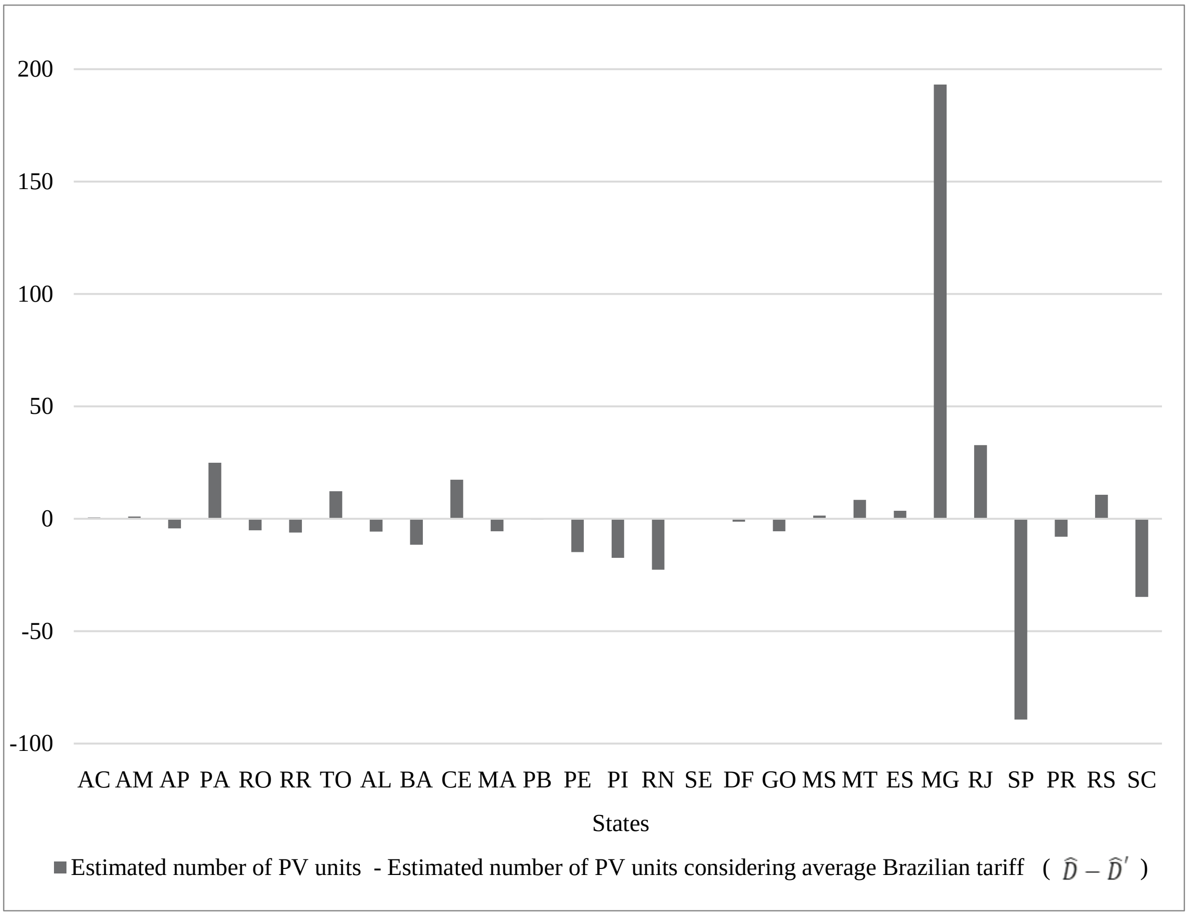
Where $\widehat{Y}_i = \hat{\alpha}_1 + \hat{\beta}_1\, lnRadiation_i + \hat{\beta}_2\, lnGDP_i + \hat{\beta}_3\, lnPOP_i + \hat{\beta}_4\, lnTariff_i$ and

$\widehat{Y_i'} = \hat{\alpha}_1 + \hat{\beta}_1\, lnRadiation_i + \hat{\beta}_2\, lnGDP_i + \hat{\beta}_3\, lnPOP_i + \hat{\gamma}_4\, ln\overline{Tariff}$

where $lnRadiation_i$ is the log-transformation of the annual average solar radiation (kWh/m^2/day) in municipality i, $lnGDP_i$ is the logarithm of the Gross Domestic Product level (R$ 1,000) in municipality i, $lnPOP_i$ is the logarithm of the population of municipality i, $lnTariff_i$ is the logarithm of average tariff (R$/MWh) of the distributor operating in municipality i , and $ln\overline{Tariff}$ is the logarithm of Brazilian average tariff (R$/MWh).

As presented before, higher energy tariffs have a positive effect on consumers' decision to install solar panels. This analysis allows us to cancel the redistributive effect of the energy tariff on PV penetration. Figure 4 shows that in states like Minas Gerais, which has the second most expensive energy price for residential consumers in Brazil, the estimated number of photovoltaic units would be reduced since the average Brazilian tariff is lower than the one actually practiced in the state. The opposite occurs with São Paulo, where the estimated number of consumers with PV would be higher considering the estimation with the average Brazilian tariff. This is also the case for the states in Northeast – with the exception of Ceará. Their negative values confirm the idea that the number of PV units in these localities is reduced by the artificially low electricity tariffs practiced in the region.

Figure 4 – Estimated Number of PV Units Vs. Estimated Number of PV Units Considering the Same Tariff – by State



Notes: Counterfactual simulation is conducted using the sample, specifications and estimated coefficients from column 3 of Table 3. Estimated number of PV units considering the same tariff is obtained by replacing the tariff applied in each municipality by the calculated average Brazilian tariff (R$ 660.1765).

6. Final Comments

Our results show that demand-side factors played a crucial role in PV penetration, thereby increasing non-hydro renewable participation in the Brazilian power matrix, as well as containing greenhouse gas emissions. This effect is so relevant that solar radiation is negatively correlated with PV adoption. This is the reason why over half of PV units in Brazil are located in the Southeast Region, which is richer, more populated, and has a higher average tariff than other regions of Brazil.

Solar radiation only appears as positively correlated with PV adoption when comparing municipalities within the same concession area, and thus the commercial policies of those electricity distribution companies. Considering the characteristics of the distributor and the municipality's income and population size, the radiation has, on average, a positive effect on the number of PV units. Indeed, distributors affect the number of PV units not only via the electricity tariff but also by providing incentives for the entry of distributed generation units in its concession area.

Our findings yield important policy implications. First, the design of renewables policies aimed at climate risk mitigation should target demand-side factors in addition to supply-side availability of natural resources. In particular, frictions caused within the system of tariffs might have important consequences for the penetration of PV. Additionally, the abundance of the physical potential can be used for specific economic development strategies since it is possible to stimulate sustainable economic development investing in PV installation.

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ANNEX 1. – Distributors (Type C – Concessionaire and type P – Permissionaire)

Name	Full Name	State	Type
AES Sul	Rge Sul Distribuidora de Energia S.A.	RS	C
AmE	Amazonas Distribuidora de Energia S.A.	AM	C
Ampla	Enel Distribuição Rio	RJ	C
Bandeirante	Bandeirante Energia	SP	C
Boa Vista	Boa Vista Energia S/A	RR	C
Caiuá	Caiuá Distribuição de Energia S.A.	SP	C
CEA	Companhia de Eletricidade do Amapá	AP	C
Ceal	Eletrobras Distribuição Alagoas	AL	C
CEB-DIS	Companhia Energética de Brasília	DF	C
CEEE-D	Companhia Estadual de Distribuição de Energia Elétrica	RS	C
Celesc-DIS	Celesc Distribuição S.A.	SC	C
Celg-D	Celg Distribuição	GO	C
Celpa	Centrais Elétricas do Pará	PA	C
Celpe	Companhia Energética de Pernambuco	PE	C
Cemar	Companhia Energética do Maranhão	MA	C
Cemig-D	Companhia Energética de Minas Gerais S.A.	MG	C
Cepisa	Eletrobras Distribuição Piauí	PI	C
Ceron	Centrais Elétricas de Rondônia	RO	C
CERR	Companhia Energética de Roraima	RR	C
CFLO	Companhia Força e Luz do Oeste	PR	C
CHESP	Companhia Hidroelétrica São Patricio	GO	C
CNEE	Companhia Nacional de Energia Elétrica	SP	C
Cocel	Companhia Campolarguense de Energia	PR	C
Coelba	Companhia de Eletricidade do Estado da Bahia	BA	C
Coelce	Enel Distribuição Ceará	CE	C
Cooperaliança	Cooperativa Aliança	SC	C
Cosern	Companhia Energética do Rio Grande do Norte	RN	C
Copel-DIS	Companhia Paranaense de Energia	PR	C
CPFL Jaguari	Companhia Jaguari de Energia	SP	C
CPFL Leste Paulista	Companhia Leste Paulista de Energia Elétrica	SP	C
CPFL Mococa	Companhia Luz e Força de Mococa	SP	C
CPFL Paulista	Companhia Paulista de Força e Luz	SP	C
CPFL Piratininga	Companhia Piratininga de Força e Luz	SP	C
CPFL Santa Cruz	Companhia Luz e Forca Santa Cruz	SP	C
CPFL Sul Paulista	Companhia Sul Paulista de Energia Elétrica	SP	C
Demei	Departamento Municipal de Energia de Ijuí	RS	C
DMED	DME Distribuição S.A	MG	C
EBO	Energisa Borborema- Distribuidora de Energia S.A	PB	C
EDEVP	Empresa de Distribuição de Energia Vale Paraanpanema S.A	SP	C
EEB	Empresa Elétrica de Bragantina S.A.	SP	C
Eflul	Empresa de Força e Luz de Urussanga Ltda.	SC	C
Elektro	Elektro Eletricidade e Serviços S/A	SP	C
Eletroacre	Eletrobras Distribuição Acre	AC	C
Eletrocar	Centrais Elétricas de Carazinho	RS	C
Eletropaulo	Eletropaulo Metropolitana Eletricidade de São Paulo S/A	SP	C
ELFSM	Empresa Luz e Força Santa Maria SA	ES	C
EMG	Energisa Minas Gerais-Distribuidora de Energia S.A.	MG	C
SEM	Energisa Mato Grosso Do Sul-Distribuidora de Energia S.A.	MS	C
EMT	Energisa Mato Grosso-Distribuidora de Energia S.A.	MT	C
EPB	Energisa Paraiba - Distribuidora de Energia Elétrica S.A	PB	C
Escelsa	Espirito Santo Centrais Elétricas S. A	ES	C
ESE	Energisa Sergipe - Distribuidora de Energia Elétrica S.A	SE	C
ETO	Energisa Tocantins Distribuidora de Energia S.A	TO	C
Hidropan	Hidroelétrica Panambi S.A.	RS	C
Ienergia	Iguaçu Distribuidora de Energia Elétrica LTDA	SC	C
Light	Light S.A.	RJ	C
MuxEnergia	Muxfeldt Marin & CIA. LTDA	RS	C
RGE	Rio Grande Energia S.A.	RS	C
Sulgipe	Companhia Sul Sergipiana de Eletricidade	SE	C
Uhenpal	Usina Hidroelétrica Nova Palma LTDA	RS	C
Ceprag	Cooperativa de Eletricidade Praia Grande	SC	P
Ceral Anitápolis	Cooperativa de Distribuição de Energia Elétrica de Anitápolis	SC	P
Cerbranorte	Cooperativa de Eletrificação Braço do Norte	SC	P
Ceriluz	Cooperativa Regional de Energia e Desenvolvimento Ijui Ltda	RS	P
Cerpalo	Cooperativa de Eletricidade de Paulo Lopes	SC	P
Cerpro	Cooperativa de Eletrificação Rural da Região de Promissão Ltda	SP	P
Cersul	Cooperativa de Eletrificação Sul Catarinense	SC	P
Coopercocal	Cooperativa Energética Cocal	SC	P
Coprel	Coprel Cooperativa de Energia	RS	P
Creluz-D	Cooperativa de Distribuição de Energia	SC	P