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Abstract

Among the major challenges for the power systems of the future, one may find the arise of a new approach of electricity production - the Distributed Generation (DG) systems - and photovoltaics (PV) is the main technology for this new approach. In this scenario, a new electricity market agent appeared - the prosumer - consumers that can also produce their own energy. The retail price is one of the main factors that encourages PV systems adoption under a net metering scheme. The present work shows an investigation on the influence of regulated electricity tariffs as volumetric charges structure on the residential DG PV systems adoption in a developing country context. I use a panel data from 2013-2017 with 5570 municipalities in Brazil, having as response variable the number of new PV installations and as explanatory variable the electricity tariffs among 105 different distribution companies. The results imply that for each one BRL cent of tariff increase, there will be an expansion of about 5.3% in new residential PV projects in the following year.

Keywords: distributed generation, prosumer, residential PV adoption, net metering, volumetric electricity tariffs, panel data.

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1 Introduction

Electricity systems are facing big changes around the globe. The traditional vertically integrated system - with generation, transmission, distribution and supply - is giving more and more space to a smarter, organic and low-carbon one. Renewables, greater energy efficiency and the transport electrification and other sectors have been gaining much more relevance throughout the years. Besides, a new electricity production approach is arising progressively, the Distributed Generation (DG) systems. A precise definition of the term is complex to set, because it depends on the electricity market of each country. However, in a broader sense, DG might be set as small-scale systems, connected to the distribution networks and based on low-carbon electricity generation technologies.

According to IEA (2019), solar PV and wind account for 70% of global power capacity expansion through 2024, in which about the half of Solar PV expansion will be distributed. The increase of energy conversion efficiency, leading the falling costs of PV technology around the globe, and its intrinsic modular feature, allowing the project customization from huge centralized plants to distributed household-scale ones with the same PV modules, may be one of the main reasons. Although, IEA (2019) states that commercial and industrial applications drive distributed PV expansion globally, the growth of residential distributed PV will be also significant.

With the development of DG systems, residential electricity consumers - the main focus of this paper - start, not only to import electricity from the grid, but also to export to it, presenting a bidirectional flow. From this configuration, a new agent arose in electricity markets - the prosumer - a consumer who also produces electricity. In fact, whenever the prosumer presents a lack of production in relation to its consumption, it counts on the distribution company's (disco) networks to supply its electricity demand. Contrariwise, if there is a surplus, the prosumer counts on the disco's grid to inject its excess of electricity into it.

In spite of being associated as an intrinsic feature of the future of power systems, DG is a disruptive concept in electricity markets around the globe. It affects negatively the actual distribution sector's business model, since, concerning residential customers, utilities obtain their revenues, generally, through volumetric structured electricity rates to cover the high distribution networks fixed costs. DG expansion presents, then, at least, a twofold impact on discos. Borenstein and Bushnell (2015) state that, firstly, it reduces the energy consumed from the grid due to self-production, shrinking discos' revenues. Secondly, IEA-RETD (2014) adds that it is related to the lack of synchronization of DG PV systems production and the unit's consumption, which will increase the investments realized on the adaptation of the current distribution networks structure to receive a bidirectional energy flow. As a consequence, discos are forced to increase tariffs in order to cover fixed investments, in turn making PV advantageous for more customers who, then, reduce their purchases, leading to a greater revenue deficit and another rate raise, and restarting the cycle. A third point may be added in the case of developing countries with high rates of social inequality as Brazil. The raise of electricity rates may also lead to an increase in the disco's risk of customer default. This scenario affects the social optimum, ending up on the "death spiral" phenomena in the words of Costello and Hemphill (2014).

Residential customers present the highest potential to contribute to the previously mentioned outline. It happens due to the lack of synchronization between prosumer's consumption and production combined with a volumetric tariff structure under a net metering scheme. Gautier et al. (2018) state that less than 30% of the electricity produced is self-consumed in households and the largest part of their production is exported to the grid. Moreover, generally, the number of residential electricity consumption units and their diffusion throughout disco's exploitation area tends to be, relatively, higher compared to commercial/industrial units in electricity markets around the globe. Therefore, industrial/commercial units might present higher loads and, consequently, larger DG systems, however, they are concentrated causing local impacts on disco's grid. Instead, residential units loads are smaller needing more reduced DG systems, but they are more spread, increasing the disco's O&M logistics costs.

Menz and Vachon (2006) and Carley (2009) are among the first authors to analyse empirically the drivers behind the rise of renewable energy sources in electricity systems. Nonetheless, just recently the interests in DG PV systems became the theme of research articles. For instance, Vasseur and Kemp (2015) and De Groote et al. (2016) investigated the numerous aspects instigating PV adoption. Two affaires were more explored adopting residential level or higher as such as municipality or supra-municipality (county or utility). Initially, Bollinger and Gillingham (2012); Müller and Rode (2013); Graziano and Gillingham (2015); Rode and Weber (2016) have examined the importance of social drivers on the spread of residential PV. Like in the article Allan and McIntyre (2017), in which the authors have applied spatial econometrics techniques to investigate and ratify the occurrence of peer effect in PV adoption using a dataset from Great Britain in a municipality-level. At last, authors as Hughes and Podolefsky (2015) and Crago and Chernyakhovskiy (2017) have examined the performance of policy incentives like upfront rebates, tax exemptions, tax credits or policies such as renewable portfolio standards.

Pricing power exchanges between DG and the grid depends on the incentive schemes in place at the electricity market target. This then affects straightly on the financial return of a DG system adoption, which is influenced by both pricing structure and the price level as discussed in Gautier et al. (2018) and Brown and Sappington (2017). Therefore, one might witness more total DG projects in those locations where there is a higher return on investment.

Papers containing estimations on the significance of electricity rates in households PV capacity deployment are scarce. Gautier and Jacqmin (2020) investigated the impact of the distribution tariffs on the residential PV systems adoption under net metering extending their analysis in Wallonia, the francophone Belgian region. Using a panel structured data in a municipality level of aggregation, containing 256 municipalities and 13 different discos, they showed that municipalities where the distribution tariffs are higher experience a larger deployment of residential DG PV systems.

Brazil presents a great solar market potential. Concerning the natural resources, the country presents values from 3 to 6 kWh/m^2/day of direct normal irradiation according to The World Bank Group (2016). Those numbers can stimulate not only DG PV systems investors, but also those interested on utility scale plants. Taking into consideration the electricity customer potential, Brazil is composed by 5570 municipalities distributed through 26 states and the Federal District composes the country. Besides, 105 discos are responsible for the electricity supply of more than 80 million consumption unities, in which about 75% are residential. Those numbers reflect the potential and the importance to carry on empirical studies concerning the Brazilian residential DG PV market.

The majority of the literature on the effectiveness of the net metering scheme in the Brazilian residential DG PV market relies on exploratory analyses and case studies (see in Mitscher and Rüther (2012); Jannuzzi and de Melo (2013); Holdermann et al. (2014); Pinto et al. (2016); Vale et al. (2017); Gomes et al. (2018); Pillot et al. (2018)). Qualitative interviews with professionals of the electricity sector are carried on in Garlet et al. (2019), exploring barriers that compromise greater diffusion of DG PV in the Southern region of Brazil. In Garcez (2017) a state-level cross-section OLS model is used to explain the total number of residential PV systems having ICMS tax (sort of Brazilian VAT) exemption on exported energy to the grid, electricity rates and population as independent variables.

This paper provides an investigation of how electricity tariffs structured as regulated volumetric charges encourages residential DG PV expansion under a net metering mechanism. A similar analysis was carried out by Gautier and Jacqmin (2020) who focused their study on the distribution tariffs only. The main contributions of this paper are threefold. Firstly, Brazil presents about 22 times more municipalities and its disco market is 10 times bigger than Walloon region, which will present more heterogeneity in the analysis and consistency on results due to a 10 times larger dataset. Secondly, the Walloon residential DG PV market is much more auspicious than the Brazilian one, because it counted not only on a net metering scheme, but also on up front subsidies and a generous tradable green certificate mechanism resulting in a scenario where about 10% of households installed PV systems up to 2016. Lastly, this is the first time a paper investigates how the retail price affects residential PV adoption in such disaggregated level out of the US-EU axis, contributing to the empirical literature on renewable energy growth in developing countries.

The remainder of the article is structured as follows. Section 2 sets the background to understand the residential DG PV Brazilian market. Section 3 describes the dataset used. Section 4 establishes the methodology to examine the drivers on residential DG PV adoption in Brazil. Section 5 presents and discuss the empirical findings. Section 6 concludes.

2 Background

2.1 The Electricity Tariff Structure in Brazil

Until the middle of the 90s, the Brazilian electricty sector was characterized by the centralized planning of the operation and expansion of the electric power system, as well as by the vertical integration of, generation, transmission, distribution and commercialization activities controlled by state-owned companies. In the 90's the Brazilian government started an important market-oriented reform with a privatization process of state-owned companies. Private companies competed through bidding process to firm concession contract with the State for the right to exploit an electricity distribution area under technical and economic rules for the concessionaires. Electricity tariffs would no longer be the same throughout all over the country and "price-cap" replaced "cost-of-service" by a regulatory regime for all discos Almeida and Junior (2001).

Brazil is composed by 5570 municipalities, distributed among 26 states and the Federal District. To characterize the importance of the residential consumption in the electricity market, there are more than 80 million consumption unities in which 75% are residential. ANEEL (National Electric Energy Agency) is the regulation authority responsible for the electricity sector in Brazil. Most of the states presents a unique disco responsible for the electricity supply and distribution system operation, excepting some southern states that may present many discos. The Brazilian disco market share is composed by 105 enterprises[1] and each of them presents its own electricity tariff for residential consumers. Figure 1 shows the boxplot of the evolution of the residential electricity tariff in Brazil while Figure 2 shows the main discos' exploitation area.

According to ANEEL (2008), the electricity tariff aims to ensure that service providers have sufficient revenue to cover efficient operating costs and to remunerate the investments needed to expand capacity and ensure quality service. Therefore, distribution concession contracts foresee three mechanisms of tariff update: Annual Tariff Readjustment (RTA), Periodic Tariff Review (RTP) and Extraordi-

[1]among distribution concessionaire, permissionaire and authorized companies according to data from ANEEL

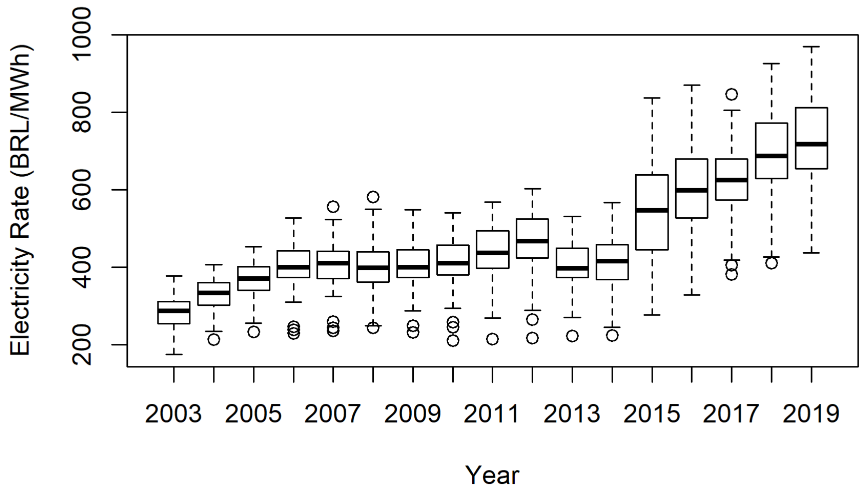

Figure 1: Boxplot of the evolution of the residential electricity tariff in Brazil (2003-2019). Current Prices.

nary Tariff Review (RTE). RTA happens annually on the anniversary date of the contract, except when RTP occurs, and aims to restore the purchasing power of the concessionaire's revenue, according to a formula established in the contract. It passes on the disco's non-manageable costs and updating the manageable costs by the inflation index less an efficiency coefficient. RTP allows the repositioning of the tariff after complete analysis of efficient costs and remuneration of prudent investments, at intervals of four or five years. This mechanism differs from RTA in that it is broader and takes into account all manageable costs, investments and revenues in order to set a new tariff level appropriate to the structure of the company and its market. RTE, on the other hand, is intended to address very special cases of justified imbalance. It can occur at any time, when an unforeseeable event affects the economic-financial balance of the concession.

The Brazilian electricity sector presents two types of consumers: free consumers, who can choose from whom to purchase electricity among several retailers; and captive consumers who are obliged to purchase their electricity from the local disco. Among the captive, one may separate them between high-voltage (HV) and low-voltage (LV) consumers. The former might be distinguished among voltage ranges and each one presents a certain tariff, based on time-of-use, load and volumetric charges structures. The latter shows two types of tariffs in which the consumer can choose: a time-of-use volumetric and an average volumetric structures. Still, they are subdivided among residential, rural, industrial and commercial consumers and each of them has a specific tariff. The great majority of residential consumers chooses the average volumetric tariffs, due to its advantages concerning the consumer profile throughout the day. There are still social subsided tariffs, but they are excluded from the analysis. In Brazil, LV consumers presents a minimum consumption depending on the type of private grid connexion.

Figure 2: Map of Brazilian main discos

2.2 Support to DG systems based on PV in Brazil

The year of 2012 was a milestone for the development of DG in Brazil and its outcome may be, when ANEEL homologated the normative resolution 482 on April 17th, which was revised several times until the current format [2]. The final normative resolution allowed prosumers to connect their DG systems to the distribution networks. It defined and set the premises for the use of distributed micro-generation (installed capacity not exceeding 75 kW) and distributed mini-generation (installed capacity greater than 75 kW and less than or equal to 5 MW) based on renewable energy resources as: small hydro, solar, wind, biomass and qualified cogeneration, henceforth considered as DG. Besides, the resolution also adopted the net metering incentive mechanism with some specific characteristics. It works in the following way, whenever the prosumer has an energy surplus, the excess is exported to the grid and stored in a sort of virtual energy bank as an energy credit. Whenever the prosumer has a lack of energy production in relation to her consumption, she may have access to the energy stored virtually and use to reduce her electricity bill. The energy credits stored in a maximum rolling period of 60 months.

There are four modalities to take advantage of DG under net metering according to the resolution 482. *Enterprise with Multiple Consumption Units* is the modality applied to buildings with several residents that share a common area that can be exploited for energy generation with DG systems. Next, in *Shared Generation*, person and/or corporate entities may gather as consortiums or cooperatives and build a DG systems in order to take advantage of net metering. Residents may install a DG systems to reduce the electricity bill of the residential unit where they live as *Generation in the Consumption Unit* or include other residential units

[2]the normative resolution 482/2012 was revised by the following normative resolutions 517/2012, 687/2015 and 786/2017

to receive the energy credits as a *Remote Self-consumption* modality, only if those units are registered under the same taxpayer registry number and under the same distribution zone. This last modality may serve, for instance, for someone who lives in a urban area in an apartment that does not have a physical space for a DG system installation, but also owns a vacation house with a rooftop. Therefore, this person may install a PV in her vacation house and also register her apartment to reduce the electricity bill in both consumption units. The two lasts modalities are the focus of this study, because they present the great majority of residential DG PV systems in Brazil, so that the other modalities are excluded from the analysis.

The outcome of the NR 482 implementation and its revisions may be seen in Figure 3, in which by the end of 2019, Brazil presented almost 100 000 households with installed PV.

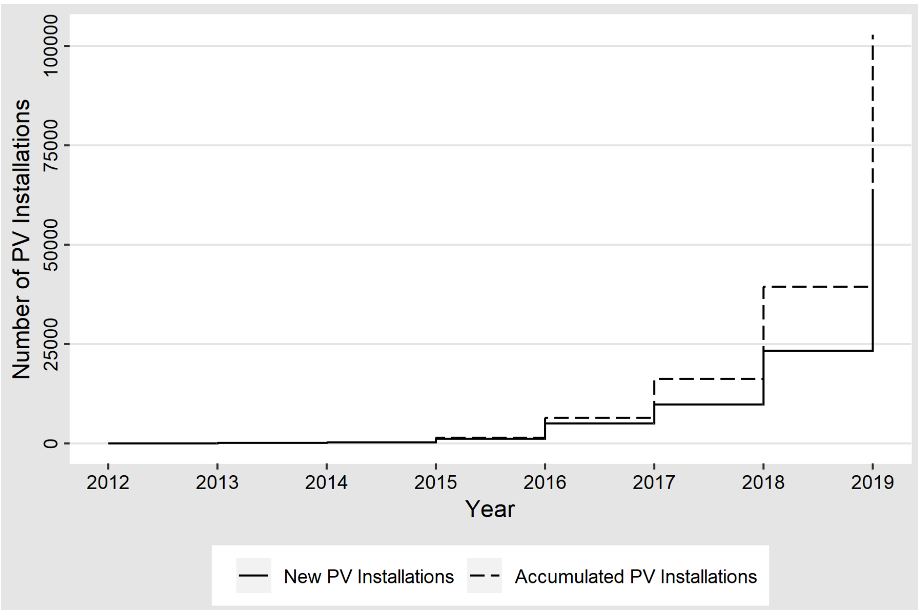

Figure 3: New and accumulated residential PV projects in Brazil (2012-2019)

3 Data

ANEEL collects the following information for each of the DG projects registered under the normative resolution 482/2012 in their public database: location (municipality and state), technology type, installed capacity and name of project developer ANEEL (2019b). Registration to the regulator is compulsory to be eligible for the net metering incentive scheme. Since the present paper is designed to estimate the demand for households DG PV systems in Brazil, I extracted the information for this purpose. From this dataset, four dependent variables are created in the municipality-level for each year: number of new *PV projects*, aggregated PV *capacity* (in kW), the number of new *credited units*[3] and the *average capacity.* The main reason for this is that all of the control variables used in the present work are only available at the municipality/year level. ANEEL also makes available the explanatory variable used in this paper *tariff* (Real prices, reference 2017). It is the final electricity rate (BRL cents/kWh) paid by households including all the relevant taxes applied in Brazil. One might expect that the more the electricity costumers pay for electricity in a given municipality and year, the more PV installations will be observed (Gautier and Jacqmin (2020); De Groote et al. (2016); Kwan (2012)). I excluded social tariffs for low-income households from the analysis, because it is a subsided tariff and those who will invest on a PV system might have a higher incomes (Gautier and Jacqmin (2020); Kwan (2012)).

Another important variable included in the analysis, *installation cost per unit* (BRL/Wp; real prices, reference 2017) for DG PV systems is obtained from IDEAL Institute and their reports on The Brazilian Distributed Generation PV Market IDEAL and AHK-RJ (2018, 2017, 2016, 2015). It is used for the sake of sensitivity as it is available just in the country-level of aggregation. It is expected that as the

[3]new *credited units* is the sum of new PV projects and other registered units concerning the remote self-consumption modality

installation costs fall, more DG PV systems will be installed.

A raster file containing the long-term yearly average of daily potential PV electricity production in Brazil from was downloaded from the World Bank Group to be included in the analysis. Further refinements are realized to build the final panel dataset. From the PV production potential raster file, I converted it into a shapefile in which each pixel became a point containing the PV production potential information. After that, I extracted the points containing in each municipality extension and obtained the average of all points to extract the municipalities' average PV production potential and form *PV output* (kWh/kW) as another important variable for the analysis. It is also used for the sake of sensitivity, as it does not varies through the years. Previous studies do not share the same conclusions regarding the impact of solar potential on PV adoption. For instance, Kwan (2012) finds statistically significance and a positive impact of insolation on residential PV adoption, following the common sense. On the other hand, Garcez (2017) states the contrary, rectifying that there are other variables that are more important on PV adoption. A possible explanation for this outcome is the level of aggregation between the studies, in which the former used the ZIP code level and the latter the state level.

The rest of data is extracted from the SIDRA system (IBGE (2020)) of the Brazilian Institute of Geography and Statistics (IBGE) to use as control variables. The institute makes available annual data from 5570 municipalities through several surveys from which we obtained data over the 2013-2017 sample period. The analysis starts in 2013 because the net metering scheme in Brazil became valid in this year and there were almost none installed PV systems before. The analysis is finished in 2017 because is the last year available for the data. As stated by Gautier and Jacqmin (2020); De Groote et al. (2016); Kwan (2012), it is expected that municipalities with wealthier population will present more investments in

PV systems. In order to capture this effect, *GDP per Habitant* (thousands of BRL/hab.; real prices, reference 2017) was included in the regressions. Besides, I extracted *population* for each municipality from IBGE. Also considered in Gautier and Jacqmin (2020), I expect that the more inhabitants, the higher the demand and, as a consequence, the more PV installations. Lastly, the municipalities' area of extension (km^2) was used to calculate the *pop. density*. De Groote et al. (2016) point that one may expect that the quantity of open space raises the possibility to capture sunlight, which should have a positive impact on the number of PV installations. Kwan (2012) uses an analogous variable by considering housing density.

It is worthy to note the following. Municipalities belonging to more than one disco zone are excluded from the analysis, because it is complex to identify the discos' intra-municipality frontier. Besides, other municipalities did not present observations of the variables used in the analysis. Therefore, the regressions were done on 4599 municipalities ending up in 22,995 municipality/year observations. The Table 1 shows the descriptive statistics.

Table 1: Descriptive statistics

	N	Mean	St. Dev.	Min	Pctl(25)	Median	Pctl(75)	Max
Dependent Variables								
# New PV Projects	22,995	0.5	5.7	0	0	0	0	475
# of New Credited Units	22,995	0.9	18.7	0	0	0	0	1,520
Capacity	22,995	4.7	83.6	0	0	0	0	5,286
Independent Variables								
Tariff[t] (BRL cents/MWh)	22,995	64.2	10.3	28.8	57.6	63.8	70.3	93.2
Installation Cost per Unit (BRL/Wp)	22,995	9.1	1.8	6.3	7.7	9.4	10.7	11.2
PV output (kWh/kWp)	22,995	4.3	0.3	3.2	4.1	4.3	4.5	4.9
Population (log of)	22,995	9.5	1.1	6.7	8.6	9.4	10.1	15.7
Pop. Density (log of) (hab./km^2)	22,995	3.2	1.4	−2.6	2.4	3.2	3.9	9.5
GDP per Habitant (log of) (BRL/hab.)	22,995	9.7	0.7	6.0	9.1	9.6	10.1	13.8

4 Empirical Strategy

I take advantage of the panel nature of the municipality-level data in order to investigate the impact of *tariff* on the decision to install DG PV systems among residential customers. Two-ways fixed effects are applied in order to capture unobserved heterogeneity across municipalities that is fixed overtime. Again, due to data limitations, *installation cost per unit* is only available in the country-level changing through the period of analysis and it will be captured whenever year fixed effects are applied. In the same way, *PV output* are available in the municipality level, but it does not vary through the period of analysis; hence, it will be captured whenever municipality fixed effects will be applied. Nonetheless, including these variables will be important for the sensitivity analysis.

Let $Y_{m,t}$ denote the number of new residential DG PV systems installed in the municipality m in the year t. $Y_{m,t}$ is modelled as a function of the explanatory and control variables. The following equation represents the specified estimation regression:

$$Y_{m,t} = \alpha + \beta tariff_{m,t} + \gamma X_{m,t} + \mu_m + \phi_t + \epsilon_{m,t} \tag{4.1}$$

where α is a constant term, $tariff_{m,t}$ is the explanatory variable, $X_{m,t}$ is a vector of municipality-level covariates described earlier and $\epsilon_{m,t}$ is the random error,representing the net effect of all other unobservable factors that might influence $Y_{m,t}$. I also include municipality fixed dummies μ_m and year dummies ϕ_t. β and γ measure the influence (i.e. marginal effect) of their associated explanatory and control variables on the dependent variable, keeping other explanatory variables constant.

From Table 1, one may realize that there is a high amount of zero-valued observation. Indeed, this is the case for about 91% of the observations, because, for the years observed, in a large proportion of the municipalities, still, there are no residential DG PV systems. Since DG PV is a new emerging market in Brazil, often the zero-valued observations were present in the early years, although sometimes they cover the whole sample period. Moreover, the dependent variable is heavily right skewed (skewness: 42.96) and has an excessive kurtosis (kurtosis: 2799.74), configuring a non-normal distribution. Taking logs reduces the skewness and the kurtosis, and yields a dependent variable that is more normally distributed, however, this also reduces considerably the number of included observations, because of the large number of zero-values.

The zero-inflated property of the dependent variable could create potentially large biases in parameter estimates when using traditional ordinary least squares (OLS) estimation techniques Santos Silva and Tenreyro (2006). Then, the main regressions are performed using the Poisson Pseudo-Maximum Likelihood (PPML) estimation technique in order to address this issue. Furthermore, when the error term is heteroskedastic, the OLS estimates are inconsistent and this can also be handled by the PPML estimator with a robust covariance matrix Zhao et al. (2013). Results from simulation show that the PPML performs better compared with other estimators Santos Silva and Tenreyro (2011), proving that the PPML approach gives consistent estimates regardless of how the data are distributed. One could find further details on the Poisson regression in Winkelmann (2008).

It is important to note that, I also build models using a lagged version of the explanatory variable. There are some explanations for this assumption. Firstly, one theoretical explanation is that households do not necessarily respond to contemporaneous tariffs but to lagged ones, as stipulated on their electricity bill which is received only later after the consumption of electricity Gautier and Jacqmin (2020). It might be difficult to residential electricity consumers to judge how new tariffs might influence their returns on investing in PV systems since electricity consumption is only paid ex-post Ito (2014). A bi-product of the one-year lag between the explanatory and dependent variable is that it reduces the scope for reverse causality Gautier and Jacqmin (2020).

5 Results and discussions

The following empirical approach is designed to estimate the repercussion of electricity tariffs, installation costs and the local solar resource on the residential decision to invest in DG PV systems. Two-ways fixed effects in the municipality-level and year are considered in the main results. The reported standard errors are robust and clustered at the municipality-level. Due to the log-linear nature of the estimator used, the coefficients for the main explanatory variables, as they are not log-transformed, are given as semi-elasticities [4]. Table 2 presents the main regression results, showing the impact of *tariff[t]*, *tariff[t-1]* , *instal. cost. per unit* and *PV output*, on the *# of new PV Projects.* I look to estimate the effect of *tariff[t-1]* on other dependent variables in Table 3. In Table 4, I look at the robustness of the main results modifying the region-level fixed effects.

The ideal specification is reported in regression (1), where I associate the number of new residential PV projects with the lagged distribution tariffs. One can note that *tariff[t-1]* has a positive and statistically significant effect on the number of new residential PV projects. As the estimator used presents a log-linear nature, one can conclude that, all else equal, an increase in one BRL cent of the volumetric electricity tariff promotes an increase in 5.3% in the number of new residential PV projects. The estimations in other regressions present also a positive significant effect, when adding other variables and/or modifying the two-ways

[4] To compute the exact effect of a variable change in percentage, one may take the calculated semi-elasticities β and calculate $exp[\beta] - 1$

Table 2: Main results

Dep. Var.: # of New PV Projects	(1)	(2)	(3)	(4)	(5)
Tariff[t-1]	0.052^{+}	0.031^{+}	0.046^{***}	0.042^{***}	
	(0.03)	(0.02)	(0.01)	(0.01)	
Tariff[t]					0.012^{*}
					(0.01)
Install. Cost per Unit		-0.634^{***}		-0.662^{***}	
		(0.06)		(0.03)	
PV Output			0.531^{+}	0.537^{+}	
			(0.31)	(0.31)	
Population (log of)			0.966^{***}	0.966^{***}	
			(0.05)	(0.05)	
Pop. Density (log of)	1.361	4.999	-0.017	-0.016	-5.058
	(6.80)	(3.83)	(0.04)	(0.04)	(9.38)
GDP per hab. (log of)	0.152	-0.727	0.916^{***}	0.909^{***}	0.145
	(0.54)	(0.52)	(0.08)	(0.07)	(0.56)
Constant	-10.046	-14.900	-24.636^{***}	-19.747^{***}	27.981
	(39.15)	(23.28)	(2.02)	(2.18)	(55.47)
Observations	22995	22995	22995	22995	22995
Pseudo-R-sqr	0.88	0.87	0.67	0.66	0.88
Log Pseudo-Lik.	-5607.27	-5945.42	-15119.41	-15511.41	-5681.96
Municipality FE	Yes	Yes	No	No	Yes
Year FE	Yes	No	Yes	No	Yes

Standard errors in parentheses

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

fixed effects, suggesting it is not largely driven by the effect of correlated unobservables. The other coefficients are not statistically significant or are absorbed by the fixed effects. Similar results were found in Gautier and Jacqmin (2020).

In regression (2), I take advantage of the availability of data concerning the *installation cost per unit* in the country-level. In order to estimate its coefficient, I need to remove the year fixed effects. As expected, the outcome shows that the installation costs per unit has negative and statistically strong effect ($p = 0.001$) on new residential PV adoption, with a semi-elasticity of -0.634.

In order to take advantage of the availability of data related to the importance of solar resource represented by PV output varying in the municipality-level, I estimate the regression (3); however, I need to remove the place fixed effects. From the results, one can observe that PV output present has a positive and significant impact ($p = 0.1$) on the number of new residential PV projects, with a semi-elasticity of 0.531. Besides, GDP per hab. and Population became statistically significant with a positive impact on new PV installations, as expected. GDP per hab. can be interpreted as a measure of people's wealth, which is essential for some on a residential PV adoption. Population can be interpreted as the a market potential, and the more inhabitants the higher the probability of PV adoption in a given municipality.

Regression (4) and (5) are inserted among the main results for the sake of sensitivity. In the former, neither place nor time fixed effects are applied. One can conclude that the signs of the coefficients do not change and the magnitude may vary slightly, but not to the point of changing the previous conclusions. In the latter I use contemporaneous tariff with place and time fixed effects. The *tariff[t]* variable also showed a positive and significant effect. Nonetheless, the dimension of the semi-elasticity is lower than when using the one year lagged version. The analysis of the Akaike Information Criteria and the Bayesian Information Criteria encourages the use of this method [5] Therefore, as also found in Gautier and Jacqmin (2020), this outcome reinforce that individuals may optimize considering the information contained on their electricity bills instead of the cost of electricity, as one of the main characteristics in the electricity markets is that bills are paid only after the good in question has been consumed.

Table 3: Further results

	(1)	(6)	(7)	(8)
	# of new PV	# of new credited units	Capacity of new PV	Average capacity
Tariff[t-1]	0.052^{+}	0.095^{**}	0.049	0.035
	(0.03)	(0.04)	(0.04)	(0.03)
GDP per hab. (log of)	0.152	-1.584	-2.142	-2.019
	(0.54)	(1.21)	(2.20)	(1.53)
Pop. Density (log of)	1.361	-24.812^{*}	-36.004^{**}	-56.644^{***}
	(6.80)	(11.38)	(11.52)	(11.43)
Constant	-10.046	132.173^{*}	201.894^{**}	218.215^{***}
	(39.15)	(57.33)	(71.06)	(43.02)
Observations	22995	22995	22995	22995
Pseudo-R-sqr	0.88	0.91	0.92	0.88
Log Pseudo-Lik.	-5607.27	-8156.35	-39315.45	-18835.27
Municipality FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Standard errors in parentheses

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Other dependent variables are used in Table 4. As specified in 2, a consumer may choose a modality of DG named as remote self-consumption. It allows the consumer to install a DG system in one of her housing unit and use the energy credited to reduce the electricity bill in another housing unit of her own if it is found in the same discos exploitation area. For instance, with this modality, if the

[5]The AIC (resp. BIC) of regression (1) is equal 11,220 (11,244) while the AIC (resp. BIC) of regression (5) is equal to 11,369 (11,394).

consumer owns one vacation house which disposes a rooftop and lives most part of the year in an apartment placed in a urban area, she may install a DG system on her vacation house roof top and reduce the electricity bill from the apartment that do not dispose of space for a DG system installation. In regression (6), I use the number of new *credited units* as the dependent variable. The results reveal that lagged tariffs presented also a positive effect, higher in magnitude and statistically stronger, on the new *credited units* (0.095, $p = 0.01$) then on the number of *new PV projects* (0.052, $p = 0.1$). In fact, every one BRL cent increment promotes an increase of 9.6% of new *credited units*. This result is interesting because it confirms that the modifications brought by the normative resolution 687/2015 boosted the growth of residential DG PV market. Still in regression (6), *pop. density* presented a negative effect on the number of *credited units*. This outcome ratifies the previous statement about the consumers owning two housing units. In general, when a consumer owns a vacation house it is located in the countryside, where the population density is lower then where she owns her living house.

In regressions (7) and (8) the total *capacity* of new PV and the *average capacity* are used as dependent variables. I observe that lagged tariffs did not play a statistically significant role concerning the total new capacity nor the average capacity of PV installations. Nonetheless, *pop. density* presents a negative impact on both dependent variables. It means that the lower the *pop. density* of a municipality, less residential PV capacity are installed and, on average, the PV projects are smaller.

Taking advantage of the availability of data concerning different regional fixed effect level, a set of robustness check is disposed in Table 4. The analysis consists in modifying the regional aggregation from the most disaggregated, already displayed in regression (1) in the municipality-level, to the least, i.e. in the country-level, and observe the stability of the coefficients of explanatory variables. In general lines,

Table 4: Robustness check

	(1)	(9)	(10)	(11)	(12)	(13)	(3)	(4)
	Municipality	Microregion	Mesoregion	Disco Area	State	Region	None	None
Tariff[t-1]	0.052^{+}	0.052^{+}	0.054^{*}	0.052^{+}	0.054^{*}	0.029^{**}	0.046^{***}	0.042^{***}
	(0.03)	(0.03)	(0.02)	(0.03)	(0.02)	(0.01)	(0.01)	(0.01)
Install. Cost per Unit								-0.662^{***}
								(0.03)
PV Output		0.159	0.205	0.010	0.263	0.690^{*}	0.531^{+}	0.537^{+}
		(0.80)	(0.41)	(0.25)	(0.24)	(0.27)	(0.31)	(0.31)
Population (log of)		1.167^{***}	1.147^{***}	1.152^{***}	1.149^{***}	1.063^{***}	0.966^{***}	0.966^{***}
		(0.07)	(0.07)	(0.05)	(0.05)	(0.07)	(0.05)	(0.05)
Pop. Density (log of)	1.361	-0.018	-0.048	-0.123^{*}	-0.133^{**}	-0.085^{+}	-0.017	-0.016
	(6.80)	(0.09)	(0.07)	(0.05)	(0.05)	(0.05)	(0.04)	(0.04)
GDP per hab. (log of)	0.152	0.716^{***}	0.750^{***}	0.735^{***}	0.700^{***}	0.662^{***}	0.916^{***}	0.909^{***}
	(0.54)	(0.17)	(0.11)	(0.11)	(0.11)	(0.11)	(0.08)	(0.07)
Constant	-10.046	-23.446^{***}	-23.916^{***}	-22.522^{***}	-23.337^{***}	-22.264^{***}	-24.636^{***}	-19.747^{***}
	(39.15)	(3.58)	(2.40)	(2.77)	(2.38)	(1.91)	(2.02)	(2.18)
Observations	22995	22995	22995	22995	22995	22995	22995	22995
Pseudo-R-sqr	0.88	0.79	0.74	0.71	0.71	0.68	0.67	0.66
Log Pseudo-Lik.	-5607.27	-9809.12	-11853.13	-13130.70	-13362.15	-14539.46	-15119.41	-15511.41
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

Standard errors in parentheses

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

the coefficients show stability in signs and magnitude. More specifically, concerning the coefficients of the lagged tariff, they remain positive and their proportion are stable; however they might change concerning the statistical significance. This happens because, as the regional fixed effects represent more extensive territories, the variable within variation also increases. *Installation cost per unit* are only available in the country-level and are presented for illustrative purposes. PV output and population are not captured by regional fixed effects when the level of disaggregation are lower than the municipality-level. This occurs because, as they are available in the municipality level, their within variation increases as disaggregation level drops. *PV output* presents a stable coefficient with a positive sign and becomes statistically significant from the moment where region fixed effects are used in regression (13). *Population* coefficients are also stable in magnitude, remaining always positive, and are strong statistical significant already in regression (9), the second level of aggregation. *Pop. density* presents stable coefficients, excepting in regression (1) in which it is not statistically significant. *GDP per hab.* is not significant when municipality fixed effects are applied; however, when lower levels of disaggregation are adopted, *GDP per hab.* remains positive, stable in magnitude and presents a strong statistical significance at $p = 0.001$. Therefore, one may conclude that the robustness check confirms the main results displayed previously.

6 Conclusions and Policy Implications

The conventional vertically integrated power systems are changing towards to a smarter system with a high presence of renewable technologies, Distributed Generation systems, greater energy efficiency and electric vehicles. Solar PV is the technology with highest share among residential DG systems and net metering is one of the main incentive mechanism adopted by many countries in the globe to boost DG adoption.

In this paper, I investigate how electricity tariffs structured as volumetric charges affect residential PV adoption under a net metering scheme in Brazil, a developing country and an emerging DG market. A two-ways fixed effects panel data regression covering 5570 municipalities over the period of 2013-2017 was employed. Since the explanatory variable showed high content of zero-valued observations I used the PPML estimator.

The empirical results suggest that electricity tariffs structured as volumetric charges have significant positive effect on the expansion of PV technology in residences and the conclusion is robust according to the techniques used. For each one BRL cent of tariff increase, there will be an expansion of about 5.3% in new residential PV projects in the following year. Nonetheless, the level of statistical significance found for electricity tariffs is 10%, meaning that other variables may also an important role on the residential decision to install PV system. Gautier and Jacqmin (2020) found similar results in Belgian Walloon region under also a net metering scheme. Nevertheless, the authors used only the distribution tariffs as explanatory variable and found a larger effect on residential PV adoption. This outcome is due to the fact that residential PV counted not only with net metering, but also up front subsidies and generous tradable green certificates mechanism.

Solar resources availability and installation costs also affect residential PV adoption. The former variable presents a positive and significant semi-elasticity when the model structure was modified as in Kwan (2012). The latter shows a statistical strong negative effect, as expected. This outcome means that if a country's energy planner wants to encourage residential PV adoption, it can develop policies in order to reduce the installation costs of PV technology as import tax or even subsidies for PV modules local production. Besides, other socio-economic variables may also play a significant role as: population, population density and GDP per habitant.

The results in the present work also revealed that the modifications realized in the normative resolution 482/2012 helped boosting the PV residential market, mainly the creation of the remote self-consumption DG modality. It means that a resident who owns two housing units in which only one of them has a rooftop, she may install a PV system on it and reduce the electricity bills from both housing units if they are under the same distribution zone. This alteration on the resolution allowed a faster growth of residential PV installations.

In spite of not addressing straightly the "death spiral" phenomena in the analysis, this paper composes the literature that investigates how the configuration of net metering scheme and electricity tariffs structured as volumetric charges may boost residential DG PV adoption. The empirical outcomes of the present work may serve to policymakers, researchers and analysts as parameters for electricity markets behaviour.

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