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Distributed energy resources in an emerging country context : Three essays on residential photovoltaic adoption in Brazil

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THÈSE

UNIVERSITE DE PAU ET DES PAYS DE L'ADOUR
École doctorale Sciences Sociales et Humanités (481)

Présentée et soutenue le 23 mars 2021

par Bruno MORENO RODRIGO DE FREITAS

pour obtenir le grade de docteur
de l'Université de Pau et des Pays de l'Adour (UPPA)

Spécialité : Sciences Economiques

RESSOURCES ÉNERGÉTIQUES DISTRIBUÉES DANS UN CONTEXTE DE PAYS ÉMERGENTS : TROIS ESSAIS SUR L'ADOPTION DU PHOTOVOLTAÏQUE RÉSIDENTIEL AU BRÉSIL

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Ph.D. Thesis

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Bruno MORENO RODRIGO DE FREITAS

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Mars, 23rd 2021

DISTRIBUTED ENERGY RESOURCES IN AN EMERGING COUNTRY CONTEXT: THREE ESSAYS ON RESIDENTIAL PHOTOVOLTAIC ADOPTION IN BRAZIL

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Abstract

The traditional vertically integrated power systems are changing towards a smarter ones with the high presence of renewable technologies, distributed generation (DG), greater energy efficiency and electric vehicles. Solar PV is the technology with the highest share among residential DG systems, due to several reasons among them: falling costs, increase of energy conversion efficiency and scalability features. The present thesis presents an investigation on the dynamics of residential PV adoption in Brazil.

In the first chapter, 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 4,995 municipalities over the period of 2013-2017 is employed. Since the explanatory variable shows a high content of zero-valued observations, I use the PPML estimator to run the regressions. The main result is 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.

In the second chapter, I investigate the determinants of residential PV adoption in an emerging country context using social, economic and environmental variables. The analysis is realized using a dataset in census sector level with 310,120 observations, with 42 covariates. Territory fixed effects are applied in the municipality-level. The main results show that 21 covariates are statistically significant and that most of them may be related to income distribution issues in some degree. Therefore, net metering incentive mechanism had a positive influence to boost residential renewable energy generation, mainly PV technology. However, those who benefit from the incentive are wealthier people, which does not make sense in respect to social justice, because those who indeed need to be subsidized in order to reduce the electricity bills and increase the purchasing power are the underprivileged population.

Finally, in the third chapter, I examine the relationship between certain socioeconomic covariates and PV market diffusion in the municipality level. I conduct a two-stage empirical analysis. At first, I use the Bass technology diffusion model to estimate the innovation and imitation coefficients. For that, I build the q/p ratio to represent a risk aversion index to each respective municipality's adoption rate over time. In the second stage, I run regressions based on the PPML estimator, due to the non-gaussian nature of the dependant variable, to investigate associations between the risk aversion index and different socio-demographic and economic covariates. The results show evidences of the association of PV technology risk aversion and households socioeconomic characteristics. This behavior may be based on several assumption as regulatory uncertainty, technology information and easy to understand rules for average customers etc.

Résumé

Les systèmes électriques traditionnels à intégration verticale évoluent vers un système plus intelligent avec une forte présence des technologies renouvelables, de la production distribuée (PD), d'une plus grande efficacité énergétique et des véhicules électriques. L'énergie solaire photovoltaïque est la technologie la plus répandue parmi les systèmes de production décentralisée résidentiels, et ce pour plusieurs raisons : baisse des coûts, augmentation de l'efficacité de la conversion énergétique et caractéristiques d'évolutivité. La présente thèse présente une enquête sur la dynamique de l'adoption du photovoltaïque résidentiel au Brésil.

Dans le premier chapitre, j'étudie comment les tarifs de l'électricité, structurés sous forme de redevances volumétriques, affectent l'adoption du photovoltaïque résidentiel dans le cadre d'un système de comptage net au Brésil, pays en développement et marché émergent de la production décentralisée. Une régression bidirectionnelle des données d'un panel à effets fixes couvrant 4 995 municipalités sur la période 2013-2017 est utilisée. Comme la variable explicative a montré un contenu élevé d'observations à valeur nulle, j'utilise l'estimateur PPML pour effectuer les régressions. Le principal résultat est que pour chaque centième de hausse des tarifs en réel Brésilien, il y aura une expansion d'environ 5,3 % des nouveaux projets PV résidentiels l'année suivante.

Dans le deuxième chapitre, j'étudie les déterminants de l'adoption du photovoltaïque résidentiel dans le contexte d'un pays émergent en utilisant des variables socioéconomiques et environnementales. L'analyse est réalisée, principalement, en utilisant un ensemble de données au niveau du secteur de recensement avec 310 120 observations, 42 covariables et l'effet fixe du territoire est appliqué au niveau municipal. Les principaux résultats montrent que 21 covariables sont statistiquement significatives et que la plupart d'entre elles peuvent être liées à des questions de distribution des revenus dans une certaine mesure. Par conséquent, le mécanisme d'incitation au comptage net a eu une influence positive pour stimuler la production résidentielle d'énergie renouvelable, principalement la technologie PV. Cependant, ceux qui bénéficient de l'incitation sont les personnes les plus riches, ce qui n'a pas de sens en matière de justice sociale, car ceux qui doivent effectivement réduire les factures d'électricité et augmenter le pouvoir d'achat sont les populations défavorisées.

Enfin, dans le troisième chapitre, j'examine la relation entre certaines covariables socioéconomiques et la diffusion du marché photovoltaïque au niveau des municipalités. Je mène une analyse empirique en deux étapes. Dans un premier temps, j'utilise le modèle Bass sur la diffusion de technologies pour estimer les coefficients d'innovation et d'imitation. Pour cela, je construis le rapport q/p pour représenter un indice d'aversion au risque du taux d'adoption de chaque municipalité respective au fil du temps. Dans un deuxième temps, j'effectue des régressions basées sur l'estimateur PPML, en raison de la nature non gaussienne de la variable dépendante, pour étudier les associations entre l'indice d'aversion au risque et différentes covariables socio-démographiques et économiques. Les résultats montrent des preuves de l'association entre l'aversion au risque de la technologie PV et les caractéristiques socio-économiques des ménages. Ce comportement peut être basé sur plusieurs hypothèses telles que l'incertitude réglementaire, les informations technologiques et des règles faciles à comprendre pour les clients moyens, etc.

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Part I

General introduction

Power systems are essential to modern lifestyle. They have served to countries to achieve their economic development. Nevertheless, power systems are facing difficult and exceptional challenges nowadays. This new framework have the power to affect all links in the electricity industry and encourage new market structures, business models and actors to emerge. The verticalized electricity industry - generation, transmission, distribution and supply - is giving place to a newborn complex one. Indeed, power systems are likely to look hugely different from the one in the present.

Distributed Generation (DG) systems conception is one of the arising disruptive upcoming trends. A precise definition of the term is complicated, because it depends on each local electricity market. Nonetheless, in a broader sense, one can characterize DG as small-scale power production systems located next to the load centers, based on low-carbon technologies, connected to the distribution system or on the consumer side and not dispatched by the local system's operator. This new electricity production approach empowers the electricity consumer and makes possible the emergence of a new actor in electricity markets - the prosumer -, which are electricity consumers that also produce electricity through a DG system. Thus, distribution networks will not only deliver electricity to consumption units but will also receive electricity from them.

According to IEA (2019), 70% of global power capacity expansion will come from solar PV and wind and the half of solar PV growth will be based on DG systems through 2024. Some of the main reasons may be pointed as the falling costs of PV technology, due to the increase of energy conversion efficiency of the modules, and the scalable feature, allowing the project customization from huge centralized plants to distributed household-scale ones. Although, IEA (2019) specifies that commercial and industrial undertakings will be the segments that will most adopt distributed PV development globally, the progress of residential distributed PV will be also significant.

Up to 2018, Europe was the continent with the largest household DG PV installed capacity, being Germany, Italy, the United Kingdom, Belgium and the Netherlands the local leader countries in this market. Japan and Australia also presented a great part of residential PV systems, being positioned in the head of Asian-Pacific region countries. The United States are the country with the largest residential PV capacity. From the total of about 60 GW, the great majority of the residential installed capacity is based in developed countries. In the future, developing countries are expected to contribute to the DG PV

expansion in Asia-Pacific region, Middle East, Africa and Latin America. Brazil is among them and has been presenting a rapid insertion (IEA (2019)).

The Brazilian electricity sector

The Brazilian electricity sector has grown steadily until the mid-1970s, when it started to lose its investment capacity in the late of the decade. By that time, the government could establish electricity rates according to the political and economic situation. During the 1980s, the government systematically reduced electricity tariffs trying to control inflation. Consequently, the artificial low tariffs and the loss of international credit diminish the electric sector investment (Mendonça and Dahl (1999)). During the 90's, the Brazilian power sector has passed through liberalized reforms in order to increase the investment rate by attracting the private capital, introducing incentives to efficiency, mainly through liberalization of electricity generation, and to diversifying the energy matrix to assure energy security (Almeida and Pinto Jr. (2005); Losekann (2008)). Still, the consequences of such problems appeared in 2001-2002 when Brazil suffered a power shortage.

To accomplish the goals of energy diversification, Brazil established its national energy policy through the federal law 9478 of 1997. It disposes the principles and objectives of the Brazilian energy policy, and it makes evident the intentions to count on the renewable energies expansion as one of the pillars to solve the Brazilian energy impasse. In order to put the policy in practice, the Brazilian government launched the Alternative Sources Incentive Program (PROINFA) through the law 10439 of 2002. The set target of the initiative was to build 3.3 GW of installed capacity divided equally among three technologies: wind, biomass and small hydroelectric power plants (SHP). Solar energy was not included in the program, because, by that time, it was not considered as a viable and strategic source, since it presented a considerably high production cost compared to other sources (ABINEE (2012)).

Arise from the liberalization process of the 90's, Brazil adopted in 2004 a centralized planning undertaking public auctions as a tool to attract private capital investments, to promote reasonable electricity tariffs at the lowest feasible cost and to expand the installed capacity. Biomass and Small Hydropower technologies started to be negotiated already in the first new energy auction. Wind power projects were included in 2009 and utility scale

solar PV in 2014.

Regarding the current electricity matrix, Brazil has a historical dependence on hydropower plants for power generation and presents a share of 71.1% in 2019. Wind power are getting space on the total capacity of the Brazilian power matrix with 9.6% and occupied the 8th place on total wind installed capacity by country up to 2018, according to IRENA (2018). The Brazilian power matrix counts on biomass thermal power plants at a share of 4.8%. Nuclear represents 2.82% of total demand. The great majority of the remaining is produced by fossil fuels thermal power plants, i.e. 15.9%. Solar PV has an insignificant participation lower than 1% (CCEE (2019)). With this performance, Brazil occupied the 19th on the environmental sustainability ranking in 2019 (WEC (2019)).

In the last years, the hydro-based profile of the Brazilian power system has been changing considerably. The main reasons are the expansion in electricity demand and the availability and the falling costs to explore other generation resources. Brazil possesses a great variety of energy resources, but their use may need large investments and cause significant environmental impacts (Pereira et al. (2008)). Regarding hydropower, the country exploits only 30% of its potential and the remainder is mainly located in the environmentally sensitive Amazon region. On the other hand, the expansion of fossil energy sources involves large investments in the recovery of natural gas and/or coal. In the latter case, the country would lose its great comparative advantage of possessing a clean energy sector (Pereira et al. (2011)).

Brazil is the largest country in the Latin American region. Most of its territory is located in the South hemisphere and it is composed by five great regions - Southeast, South, Northeast, Centre-west and North -, divided into 26 states plus the Federal District. In 2019, the estimated population was 210,147,125 inhabitants. In order to supply electricity for its population, the Brazilian electric power system is divided in two areas: the Isolated Systems and the National Interconnected System (SIN).

There are 272 isolated systems in Brazil and they are supplied mainly by diesel thermal power plants. The great majority stays in North region, distributed throughout eight states (EPE (2019)). Decree 7246/2010 defines the Isolated Systems as electric power distribution utility systems that, in their normal configuration, are not electrically connected to the SIN, due to technical or economic reasons. The demand represents 0.6% of the country's total electricity consumption and supplied about 835 thousands consumption units (EPE

(2020)).

In turn, more than 72.6 million households (29% the total consumption) rely on the SIN for electricity supply. The SIN is a large hydro-thermal-wind electric power generation and transmission system composed by four subsystems: Southeast/Centre West (SE/CO); Northeast (NE); South (S); and North (N). The SIN's subsystem interconnection, by means of the transmission grid, allows energy transfer among them, favor synergistic gains and exploits the diversity of the basins hydrological regimes. The integration of generation and transmission resources allows the market to be served safely and economically.

The Brazilian Independent Power System Operator (ONS) is the entity responsible for the SIN's operation and control. In order to make electrical and energy safety compatible with the economic optimization of the operation, the ONS utilises a chain of stochastic models, so that the entity can determine the system's operation planning for the short, medium and long terms. From that, a weekly operational marginal cost is calculated for each subsystem, which is one of the bases for the Brazilian electricity spot market pricing. One may find further details in Saporta (2017).

According to EPE (2020b), between 2019 and 2029, the Brazilian population will expand at decreasing rates. The Brazilian GDP will grow at 2.9% per annum (p.a.) on average, due to international trades' slowdown and internal issues. The Brazilian economy scenario will then reflect directly on the national energy demand, which is expected to increase by 2.5% p.a. on the ten-year horizon. Regarding centralized power generation planning, Brazil tends to follow a predominantly renewable offer in the next ten years. It will represent about 80% of the generator park composed of hydroelectric plants (large and small), wind, solar and biomass power plants. In addition to these important resources, there will be natural gas and coal-fired thermal power complementation in order to ensure security of supply. DG will gain space on the power matrix and will achieve 11.4 GW of installed capacity, of which 86% will come from PV technology.

Residential Consumption in Brazil

According to Pereira Uhr et al. (2019), electricity consumption has been increasing since 1970s. The use of environment-impacting energy sources as firewood and others has declined with universalization of electricity towards rural areas. The most noteworthy mea-

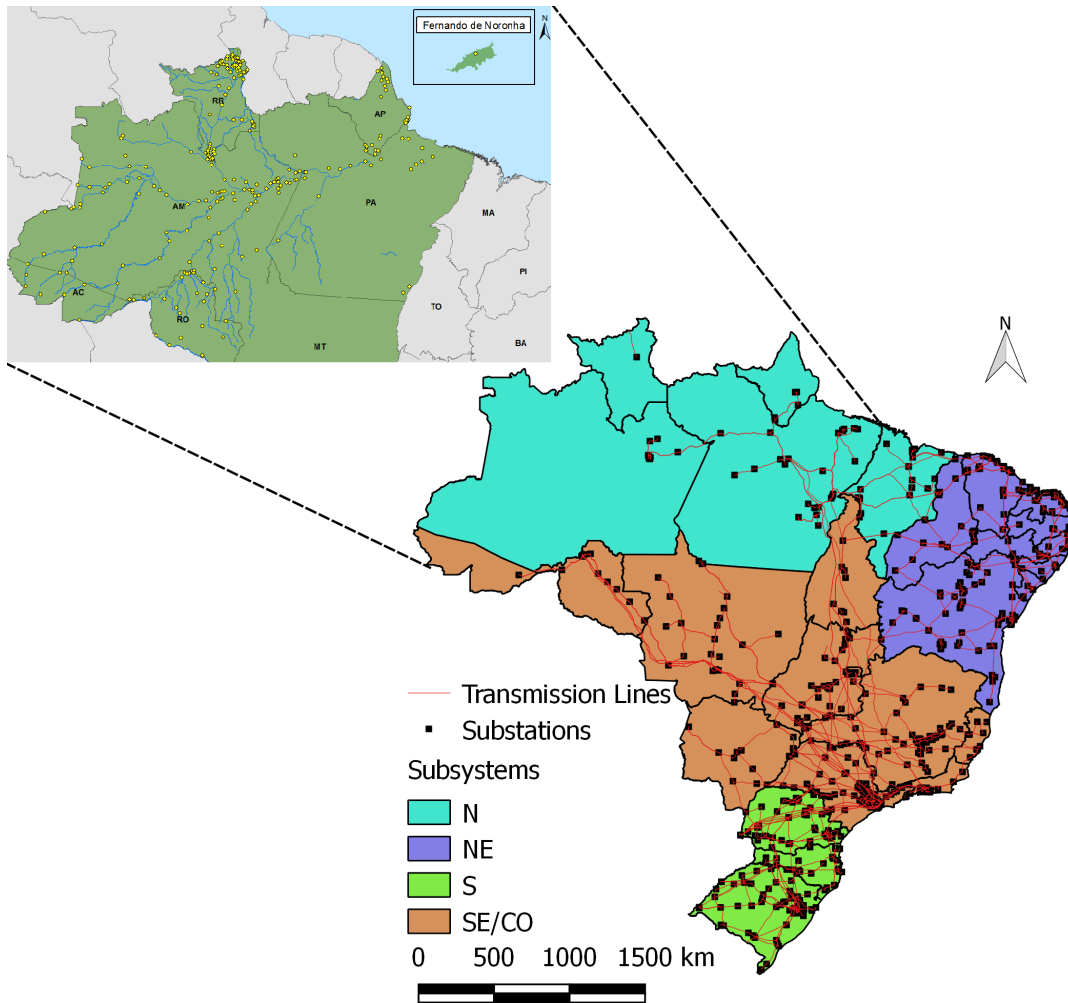


Figure 1: Location of the isolated systems and the SIN. Own elaboration based on data from EPE (2019, 2020)

sure to expand energy access in Brazil, so far, has been the *Luz Para Todos* (Light for All in free translation) federal program, which benefited more than 10 million inhabitants occupying exposed rural surroundings.

In 2019, residential electricity consumption achieves 316,355.8 GWh in Brazil, representing 45.13% of the total consumption. 85.9% of the consumption units belong to the residential segment in the same year (EPE (2020)). Households consume on average 162.9 kWh/month, while non-residential segments consume 336.2 kWh/month. Regarding electricity universalization, 99.8% of households has access to electricity from the general grid (IBGE (2019)). Industrial, commercial and other consumers have a share of 35%, 19% and 17% of total consumption. From 2004 to 2019, residential electricity consumption increased by 4.05% yearly and the number of residential consumption units increased by 3.01%, both on average (EPE (2020)). According to Villareal and Moreira (2016), Achão

and Schaeffer (2009) and Pereira Uhr et al. (2019), the main reasons for these results are the higher sales of home electrical appliances due to easy credits for consumers. Nevertheless, Villareal and Moreira (2016) states that Brazil still presents a marginal residential electricity consumption when compared to developed countries.

In the early 90s, following the liberal reforms, the Brazilian government ended the model in which there was a uniform and unique electricity rate for the whole territory, according to Pereira Uhr et al. (2019). Instead, the new model established that distribution companies (discos) must sign contracts with the government for the rights of electricity supply exploitation of definite geographic zones, i.e., the concession areas. From that moment on, electricity rates would be established for each disco, reflecting the idiosyncrasies of the concession areas, for instance, the amount of consumers, the consumer market, distribution grid magnitude, the local taxes, among other factors.

The National Electric Energy Agency (ANEEL in Portuguese abbreviation) is responsible for defining the electricity prices, regulating, supervising and increasing energy efficiency of the electricity sector. Most of the states presents a unique disco responsible for the electricity supply. The current Brazilian disco market share is composed by 105 discos¹. Figure 1 shows the boxplot of the residential electricity tariff evolution in Brazil, while Figure 2 displays the main discos and their distribution exploitation area.

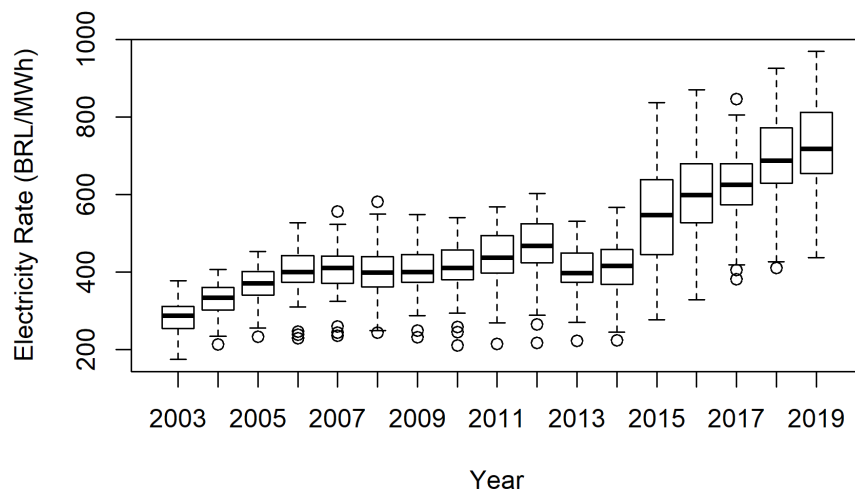


Figure 2: Boxplots of residential electricity tariffs in Brazil (2003-2019). Nominal prices. Own elaboration based on data from ANEEL (2020a)

¹ Among distribution concessionaire and permissionaire according to ANEEL (2020c).



Figure 3: Map of Discos in Brazil. Own elaboration based on data from ANEEL (2020c)

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 the quality of service. Therefore, distribution concession contracts foresee three mechanisms of tariff update: Annual Tariff Readjustment (RTA), Periodic Tariff Review (RTP) and Extraordinary 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 disco's revenue, according to a formula preestablished in the contract. It passes on the company's non-manageable costs and updates the manageable costs by the inflation index less an efficiency coefficient. RTP allows the repositioning of the tariff after complete analyses of efficient costs and remuneration of prudent investments, at intervals of four or five years, depending on the contract. This mechanism differs from RTA in that it is more complex, 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 consumer market. Lastly, RTE is intended to address very special cases of justified imbalance. It can occur whenever an unforeseeable event affects the economic-financial balance of the concession (ANEEL (2008)).

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 electricity from the local disco. Among captive consumers, one may separate them between low-voltage and high-voltage consumers. The former might be distinguished among voltage ranges and each one presents a certain tar-

iff, based on time-of-use, load and/or volumetric charges structures. The latter shows two types of tariffs in which the consumer can choose: time-of-use or average volumetric flat structures. Besides, each consumption class presents different tariff structures and calculation methods: residential, industrial, commercial and services, rural, public power, street lighting, public service, or own-consumption. The great majority of residential consumers chooses the average volumetric flat tariffs, due to its advantages concerning the consumer profile throughout the day. In Brazil, low-voltage consumers present a minimum cost consumption depending on the type of private grid connexion. On average, the consumer's bill includes the costs of production (31.33%), transmission (6.25%) and distribution (28.98%), plus taxes and charges from different levels of government (33.45%) (ANEEL (2008)). There are also low income and indigenous groups that receive considerable energy subsidies through the Social Energy Tariff program, which was created to give electric-bill discounts to low-income consumers in different consumption categories, with the objective of expanding and democratizing access to electricity.

As the SIN's storage capacity decreases with the lack of expansion of new hydropower with reservoirs, the system has been becoming more sensible to prolonged droughts. With this scenario, the dispatch of thermal power plants becomes more common, increasing disco's costs. Then, those were passed on to the consumer during the RTA process, by the incorporation of interest on this difference. Consequently, this situation affected directly the discos revenues due to the mismatch of the cash flow. In order to reduce these effects, ANEEL built a price signal system in 2015 named "tariff flags" to reveal the actual system's energy costs to customers. It mimics a scheme of traffic lights, dividing four levels: (i) green: does not generate additional costs to the consumer; (ii) yellow: generates an additional tariff of BRL 0.010/kWh; (iii) red-level 1: generates an additional tariff of BRL 0.030/kWh; (iv) red-level 2: generates an additional tariff of BRL 0.050/kWh (Pereira Uhr et al. (2019)).

It is worthy to highlight the relation between household income and electricity consumption. There is an extensive literature on investigations relating these two attributes in electricity markets around the globe (Dilaver and Hunt (2011); Jamil and Ahmad (2011); Zaman et al. (2012); Schulte and Heindl (2017); Yalcintas and Kaya (2017); Zhu et al. (2018); Csereklyei (2020)) and also in Brazil (De Martino Jannuzzi and Schipper (1991); Cohen et al. (2005); Achão and Schaeffer (2009); Villareal and Moreira (2016); Grottera

et al. (2018); Pereira Uhr et al. (2019)). Since income is a variable that is not evenly distributed spatially, one can figure out that neither is electrical demand of households. Indeed, this statement can be observed in the comparison of Brazilian regions Table 1 in 2017. The Southeast region (SE) is the most populated followed by Northeast (NE), South (S), Central-west (CO) and North (N). This order is also observed on the proportion of the residential consumption. However, the S region presents the highest average residential consumption, followed by CO, N, SE and NE. These results can be associated with variables representing the population's income, as GDP per habitant, the region's income inequality, the Gini index, being 1 the maximal inequality and 0 the perfect equality. For instance, in spite of showing the highest results for residential consumption and GDP proportions, SE is placed as fourth in the ranking for the average residential consumption. This can be explained in part by the fact that SE is the region showing the highest income inequality among all regions. The same reasoning can be realized to explain the number of the S region, which presents the third place in residential consumption proportion, the second in GDP proportion, but the first places in Gini index and average residential consumption.

Table 1: Brazilian regions comparison in 2017.

	SE	NE	S	CO	N
Resid. Cons. Proportion (%)	48.56	20.14	15.81	8.42	7.07
GDP Proportion (%)	52.87	14.48	17.04	10.02	5.59
Population (million of inhabitants)	86.95	57.25	29.65	15.88	17.94
GDP per Hab. (BRL)*	40,032	16,649	37,838	41,557	20,509
Gini Index	0.88	0.79	0.77	0.84	0.78
Avg. Resid. Cons. (kWh/month)	168.99	119.53	177.02	176.45	175.15

*Real prices, reference 2010

Own elaboration based own data from IBGE (2017b,a); EPE (2020)

Regarding the future, according to EPE (2020b), the number of households has a growing trajectory arriving at 81.6 million households in 2029, but it is expected that there will be less residents per household. Energy consumption in households should grow by 2.0% p.a., because of the increase in household income, the number of households and the expansion of the fuel distribution network. Residential customers will then continue to count on electricity as the main energy source, and its quota will pass from 47% to 56% on the residential final energy consumption.

Distributed PV Technology in Brazil

Brazil is a country with continental dimensions set between the 5°16'20"N and 33°45'03"S latitudes. Due to this reason, Brazil has a huge climate diversity. Those regions closer to the equator axis take advantage of privilege climatic features with higher constant temperatures and more sunny days. On the other hand, southern regions may present more tempered weather and temperature closer to 0°C during winter season. Therefore, the Brazilian territory can present about 2.8 kWh/m²/day to 6.4 kWh/m²/day of direct normal irradiation (DNI). For the sake of comparison, the highest DNI in Brazil presents almost 100% higher than the highest DNI in Germany, one of the most developed PV market in the globe (ESMAP (2020)). Even though it is present on the Brazilian energy planning and the great solar irradiation potentials, PV is still underexplored compared to other countries.

The usage of PV technology in Brazil started in 1994 with the establishment of the Programme for Energy Development of States and Municipalities (PRODEEM). According to Galdino and Lima (2002), the Program's main objective was to promote the electricity supply to underprivileged rural communities located far from distribution networks connection points. As those communities were isolated, their connection to the grid were not economically viable because of the high costs of transmission/distribution lines implementation. In 2005, PRODEEM was incorporated by the *Luz Para Todos* federal program, mentioned previously, and ended in 2014.

The year of 2012 was a milestone to the DG market development in Brazil when ANEEL homologated the normative resolution (NR) 482 on April 17th, which was revised several times until the current format ². The final NR allowed prosumers to connect their DG systems to the distribution networks. Still, 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

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

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 is stored in a maximum rolling period of 60 months.

There are four DG modalities to benefit from net metering according to the NR 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 through DG systems. Next, in *Shared Generation*, person and/or corporate entities may gather as consortiums or cooperatives and build 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 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 to install a DG system, 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.

By the end of 2019, Brazil presented about 2 GW of installed capacity with almost 167 thousands projects. Generation in the Consumption Unit and Remote Self-consumption modalities counted for 84.9% and 14.8%, respectively, of total DG systems. 99.8% of the total installed DG systems were based on the PV technology, due to its scalability feature and the falling costs. Minas Gerais, São Paulo, Rio Grande do Sul, Santa Catarina and Paraná are the top five states with most installations with, respectively, 53,317, 32,117, 26,659, 14,177 and 11,478 DG PV projects. 78.7% of the DG PV systems were residential with almost 100 thousands PV installations, spread throughout the Brazilian territory, as one can observe in Figures 3 and 4.

Misinterpretations occurred in the first years of DG regulation in Brazil. After the NR 482 launching, the Council of State Finance Secretaries (CONFAZ) decided to apply the ICMS tax (Tax on Merchandises Circulation and Services) on the energy produced from DG projects. They understood that net metering was an operation of energy selling and purchasing and that states could collect the tax over the amount of energy traded. After some discussions, in April 2015 CONFAZ launched the CONFAZ 16 agreement authorizing the exemption of the ICMS state tax. However, as it is a confederation of

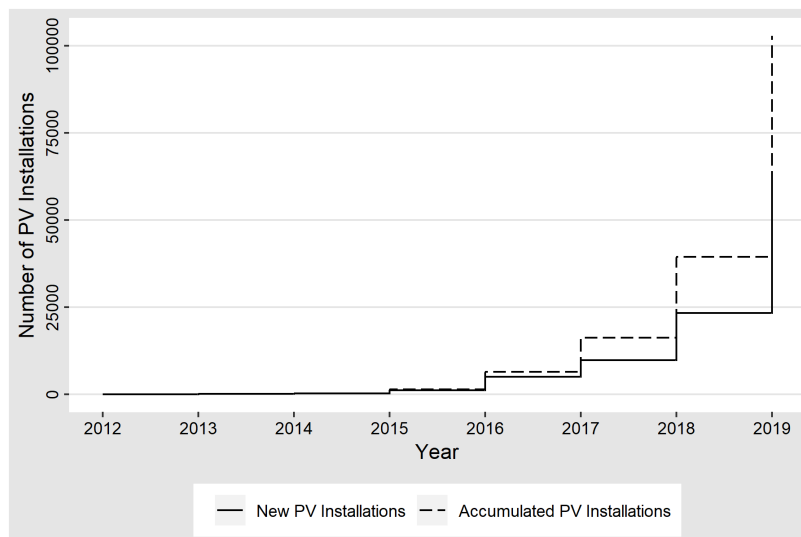


Figure 4: New and accumulated residential PV projects in Brazil (2012-2019) Own elaboration based on data from ANEEL (2020b)

finance ministers, it was up to states to adhere to the new agreement or not. The majority of states followed the agreement already in 2015 and in 2018 all the states had already adhered to it.³

The NR 687/2015 foresaw modifications in the DG regulation in Brazil in 2019. In the same year, ANEEL organized public audiences and consultations opened to the society to discuss a proposal to modify the rules in place. It suggested improvements to the net metering, considering the advances of DG in recent years. In sum, ANEEL understands that the energy credits should not be valued at the retail price, because this approach affects the discos' financial and economic equilibrium. Instead, the energy credits should be valued at a price that guarantees discos' cost-effectiveness. Several modifications are still being considered and may be followed in more details in ANEEL (2018). The revision will impact on the return of investment on DG systems in Brazil. Nonetheless, even in the worst scenario to prosumers' return on investment, it is expected that DG will achieve 16.8 GW in 2030, according to EPE (2020a).

³The states adherence to CONFAZ 16 agreement occurred in 2015 for: Pernambuco, São Paulo, Goiás, Rio Grande do Norte, Tocantins, Ceará, Maranhão, Bahia, Mato Grosso, Distrito Federal, Acre, Alagoas, Minas Gerais, Rio de Janeiro and Rio Grande do Sul; in 2016 for: Rorãima, Rondônia, Piauí, Paraíba, Sergipe, Pará and Mato Grosso do Sul; in 2017 for Amapá; and in 2018 for Espírito Santo, Amazonas, Paraná and Santa Catarina.

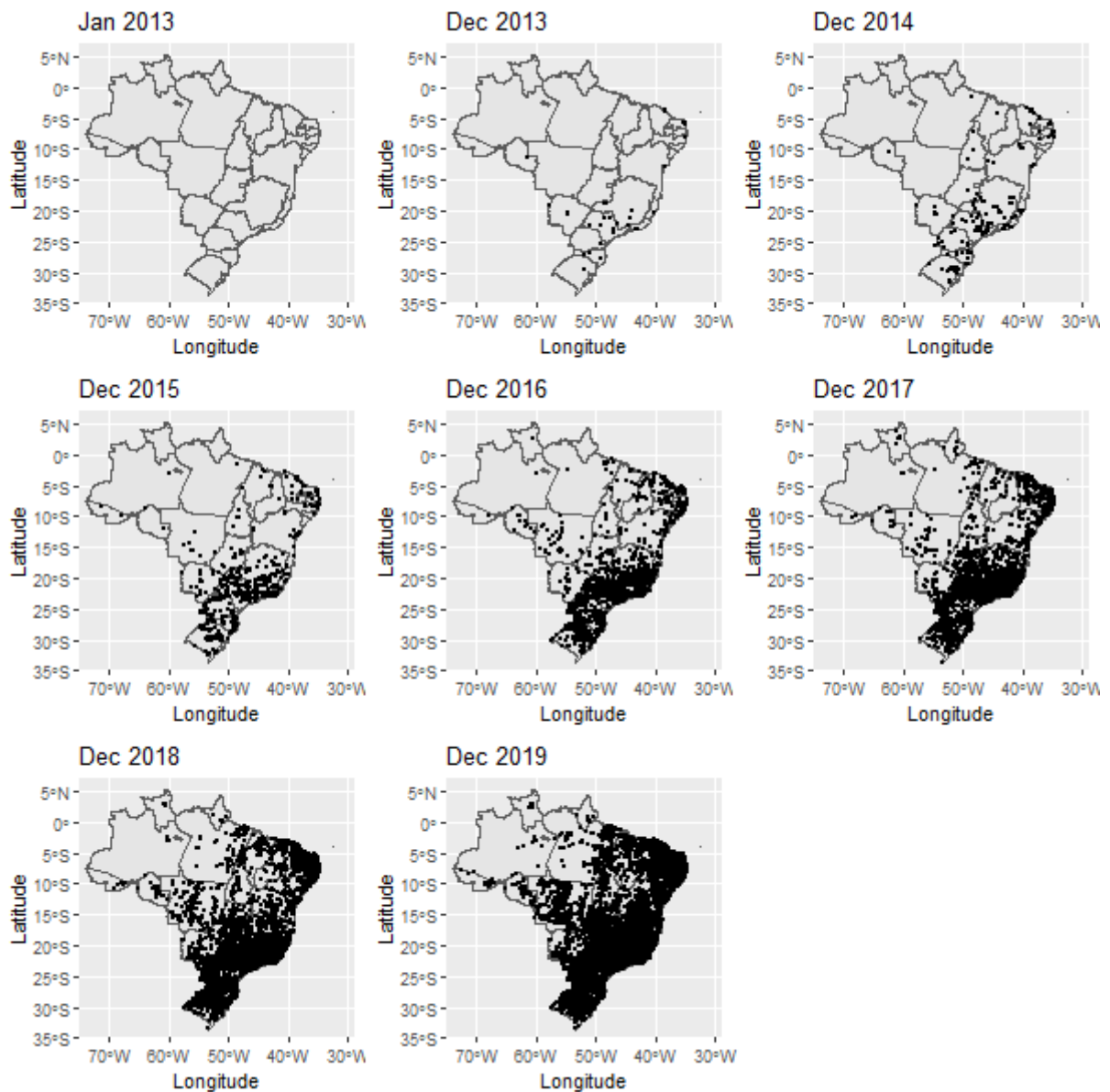


Figure 5: Map of Residential PV adoption in Brazil. Own elaboration based on data from ANEEL (2020b)

Chapters Summary

The major goal of this thesis is to investigate the dynamics of residential PV adoption in Brazil. The specific objectives are threefold. Firstly, I am interested in discussing the importance of regulated volumetric electricity tariffs and calculating their effect on residential PV adoption. Secondly, I am concerned about finding who are those PV residential adopters and if they can be associated to certain socioeconomic factors. Thirdly, I analyse the heterogeneity on imitation and innovation patterns among Brazilian municipalities and associate socioeconomic characteristics to risk aversion behavior regarding the PV technol-

ogy.

The retail price is one of the main elements that encourages PV systems adoption under a net metering scheme. In the first chapter, I carry out an investigation on the influence of regulated electricity tariffs as volumetric charges structure on the residential DG PV systems adoption. I use a panel data from 2013-2017 with 5,570 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.

However, retail prices are not the unique factor that explains a new technology adoption. In fact, the spatial distribution of PV adoption in Brazil is not uniform under areas presenting the same electricity tariff. Therefore, the second chapter paper aims to answer who are the residential PV adopters. This investigation is realized in such fine territory disaggregation, so that I take advantage of a rich set of socioeconomic and environmental characteristics with 310,120 census sectors. One of the main findings is that income plays an important role on residential PV adoption in Brazil, so that wealthier people benefit from the cross subsidies produced by the net metering scheme adoption.

The diffusion of innovations is a complex phenomenon and has been the subject of many academic works. An occurring specific behavior is the risk aversion when a new product appears in the market and it can be related to customers' socioeconomic features. In the fourth chapter, I firstly estimate the innovation and imitation coefficients through an epidemic model. Next, I analyse the relationship between socioeconomic variables and the risk aversion behavior in the municipality level. Investigating economic covariates reveals that underprivileged people are more risk averse than wealthy ones concerning residential PV adoption. Urbanization related covariates, age, ethnicity, level of education and the familiar arrangement may play an important role as well.

Part II

Residential PV adoption in Brazil

1

Quantifying the effect of regulated volumetric electricity tariffs on residential PV adoption under net metering scheme

1.1 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 and low-carbon one. Renewable energy technologies, greater energy efficiency and transport electrification have been gaining much more relevance throughout the years. Moreover, a new electricity production approach is arising progressively, the Distributed Generation (DG) systems. 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. Some of the main reasons are the increase of energy conversion efficiency, leading the falling costs of PV technology around the globe and PV's intrinsic modular feature, allowing the project customization from huge centralized plants to distributed household-scale ones. Although, IEA (2019) states that commercial and industrial applications will 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 work - start, not only to import electricity from the grid, but also to export to it, presenting a bidirectional energy 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. It affects negatively the actual distribution sector's business model. 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, 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 increase the investments realized on the adaptation of the current distribution networks structure to receive a bidirectional energy flow. Consequently, 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 in 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" phenomenon 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, 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. 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. Allan and McIntyre (2017) have applied spatial econometrics techniques to investigate and ratify the occurrence of peer effects 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 target electricity market. This then affects straight 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 DG projects in those locations presenting 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 experience a larger deployment of residential DG PV systems where the distribution tariffs are higher.

Brazil presents a great solar market potential. Concerning the natural resources, the country presents values from 3 to 6 kWh/m²/day of direct normal irradiation according to ESMAP (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 5,570 municipalities distributed through 26 states and the Federal District. 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 study cases (see in Mitscher and R  ther (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 exemption on exported energy to the grid, electricity rates and population as independent variables.

This chapter 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 work are threefold. Firstly, Brazil presents about 22 times more municipalities and its disco market is 10 times bigger than Walloon region, which presents 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, to my knowledge, this is the first time a work investigates how the retail price affects residential PV adoption in such disaggregated level aiming a developing country, contributing to the empirical literature on renewable energy growth.

The remainder of this chapter is structured as follows. Section 1.2 describes the dataset used. Section 1.3 establishes the methodology to examine the drivers on residential DG PV adoption in Brazil. Section 1.4 presents and discuss the empirical findings. Section 1.5 concludes.

1.2 Data

The Brazilian Electricity Agency (ANEEL) collects the following information for each of the DG projects registered under the normative resolution 482/2012 in their public database: location (municipality, state and coordinates), technology type, installed capacity and name of project developer (ANEEL (2020b)). Registration to the regulator is compulsory to be eligible for the net metering incentive scheme. Since the present chapter is designed to estimate the demand for households DG PV systems in Brazil, I extract 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*¹ and the *average capacity*. ANEEL also makes available the explanatory variable used in this work; the **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 customers pay for electricity in a given municipality and year, the more PV installations is observed (Gautier and Jacqmin (2020); De Groote et al. (2016); Kwan (2012)). I excluded social tariffs for low-income households from the analysis, because they are subsidized and those who invest on a PV system are related to higher income (Gautier and Jacqmin (2020); Kwan (2012)).

Another important variable included in the analysis is the **installation cost per unit** (BRL/Wp; real prices, reference 2017) for DG PV systems. It is obtained from IDEAL and

¹New *credited units* is the sum of new PV projects and other registered units concerning the remote self-consumption modality.

AHK-RJ (2015, 2016, 2017, 2018) and is used for the sake of sensitivity as it is available just in the country-level of aggregation. It is expected that as the installation costs fall, more DG PV systems will be installed.

From ESMAP (2016), I collect a raster file containing the long-term yearly average of daily potential PV electricity production in Brazil to include in the analysis. Further refinements are realized to build the final panel dataset. From the PV production potential raster file, I convert it into a shapefile, in which each pixel becomes a point containing the PV production potential information. Next, I extract the points containing in each municipality extension and obtain 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. I use it 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, because the former used the ZIP code level and the latter the state level.

The rest of data is extracted from the SIDRA system of the Brazilian Institute of Geography and Statistics (IBGE) to use as control variables (IBGE (2020)). The Institute makes available annual data from 5,570 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. 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 present more investments in PV systems. In order to capture this effect, **GDP per habitant** (thousands of BRL/hab.; real prices, reference 2017) is included in the regressions. In addition, I extract **population** for each municipality from IBGE. Also considered in Gautier and Jacqmin (2020), I expect that the more inhabitants, the higher the potential market and, as a consequence, the more PV installations. Lastly, the municipalities' area of extension (km²) is used to calculate the **pop. density**. De Groote et al. (2016) point that one may expect that the extension of open space raise 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, I run regressions on 4,599 municipalities ending up in 22,995 municipality/year observations. The Table 1.1 shows the descriptive statistics.

Table 1.1: 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
Inst. Cost (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)	22,995	9.5	1.1	6.7	8.6	9.4	10.1	15.7
Pop. Density (log) (hab./km ²)	22,995	3.2	1.4	-2.6	2.4	3.2	3.9	9.5
GDP per Hab. (log) (BRL)	22,995	9.7	0.7	6.0	9.1	9.6	10.1	13.8

1.3 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. Likewise, **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 are applied. Nonetheless, including these variables is 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. Equation 1.1 represents the specified estimation regression:

$$Y_{m,t} = \alpha + \beta \text{tariff}_{m,t} + \gamma X_{m,t} + \mu_m + \phi_t + \varepsilon_{m,t} \quad (1.1)$$

where α is a constant term, $\text{tariff}_{m,t}$ is the explanatory variable, $X_{m,t}$ is the vector of municipality-level covariates described earlier and $\varepsilon_{m,t}$ is the random error, representing the net effect of all other unobservable factors that might influence $Y_{m,t}$. I also include municipality μ_m and year dummies ϕ_t . The β and γ coefficients 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 1.1, 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 an 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 may 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. 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)). Residential electricity consumers might find difficult 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)).

1.4 Results and discussions

Table 1.2: Main results

Dep. Var.: # of New PV Projects	Model 1	Model 2	Model 3	Model 4	Model 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
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

Robust clustered standard errors are reported in parentheses.

⁺ $p < 0.10$, $*$ $p < 0.05$, $**$ $p < 0.01$, $***$ $p < 0.001$

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 and year levels 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 ². Table 1.2 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 1.3. In Table 1.4, I look at the robustness of the main results modifying the region-level fixed effects.

The ideal specification is reported in Model 1, where I associate the number of new residential PV projects with the lagged distribution tariffs. One may note that **tariff[t-1]** has a positive and statistically significant effect on the number of new residential PV projects. As the used estimator presents a log-linear nature, one may 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 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.

In Model 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 drop 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.

I estimate the Model 3 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; however, I need to drop the municipality fixed effects. From the results, one can observe that **PV output** 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 a residential customer to adopt PV. Population can be interpreted as the a potential market, so that the more inhabitants the higher the probability of PV adoption in a given municipality.

Models 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

²To compute the exact effect of a variable change in percentage, one may take the calculated semi-elasticities β and calculate $\exp[\beta] - 1$

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 ³. Therefore, this outcome reinforces 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 1.3: Further results

	Model 6 # of new Credited Units	Model 7 Capacity of New PV	Model 8 Average Capacity
Tariff[t-1]	0.095** (0.04)	0.049 (0.04)	0.035 (0.03)
GDP per hab. (log of)	-1.584 (1.21)	-2.142 (2.20)	-2.019 (1.53)
Pop. Density (log of)	-24.812* (11.38)	-36.004** (11.52)	-56.644*** (11.43)
Constant	132.173* (57.33)	201.894** (71.06)	218.215*** (43.02)
Observations	22995	22995	22995
Log Pseudo-Lik.	-8156.35	-39315.45	-18835.27
Municipality FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Robust clustered standard errors are reported in parentheses.

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Other dependent variables are used in Table 1.4. As specified Part I, a consumer may choose a modality of DG named as remote self-consumption. It allows her 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 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 rooftop and reduce the electricity bill from both consumption units. In Model 6, I use the number of new *credited units* as the dependent

³The 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).

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, $p = 0.1$). Thus, 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 Model 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 than where her living house is located.

In Models 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.

Table 1.4: Robustness check

	Model 1	Model 9	Model 10	Model 11	Model 12	Model 13	Model 3	Model 4
	Municipality	Microregion	Mesoregion	Disco Area	State	Great Region	None	None
Tariff[t-1]	0.052 ⁺ (0.03)	0.052 ⁺ (0.03)	0.054* (0.02)	0.052 ⁺ (0.03)	0.054* (0.02)	0.029** (0.01)	0.046*** (0.01)	0.042*** (0.01)
Install. Cost per Unit								-0.662*** (0.03)
PV Output		0.159 (0.80)	0.205 (0.41)	0.010 (0.25)	0.263 (0.24)	0.690* (0.27)	0.531 ⁺ (0.31)	0.537 ⁺ (0.31)
Population (log of)		1.167*** (0.07)	1.147*** (0.07)	1.152*** (0.05)	1.149*** (0.05)	1.063*** (0.07)	0.966*** (0.05)	0.966*** (0.05)
Pop. Density (log of)	1.361 (6.80)	-0.018 (0.09)	-0.048 (0.07)	-0.123* (0.05)	-0.133** (0.05)	-0.085 ⁺ (0.05)	-0.017 (0.04)	-0.016 (0.04)
GDP per hab. (log of)	0.152 (0.54)	0.716*** (0.17)	0.750*** (0.11)	0.735*** (0.11)	0.700*** (0.11)	0.662*** (0.11)	0.916*** (0.08)	0.909*** (0.07)
Constant	-10.046 (39.15)	-23.446*** (3.58)	-23.916*** (2.40)	-22.522*** (2.77)	-23.337*** (2.38)	-22.264*** (1.91)	-24.636*** (2.02)	-19.747*** (2.18)
Observations	22995	22995	22995	22995	22995	22995	22995	22995
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

Robust clustered standard errors are reported in parentheses.

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Taking advantage of the availability of data concerning different regional fixed effect level, a set of robustness check is disposed in Table 1.4. The analysis consists in modifying the regional aggregation from the most disaggregated, already displayed in Model 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, 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 when great region fixed effects are used in Model 13. **Population** coefficients are also stable in magnitude, remaining always positive, and are strong statistical significant already in Model 9, the second level of aggregation. **Pop. density** presents stable coefficients, excepting in Model 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.

1.5 Conclusion

In this chapter, 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 4,995 municipalities over the period of 2013-2017 was employed. Since the explanatory variable shows 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.

2

Determinants of residential PV adoption in a developing country context: Evidences from Brazil

2.1 Introduction

Electricity prosumption is a new phenomenon in electricity markets occurring when a consumption unit also produces electricity by a distributed generation (DG) system for self-consumption and exchange energy flow with the grid. Although associated as an intrinsic feature in power systems of the future, it is indeed a disruptive concept that must be better investigated by researchers and policymakers, because it might influence negatively the whole electricity industry chain, mainly the distribution sector.

One of the most used incentive mechanisms concerning residential prosumption - the focus of this analysis - is the net metering system. Whenever a residential prosumer

presents an energy surplus in a given billing period, she exports electricity into the grid. Contrariwise, if the prosumer presents a lack of production in relation to her consumption, she counts on the grid to achieve her electricity instantaneous demand. Consumption units are equipped with a single meter, so that it runs backwards when electricity is exported to the grid. Only net energy imports are used as the basis for electricity billing. Therefore, in the net metering system, the grid works as a virtual energy storage device.

Distribution companies (discos) receive a great part of their revenues through regulated volumetric structured electricity rates to cover the high distribution networks' fixed costs. Prosumption associated with net metering schemes present a twofold impact in business models of the electricity distribution sector. To begin with, it diminishes the energy consumed from the grid due to self-production, shrinking discos' revenues (Borenstein and Bushnell (2015)). Besides, the lack of synchronization between DG PV systems production and households consumption demands an increase in investments for the adaptation of the current distribution networks structure to receive a bidirectional energy flow (IEA-RETD (2014)). As a result, discos are required to raise tariffs with the purpose to cover fixed investments. This decision makes DG profitable for more customers who diminish their consumption. Consequently, it leads to a larger revenue shortfall and another rate increase, resurrecting the vicious cycle. A third point may be added in the case of developing countries with high rates of social inequality. The raise of electricity rates may also lead to an increase in the disco's risk of customer default, which may aggravate the scenario. The exposed outline affects upon the social optimum.

Previous authors dedicated their studies to investigate empirically the residential PV adoption experience approaching different aspects. Müller and Rode (2013); Bollinger and Gillingham (2012) analyzed the peer effects and Rode and Weber (2016) investigated how imitation dynamics happens spatially in residential PV. De Groote et al. (2016) and Kwan (2012) were interested in the relationship between social, economic, environmental and political drivers behind the residential PV adoption decision. Lan et al. (2020) evaluate the efficiency of feed-in tariffs on residential PV diffusion using spatial econometrics and Poruschi and Ambrey (2019) show a dynamic panel data model to analyse the impact of built environment and feed-in tariffs on the installation of solar rooftop PV. Gautier and Jacqmin (2020) and Moreno Rodrigo de Freitas (2020) were interested in how electricity tariffs under net metering system affect residential PV diffusion.

Understanding the residential PV prosumers characteristics is crucial to mitigate possible impacts that net metering may cause on electricity markets and for the proposition of solutions. Nonetheless, the great majority of empirical investigation on residential PV diffusion occurs in developed economies. One may understand that the main reasons are that residential PV adoption started earlier in developed economies and their governments make reliable data available to society making it easier for researchers and policymakers to explore it. Nonetheless, there are already some developing countries starting to implement policies to boost renewable energy share, including residential PV.

Brazil shows a great solar potential market. Concerning the natural resources, the country presents values from 3 to 6 kWh/m²/day of direct normal irradiation according to ESMAP (2016). Those numbers can stimulate not only DG PV systems investors, but also those interested in utility scale plants. Taking into consideration the electricity customer potential, 5,570 municipalities distributed through 26 states and the Federal District composes the country. Brazil has a huge population with about 210 million people and 69 million households. There are more than 84 million of electricity consumption unities, in which 75% are residential. Those numbers reflect the importance but also the potential to carry out empirical studies in the Brazilian household DG PV market.

This work contributes to a literature branch that focuses on understanding environmental, economic, social drivers on PV adoption behavior (Kwan (2012), Davidson et al. (2014) and De Groote et al. (2016)). Nevertheless, to my knowledge, this is the first study focusing on explaining heterogeneity in the residential adoption, using the complete installed base of PV in a developing country. As this study is realized at a census sector-level, I take advantage of a very rich set of socioeconomic and environmental characteristics with a total of 310,120 census sectors. This is the first work using that much large data set at such fine level of disaggregation, with on average 185 households per territory level.

The remainder of this chapter is structured as follows. Section 2.2 describes the used data. Section 2.3 establishes the methodology for the empirical proposal. Section 2.4 presents and discuss the findings. Section 2.5 concludes.

2.2 Data

The current empirical study is based on two main publicly available data sources. The database concerning distributed generation systems is provided by the Brazilian Electricity Agency, ANEEL. It comprises information about all DG systems under the net metering mechanism in Brazil. A second data source is the census 2010 realized and made available by the Geography and Statistics Brazilian Institute, IBGE. With further explained manipulations, it is possible to link both databases. Table 2.1 shows descriptive statistics of all used variables and I briefly describe them in the following subsections.

2.2.1 Dependent variables

The following information are available in ANEEL's public database concerning each of DG projects in Brazil: location (coordinates, municipality and state), technology type, installed capacity, number of registered households to receive energy credits and name of project developer (ANEEL (2020b)). To be eligible for the net metering scheme, DG systems adopters must register their project to the regulator. As the focus of this analysis is to investigate residential PV adoption, non-residential PV were excluded, remaining 112,231 PV projects, with a total capacity of 690,502.63 kWp and 133,324 registered households to receive credits up to December 31st 2019. With 112,231 households with installed PV systems on a total of 69.3 million households, the national adoption rate amounted to 0.16%.

The census sector is the territorial unit established for cadastral control bonds, formed by continuous area, located in a single urban or rural setting, with size and number of households that allow the survey by a census taker. I aggregate the total # of PV projects, the total # of credited housing units, the adoption rate, which is the quotient of the number of residential PV projects by the number of housing units, the total capacity and average capacity by census sectors to build the dependent variables used in the present work. In turn, it enables one to link the data to socioeconomic information at the census sector level. From 310,120 census sectors, only 27,320 had at least one PV project, which makes the used dependent variables highly non-gaussian.

Table 2.1: Descriptive statistics

Dependent Variables	N	Mean	St. Dev.	Min	Pctl(25)	Median	Pctl(75)	Max
PV Projects	310,120	0.4	2.0	0	0	0	0	459
Credited Housing Units	310,120	0.4	2.0	0	0	0	0	459
Adoption Rate	309,347	0.003	0.1	0.0	0.0	0.0	0.0	22.0
Capacity (kW)	310,120	2.2	12.1	0	0	0	0	1,005
Average Capacity	310,120	1.0	3.8	0	0	0	0	392
Independent Variables								
Housing Units (log)	309,347	5.0	0.9	0.0	4.7	5.2	5.5	7.5
Avg. Income (BRL) (log)	303,099	7.4	0.7	1.1	6.9	7.3	7.7	11.8
Age: under 25	309,525	0.1	0.05	0.0	0.03	0.1	0.1	1.0
Age: 25-34	309,525	0.2	0.1	0.0	0.1	0.2	0.2	1.0
Age: 35-44	309,525	0.2	0.1	0.0	0.2	0.2	0.3	1.0
Age: 45-54	309,525	0.2	0.1	0.0	0.2	0.2	0.2	1.0
Age: 55-65	309,525	0.2	0.1	0.0	0.1	0.2	0.2	1.0
Age: over 65	309,525	0.1	0.1	0.0	0.1	0.1	0.2	1.0
Male	303,327	0.6	0.2	0.0	0.5	0.6	0.7	1.0
Literate	303,327	0.9	0.2	0.0	0.8	0.9	1.0	1.0
White	303,818	0.5	0.3	0.0	0.3	0.5	0.7	1.0
Black	303,818	0.1	0.1	0.0	0.02	0.1	0.1	1.0
Asian	303,818	0.01	0.02	0.0	0.0	0.005	0.01	1.0
Brown	303,818	0.4	0.2	0.0	0.2	0.4	0.6	1.0
Indigenous	303,818	0.01	0.1	0.0	0.0	0.0	0.0	1.0
Residents: 1	303,178	0.1	0.1	0.0	0.1	0.1	0.2	1.0
Residents: 2	303,178	0.2	0.1	0.0	0.2	0.2	0.3	1.0
Residents: 3	303,178	0.2	0.1	0.0	0.2	0.2	0.3	0.9
Residents: 4	303,178	0.2	0.1	0.0	0.2	0.2	0.2	0.9
Residents: 5	303,178	0.1	0.05	0.0	0.1	0.1	0.1	0.9
Residents: over 5	303,178	0.1	0.1	0.0	0.04	0.1	0.1	1.0
PV Output (kWh/kWp) (log)	310,120	6.0	0.1	5.7	6.0	6.0	6.1	6.2
Housing type: house	303,178	0.9	0.3	0.0	0.9	1.0	1.0	1.0
Housing type: condo house	303,178	0.02	0.1	0.0	0.0	0.0	0.0	1.0
Housing type: apartment	303,178	0.1	0.2	0.0	0.0	0.0	0.03	1.0
Housing type: other	303,178	0.2	0.5	0.0	0.0	0.01	0.1	2.0
Ownership: own	303,178	0.7	0.2	0.0	0.7	0.8	0.8	1.0
Ownership: rent	303,178	0.2	0.1	0.0	0.1	0.2	0.2	1.0
Ownership: others	303,178	0.1	0.2	0.0	0.03	0.1	0.1	1.0
Bathrooms: 0	303,178	0.1	0.2	0.0	0.0	0.01	0.05	1.0
Bathrooms: 1	303,178	0.7	0.2	0.0	0.5	0.7	0.8	1.0
Bathrooms: 2	303,178	0.2	0.1	0.0	0.1	0.2	0.3	1.0
Bathrooms: 3	303,178	0.1	0.1	0.0	0.005	0.02	0.1	1.0
Bathrooms: over 3	303,178	0.02	0.1	0.0	0.0	0.004	0.02	1.0
Electricity 1	303,178	0.02	0.1	0.0	0.0	0.0	0.01	1.0
Electricity 2	303,178	0.01	0.1	0.0	0.0	0.0	0.0	1.0
Electricity 3	303,178	0.8	0.2	0.0	0.8	0.9	1.0	1.0
Electricity 4	303,178	0.1	0.1	0.0	0.01	0.04	0.1	1.0
Electricity 5	303,178	0.04	0.1	0.0	0.0	0.0	0.03	1.0

2.2.2 Economic variables

I use average **income**, defined as the average household income to represent the household purchasing power. As the Brazilian DG market is still emerging, funding opportunities are still scarce, so that PV systems installations present high initial costs. As wealthier people tends to have higher marginal propensity to save, they are the ones who can afford PV adoption. In the same reasoning, environmental preferences are considered as luxury good (Fransson and Gärling (1999)) and investing in PV systems reveals such condition. Income might indeed play an important role on household PV adoption process, being one of the main findings in previous works. Drury et al. (2012) found that PV adoption and income are highly correlated in the south of California. Kwan (2012) estimated a positive effect on PV installations and household annual income between 25,000 and 100,000 US dollars. Therefore, census sectors presenting higher incomes are expected to have higher PV adoption cases.

2.2.3 Social variables

The total number of **housing units** is used as a first variable in order to determine the residential PV systems potential market. It is expected that the number of PV projects will increase with the number of housing units.

PV systems need to capture the sunlight to produce electricity. If some part of the modules is shaded, the whole system suffers from production performance reduction. Thus, areas with open spaces, i.e. less urbanized, increase the potential for PV installations (De Groote et al. (2016)). This hypothesis may be tested using different variables. For instance, Kwan (2012) uses housing density and urban categories and De Groote et al. (2016) includes population density. In this work, I include census sector situation, a dummy variable that classifies the census sector within 4 groups: **urban 1** (developed area of town or village); **urban 2** (undeveloped area of town or village); **urban 3**: (isolated urban area); and **rural**, being this last dummy variable omitted from the investigation.

Next, **age**, explained as the age of housing unit's reference person whom the family considers the one for making important decisions. Willis et al. (2011) states that younger people are more motivated to adopt new technologies in general, while older people are less inclined to adopt such technologies. Kwan (2012) finds statistical significance in 25-

34 and 55-64 age ranges in the US. In turn, De Groote et al. (2016) point the propensity for PV adoption is the highest for the age group 34-44, followed by the age group 25-34. In this study, the age group under 25 is dropped.

Ethnicity is also explored as an important independent variable on new PV systems installation. I measure it including variables representing the proportion of **black**, **asian**, **brown** and **indigenous** in each census sector's population. Kwan (2012) estimate a negative impact on statistical sectors where the population is asian or black in the US. This findings are ratified in Bollinger and Gillingham (2012), in which they find a positive effect between white population and PV adoption. De Groote et al. (2016) measured ethnicity issues including a variable presenting the percentage of foreigners in the population and they found a high negative causality. The white population is omitted for the present analysis.

Some authors also point out gender issues concerning PV adoption, concluding that men are more likely to adopt solar panels (Bollinger and Gillingham (2012)) and new technology in general (Venkatesh et al. (2000)). On the other hand, Brough et al. (2016) suggest that the link between eco-friendly products and being feminine is complex to make any sort of *ex-ante* prediction. I use the **male** variable representing the gender of the housing unit's reference person to verify how it occurs in Brazil.

Education is a crucial variable on PV technology adoption, according to previous studies. For instance, Willis et al. (2011) specify that PV adoption is positively correlated to the fractions of the population with bachelor's or graduate degrees. Bollinger and Gillingham (2012) estimate a positive coefficient with statistical significance of population with college degrees and PV adoption in California. Kwan (2012) also estimates positive and statistical significance coefficients of people with college or more advanced studies and PV adoption. Unfortunately, there is no available data concerning the proportion of the population belonging to categorical variables representing levels of education in the census sector level for the present case study. Instead, as a proxy of education, I use **literate** representing the percentage of literate household unit's reference person, since it is considered as an important factor on the decision to adopt a new technology.

2.2.4 Environmental variable

A raster file containing the long-term yearly average of daily potential PV electricity production in Brazil, measured in kWh/kWp, is obtained from ESMAP (2016). Further refine-

ments are realized to build the final dataset. From the PV production potential raster file, I convert it into a shapefile in which each pixel centroid becomes a point containing the PV production potential information. Next, I extract these data points within each census sector extension and obtain the average of all points to extract the census sectors' average PV production potential and form **PV output** (kWh/kW). Previous studies mention that areas with higher solar irradiation tend to have more use of PV technology (Carley (2009); Kwan (2012)). In fact, if an area presents high PV production potential patterns, smaller PV systems are required to achieve the electricity consumption needed. Consequently, PV adoption are less costly for customers. Therefore, census sectors presenting higher **PV output** are expected to reveal higher PV adoption in comparison to those with lower.

2.2.5 Housing variables

Usually, residential customers use rooftops to install their PV systems. Therefore, I insert **housing type** variables to investigate which kind of building is relevant to explain the household PV adoption among house, condo house and apartment. De Groote et al. (2016) found a negative and a positive causality for apartments and semi-detached houses, respectively, and residential PV systems installation.

The variable **ownership** is described as the proportion of households occupied by their owners, rented or other sort of arrangement. Previous work indeed identified that owners are more likely to increase the expenditures on the residence (Mills and Schleich (2009); De Groote et al. (2016); Crago and Chernyakhovskiy (2017)). Other types of ownership are omitted from the regressions.

Housing size seems to exhibit a statistically significant positive effect on household PV adoption as related in previous research works. Davidson et al. (2014) used the number of rooms as a proxy for housing size. De Groote et al. (2016) adopted a straight variable informing the size of the housing units in square meters. As in Davidson et al. (2014), I also insert a proxy to represent housing unit size; however, instead of the number of rooms, I adopt the number of **bathrooms**.

In a net metering scheme, customers need the distribution networks to export their energy surplus. In households where there are no electricity distribution networks, for obvious reasons, it is not possible to install PV systems under net metering mechanism. Besides, customers must be associated to the local disco for the sake of energy billing. If

electricity exists in a given household, but no disco is responsible for the electricity supply, it is also impossible to install PV systems under net metering scheme. For net metering, it is essential to have a meter in the household, because it is based on its measurements that customers receive reductions on energy bills. Households with shared meters might be a constraint on PV adoption, because the decision to install a PV system must be agreed among all the households' decision makers sharing the meter. To explore all this complexity, I insert the variable **electricity** with five subspecifications: (1) without electricity; (2) with electricity but no responsible disco; (3) with disco but no meter; (4) with disco with shared meter; and (5) with disco and own meter. It is expected that census sectors with more households with own meters may have higher potentials for PV adoption. The subspecification without electricity is dropped from the regressions.

2.3 Empirical Strategy

I take advantage of the census sector-level data in order to investigate the impact of several census variables on the decision to install PV systems among residential customers. Municipality-level fixed effect is applied in order to capture unobserved heterogeneity across municipalities. I use municipality because it is the smallest territory level with the power to establish its own laws.

Let Y_c denote the amount of PV projects installed in census sector c . I model Y_c as a function of the explanatory variables. The following equation represents the specified estimation regression:

$$Y_c = \alpha + \beta housing.units_c + \gamma X_c + \mu_m + \varepsilon_c \quad (2.1)$$

where α is a constant term, X_c is a vector of census sector-level covariates described earlier and ε_c is the random error, representing the net effect of all other unobservable factors that might influence Y_c . The μ_m parameter is the municipality fixed dummy. The β and γ parameters measure the influence (i.e. marginal effect) of their associated explanatory variable on the dependent variable, keeping other explanatory variables constant.

From Table 2.1, it is possible to realize that about 83.4% of the observations are zero-valued, because in a large proportion of the census sectors there are not yet households

with PV systems installed. It happens since DG PV is a new emerging market in Brazil. Moreover, the dependent variable is heavily right skewed (skewness: 59.04) and has an excessive kurtosis (kurtosis: 10,136.64), configuring a non-normal distribution.

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 estimations 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)). In Santos Silva and Tenreyro (2011), results from simulation show that the PPML performs well compared with other estimators, proving that the PPML approach gives consistent estimates regardless of how data is distributed. One could find further details on the Poisson regression in Winkelmann (2008).

Another candidate is the Zero-Inflated Negative Binomial (ZINB) model also used to study PV adoption by Kwan (2012). However, as pointed out in De Groot et al. (2016), since PPML does not independently deal with the existence of zeros, the scale and significance of the coefficients estimates from PPML are easier to deduce. Moreover, the estimates from ordinarily applied zero-inflated models as ZINB are not robust to distributional misspecification, so that inference on the estimated parameters may be biased.

2.4 Results and discussions

In this section, I consider the regression results. Section 2.4.1 brings the discussion about the main model with the explanation of the total *# of new PV projects* per census sector. In Section 2.4.2, I realize several robustness check in order to validate the main model results.

It is worth mentioning that the categorical variables are relative proportions of a specific feature in the census sector, described as a portion of the total number of inhabitants, household representatives, households or housing units. For each of these cases, I drop one variable per set to be interpreted as the reference groups, because the categorical variable sets add up to one. Therefore, these reference groups receive a zero-valued coefficient in all results tables.

2.4.1 Main model: the drivers behind residential PV adoption

Table 2.2 compiles the results of regressions using PPML as estimator having the number of new residential PV projects as dependent variable. In Model 1, I include a set of economic, environmental and social variables. Model 2 is the preferred arrangement including not only the variables found in Model 1, but also a set of housing variables.

Models 1 and 2 present significant statistical effects on the number of **housing units** with elasticities of 0.623 and 0.759, respectively. Still, the unconditional housing units elasticity (without controlling for other covariates) is equal to 0.481. Therefore, these outcomes show that the number of new residential PV projects expands as the number of housing units rise. De Groote et al. (2016) found higher coefficients, close to one. This may occur because the Belgian region Flanders, the case of their study, counts not only on net metering scheme but other generous incentives concerning residential PV adoption as installation subsidy and tradable green energy certificates.

I specify the Model 1 with a set of variables as close as possible to the ones considered in the main model by Kwan (2012) and in the second model by De Groote et al. (2016) with some exception. Firstly, the cost of electricity, because it is not available at the level of census sector in Brazil. Regarding incentives, the most expressive is the net metering per se that covers all the Brazilian territory. The *CONFAZ* decision as explained in Part I may be interpreted as a state-level incentive and is explored in Section 2.4.2. Any sort of housing units value are neither available at census sector-level in Brazil. Thirdly, I dropped any political variables, due to the difficulty to explore it in Brazil. Differently from the US, there are thirty-three political parties in Brazil. Therefore, it is complex to classify the Brazilian parties according to an ideological spectrum, because their political support are not always related to their names. For some attempt methodologies see in Maciel et al. (2018); Scheffer (2018). Overall, the Model 1 results converges into those found by Kwan (2012) and De Groote et al. (2016).

Consider, firstly, the economic variables. Average **income** is statistically significant with an estimated elasticity of 1.236, playing an essential economical role on the number of PV projects. This result is expected because PV systems installation is still an expensive investment for the great majority of populations in emerging countries like Brazil. De Groote et al. (2016) found the unconditional income elasticity equal to 1.6, higher than what I find equal to 1.23. This may be associated to the fact that, in Flanders, PV adopters

Table 2.2: Regression results for main model: PV projects at the end of 2019

Dep. Var.: # of new PV Projects	Model 1		Model 2	
Housing Units (log)	0.623***	(0.03)	0.759***	(0.03)
Income: average (log)	1.236***	(0.03)	1.099***	(0.05)
Urban 1	-0.161*	(0.06)	0.117 ⁺	(0.07)
Urban 2	0.640***	(0.09)	0.730***	(0.09)
Urban 3	-0.008	(0.08)	0.016	(0.09)
Rural	0.000	(.)	0.000	(.)
Age: 25-34	-0.473	(0.42)	0.539	(0.43)
Age: 35-44	0.206	(0.35)	0.127	(0.36)
Age: 45-54	-1.427***	(0.35)	-1.495***	(0.36)
Age: 55-65	-0.498	(0.38)	-1.159**	(0.40)
Age: over 65	-1.800***	(0.38)	-2.202***	(0.39)
Age: under 25	0.000	(.)	0.000	(.)
Male	1.013***	(0.09)	0.512***	(0.08)
Literate	0.051	(0.24)	-0.002	(0.26)
Black	-1.769***	(0.25)	-2.463***	(0.25)
Asian	0.284	(0.68)	0.077	(0.69)
Brown	-0.591**	(0.19)	-0.810***	(0.21)
Indigenous	-2.353***	(0.46)	-2.101***	(0.51)
Residents: 1	-2.976***	(0.38)	0.957*	(0.40)
Residents: 2	-0.705 ⁺	(0.37)	1.221**	(0.38)
Residents: 3	-1.063**	(0.40)	-0.312	(0.41)
Residents: 4	0.126	(0.39)	-0.608	(0.40)
Residents: 5	-0.013	(0.58)	-0.811	(0.60)
Residents: over 5	0.000	(.)	0.000	(.)
PV Output (log)	-2.066*	(0.92)	0.470	(0.85)
Housing type: house			0.956**	(0.32)
Housing type: condo			0.847**	(0.32)
Housing type: apartment			-1.513***	(0.32)
Housing type: other			0.000	(.)
Ownership: owned			-1.217***	(0.11)
Ownership: rent			-1.965***	(0.14)
Ownership: others			0.000	(.)
Bathrooms: 1			-0.494**	(0.18)
Bathrooms: 2			0.750***	(0.22)
Bathrooms: 3			0.186	(0.24)
Bathrooms: over 3			1.728***	(0.25)
Bathrooms: 0			0.000	(.)
Electricity 1			-0.091	(0.42)
Electricity 2			0.226	(0.42)
Electricity 3			-0.312	(0.40)
Electricity 4			-0.548	(0.62)
Electricity 5			0.000	(.)
Constant	0.575	(5.53)	-14.268**	(5.16)
Observations	303099		303099	
Log Pseudo-Lik.	-214328.58		-204111.45	

Robust clustered standard errors are reported in parentheses.

⁺ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

benefited, not only from the net metering mechanism, but also others incentive schemes as green tradable certificates. Furthermore, the authors complete mentioning that the difference of lower and higher effect of income implies that a Mathew effect exists, in which richer dwellings take advantage proportionally more from the government support policies for PV as they have higher adoption rates and the same happens in Brazil.

Next, let us aim the social variables. As explained previously, **urban** is a dummy variable that classifies the census sectors according to their degrees of urbanization, being **urban 1,2,3** the several degrees of urbanization. The regression outcome shows that **urban 2** has a strong and positive correlation on residential PV adoption and **urban 1** has only a mildly significant negative effect. This outcome means that residential PV adoption in Brazil occurs more frequently in undeveloped area of town or village, which is the description for the **urban 2** dummy. Since Brazil is an emerging country, there is a great social and income inequalities between urban and rural areas. The latter may also present a lack of infrastructure concerning the basic needs for development. Therefore, PV adoption happens in those areas with enough infrastructure, but less likely in those highly populated. De Groote et al. (2016) specify that PV systems need horizontal open space as in areas with lower degree of urbanization and their findings also go to the same conclusion, in which population density has a significant negative influence on PV adoption in Flanders region. The omitted category is the rural dummy.

Next, let us consider variables concerning household's reference person characteristics. Two **age** groups, 45-54 and over 65 present a negative and significant impact on household PV adoption. Note that the group 55-65 also has a negative influence in Model 2 results, discussed further. Kwan (2012) and De Groote et al. (2016) found similar results. Concerning gender, **male** produces a positive effect on PV adoption ratifying the Venkatesh et al. (2000) suggestions, in which gender guides technology adoption. The only variable concerning education available for the analysis in the census sector was **literate** and it is not significant.

Ethnicity plays an important role on PV adoption. **Black, brown** and **indigenous** indicate a strong negative correlation on the dependent variable. Every 1% increase on these variables, reduces by 0.18%, 0.06% and 0.24% on PV installations, respectively. Kwan (2012) and De Groote et al. (2016) identify related results. The latter explains that this may reveal imbalances in the endorse for environmentalism and environmentally respon-

sible actions across various ethnical groups. I go beyond this explanation. In Brazil, there is a great social and income inequality between white and other ethnical groups as black, brown, and indigenous people. Almeida and Ribeiro (2019) defend the idea of the presence of a structural racism in the country. An evidence of this is the access to a new technology by only a certain ethnicity considered socioeconomically dominant. Previously, I mentioned the suggestion that PV adoption is strongly related to income, being this last is positive correlated to **white** and negatively **black, brown and indigenous**. It suggests that ethnical groups other than white may not adopt PV technology; however, it is not a matter of people's choice, but of social justice.

Regarding the number of **residents** in households, in spite of significant statistically, the results are inconclusive because the models yield different results. This may be an effect of omitted variables that are correlated with **residents** with one and two persons. The same happens to **PV output** which in Model 1 presented a mildly negative significance and not in Model 2.

Model 2 deems not only covariates estimated in Model 1, but also some related to housing units features. Most of the new covariates included are significant with the expected sign. Besides, some social variables become less important as housing unit characteristics are included.

As mentioned previously, residential PV systems generally need a rooftop to be installed like those in houses. I find that **house and condo house** are statistically significant with a positive effect on PV adoption, different from **apartment** that also presents significance but with a negative influence. Other housing types are used are dropped from analysis.

I expect that owners who live in their housing unit are those who install PV systems. There is some possibility that one may adopt a PV system and rent the household to a third part, however it is expected that the rent increases proportionally as the tenant reduces her electricity bill. Concerning **ownership**, rented housing units present a significant and negative influence on the target dependent variable. Surprisingly, the opposite occurs to those housing units that the owner lives in, presenting also a negative and significant effect. Other types of **ownership** are the omitted category.

Housing unit size is an important variable on PV adoption and it is expected that larger households may be related to larger electricity consumption. Still, it may be related to the

household income, with larger housing units belonging to wealthier people. Nevertheless, housing unit size was not available in the census sector level, so that I use the number of **bathrooms** as a proxy. The regression outcomes show that the number of **bathrooms** influences residential PV adoption. Households with one **bathroom** are statistically significant and has a negative effect, whereas households with two and over three **bathrooms** are also significant, but with a positive effect on PV adoption. I omit dwellings with no **bathrooms** from the regressions.

Concerning **electricity**, none of its related covariates is statistically significant. In Brazil, residential consumers can benefit from the net metering scheme, only if they are connected to the distribution grid and possess a meter. *A priori*, I expected that census sectors with a higher proportion of households connected to the local disco's grid and having its own meter, should influence PV adoption. Concerning the covariates, if a household does not have a meter, it is not possible to benefit from the net metering for the sake of energy counting. If a household has a shared meter, all the implied households owners must agree on the PV system installation, which is a more complex scenario. At last, if a dwelling has electricity, but no disco responsible for its electricity supply, it means that another source of energy production is used. Households with no electricity supply are dropped from the analysis.

2.4.2 Robustness check

In this section, I realize three different robustness analysis. Firstly, I obtain regression results for three subsampled periods fixed due to important changes in the support mechanisms implemented on the state-level and compare to the results of the whole sample. Secondly, I investigate the outcomes for models with other four dependent variables: the *# of new credited units*, the ratio *PV projects per households*, the total *capacity of new PV* and the *average capacity* of the PV systems. At last, I discuss the results of models applied to other levels of territory aggregation as dummies for the sake of robustness check.

As discussed in Part I, in the beginning of the Brazilian DG market, the federal states were applying the ICMS tax to the electricity exported to the grid. This decision was affecting negatively the return on investment of DG systems, in such way that it was inhibiting the development of the DG market in Brazil. In order to deal with this situation, CONFAZ set the agreement 16/15 authorizing the exemption of those taxes, so that the federal

Table 2.3: Regression results over time

Dep. Var.:	Model 3		Model 4		Model 5	
# of new PV Projects	2013-2015		2016-2017		2018-2019	
Housing Units (log)	0.861***	(0.08)	0.894***	(0.09)	0.740***	(0.02)
Income: average (log)	1.388***	(0.15)	1.243***	(0.08)	1.074***	(0.05)
Urban 1	-0.306	(0.23)	-0.476 ⁺	(0.25)	0.197***	(0.06)
Urban 2	0.433	(0.30)	0.249	(0.22)	0.793***	(0.09)
Urban 3	-0.300	(0.50)	-0.510*	(0.23)	0.087	(0.08)
Rural	0.000	(.)	0.000	(.)	0.000	(.)
Age: 25-34	1.651	(1.50)	-0.793	(1.55)	0.732 ⁺	(0.41)
Age: 35-44	1.028	(1.28)	-0.429	(1.13)	0.232	(0.36)
Age: 45-54	-2.349 ⁺	(1.40)	-2.607*	(1.18)	-1.271***	(0.35)
Age: 55-65	-0.374	(1.29)	-1.081	(1.28)	-1.170**	(0.40)
Age: over 65	-1.636	(1.26)	-3.329*	(1.30)	-2.026***	(0.38)
Age: under 25	0.000	(.)	0.000	(.)	0.000	(.)
Male	0.565 ⁺	(0.30)	0.510*	(0.25)	0.504***	(0.08)
Literate	2.436**	(0.93)	0.239	(0.84)	0.019	(0.26)
Black	-3.295**	(1.16)	-3.182***	(0.74)	-2.297***	(0.25)
Asian	-0.455	(2.35)	-3.742	(3.29)	0.581	(0.62)
Brown	-1.076*	(0.45)	-2.122*	(1.00)	-0.583***	(0.13)
Indigenous	-1.881	(1.45)	-1.472	(0.90)	-2.170***	(0.57)
Residents: 1	3.145*	(1.44)	0.393	(0.88)	1.009*	(0.40)
Residents: 2	0.089	(1.42)	1.988*	(0.87)	1.147**	(0.38)
Residents: 3	-0.017	(1.36)	-2.097*	(1.00)	-0.044	(0.41)
Residents: 4	-0.916	(1.40)	-0.797	(0.86)	-0.590	(0.41)
Residents: 5	0.041	(1.97)	0.177	(1.20)	-0.909	(0.61)
Residents: over 5	0.000	(.)	0.000	(.)	0.000	(.)
PV Output (log)	1.400	(2.90)	2.359	(2.07)	0.081	(0.83)
Housing type: house	5.285*	(2.13)	-0.225	(0.66)	1.092***	(0.33)
Housing type: condo	5.221*	(2.14)	-0.229	(0.67)	0.968**	(0.34)
Housing type: apartment	2.322	(2.14)	-2.930***	(0.69)	-1.336***	(0.33)
Housing type: other	0.000	(.)	0.000	(.)	0.000	(.)
Ownership: owned	-1.244***	(0.31)	-1.831***	(0.28)	-1.145***	(0.10)
Ownership: rent	-1.952***	(0.52)	-2.320***	(0.40)	-1.902***	(0.14)
Ownership: others	0.000	(.)	0.000	(.)	0.000	(.)
Bathrooms: 1	-0.838	(0.88)	-0.062	(0.47)	-0.563**	(0.19)
Bathrooms: 2	0.041	(0.97)	0.621	(0.63)	0.798***	(0.22)
Bathrooms: 3	0.115	(1.01)	0.658	(0.62)	0.121	(0.24)
Bathrooms: over 3	1.754 ⁺	(1.01)	1.672*	(0.68)	1.708***	(0.25)
Bathrooms: 0	0.000	(.)	0.000	(.)	0.000	(.)
Electricity 1	-1.514	(1.37)	-0.907	(1.21)	-0.026	(0.42)
Electricity 2	-1.113	(1.32)	-1.169	(1.30)	0.356	(0.42)
Electricity 3	-1.764	(1.28)	-0.747	(1.09)	-0.303	(0.39)
Electricity 4	-1.100	(1.73)	-1.568	(1.35)	-0.454	(0.64)
Electricity 5	0.000	(.)	0.000	(.)	0.000	(.)
Constant	-31.420 ⁺	(17.76)	-25.624*	(11.98)	-12.267*	(5.12)
Observations	303099		303099		303099	
Log Pseudo-Lik.	-5081.80		-40980.35		-184016.82	

Robust clustered standard errors are reported in parentheses.

⁺ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

states were free to comply with it. The adherences of the states to the agreement varied over time. Until the end of 2015, fifteen states were applying what the agreement stated in their territory; eight states from 2016 to 2017; and the last four states adhered in 2018. In this section, I split the sample into the three periods mentioned previously to evaluate if the effect of some variables alter over time. Table 2.3 assembles the regression outcomes contrasting the drivers of residential PV adoption for the three periods of analysis. Some covariates do not present any difference on the effect in the set periods. I analyse those showing any variation.

Let us first consider the economic variables presented by household income. I observe that as in Model 2, the effects of income are positive and significant for all the analyzed periods. However, it is worthy to note that the effects of income decays over the years. This may be attributed to the following facts. Firstly, the cost reduction of PV technology in Brazil, democratizing its residential adoption. In fact, the installation cost per unit reduced 30% from 2013 to 2018 (IDEAL and AHK-RJ (2019)). Secondly, due to the fact that before 2015, the federal states were taxing the energy exported to the grid making residential PV adoption less profitable. It may lead one think that early PV adopters in Brazil were not investing, but perhaps putting in practice sustainable choices.

Regarding the social variables, I observe the following. In the first period of analysis, the classification of the degree of urbanization of the census sector do not play an important role on PV adoption. In the second period, represented by Model 4, urban 1 and 3 present negative and significant effects. In the late period of analysis, urban 1 and 2 are positive and significant, but the latter has a larger effect than the former. Therefore, from 2018 onwards, the statement that residential PV adoption in Brazil is an "urban but not so dense" phenomenon gains support.

Concerning age, the unique presenting a constant effect over time in the matters of sign and significance is the 45-54 group. The over 65 group becomes significant in Model 4 and the 55-65 group in Model 5. The 25-34 group turn into positive and significant in the period 2018-2019. This may reveal the opportunity cost of the time, because, as younger people have smaller amounts of saved income, they would only invest on PV if there are no other investments options in the market. Literate also presents an interesting result. The covariate is significant with a positive effect only in the early periods of analysis. It may suggest that those early PV adopters present higher levels of education and that PV adoption may

have initially higher information costs. Regarding the housing units size represented by bathroom as a proxy, the effect of housing units with more than 3 bathrooms is the unique significant over the three subsampled period of analysis remaining always positive and amplifying its significance over the years. This may lead to the conclusion that early PV adopters have larger housing units, which may be related to wealthier households.

Up to now, I have analyzed the effect of several covariates only on the total number of PV projects. In the next analysis, I consider other dependent variables and Table 2.4 displays the regression results. As specified in Part I, a consumer may choose a modality of DG named as remote self-consumption and register other housing units of her own to benefit from the net metering scheme. In Model 6, I use the total number of credited units, in order to evaluate the impact of this remote self-consumption DG modality. In Model 7, I evaluate how covariates influence on the rate of adoption setting the ratio total number of PV project per housing units. Capacity and average capacity are then assessed in Models 8 and 9, in order to explore the impact of covariates in the size of PV projects.

Model 6 points that there is almost no difference between the effects on the total number of PV projects and the total number of credited units. Model 7 explicates that there are several differences of the impact of the covariates on the adoption rate and the total number of PV projects. The number of housing units influences negatively and significantly the adoption rate. It means that territories with less housing units present higher adoption rates. Concerning the degree of urbanization, different from Model 2, the category urban 1 is also statistically significant with a positive sign as urban 2 category. This result leads to the reasoning that the adoption rate is higher also in highly urbanized areas. Regarding age, the only group keeping the effect is over 65, in spite of reducing its significance. Hence, age has lower power of explaining adoption rate than explaining the total number of PV projects. Housing type also loses its capacity of explaining using adoption rate as a dependent variable. Regarding housing unit size represented by the number of bathrooms as a proxy, those categories with 2 and over 3 bathrooms are still statistically significant with a positive sign. Therefore, housing unit size matters on the PV adoption rate as well.

I use the total capacity as the dependent variable in Model 8. The effects of capacity and total PV projects are very similar, however some covariates gain statistical significance. Firstly, household with 4 and 5 residents become significant with a negative coefficient. In fact, these results ratify the findings in Model 2, in which territories with households

Table 2.4: Regression results for other dependent variables at the end of 2019

	Model 6		Model 7		Model 8		Model 9	
	# of Credited Units		Adoption Rate		Capacity		Average Capacity	
Housing Units (log)	0.756***	(0.03)	-0.442***	(0.03)	0.732***	(0.03)	0.555***	(0.01)
Income: average (log)	1.089***	(0.05)	0.795***	(0.08)	1.124***	(0.05)	0.704***	(0.03)
Urban 1	0.090	(0.07)	0.395***	(0.12)	0.084	(0.06)	0.136***	(0.04)
Urban 2	0.698***	(0.09)	0.939***	(0.19)	0.724***	(0.09)	0.560***	(0.05)
Urban 3	-0.019	(0.08)	0.019	(0.14)	0.112	(0.10)	0.284**	(0.09)
Rural	0.000	(.)	0.000	(.)	0.000	(.)	0.000	(.)
Age: 25-34	0.540	(0.42)	0.388	(0.87)	0.115	(0.68)	0.335	(0.28)
Age: 35-44	0.111	(0.36)	-0.510	(0.65)	-0.475	(0.59)	-0.261	(0.25)
Age: 45-54	-1.458***	(0.36)	-0.421	(0.69)	-1.776**	(0.60)	-0.671**	(0.25)
Age: 55-65	-1.140**	(0.40)	0.123	(0.75)	-2.000**	(0.62)	-0.626*	(0.26)
Age: over 65	-2.177***	(0.38)	-1.505 ⁺	(0.80)	-2.075***	(0.59)	-0.260	(0.24)
Age: under 25	0.000	(.)	0.000	(.)	0.000	(.)	0.000	(.)
Male	0.517***	(0.08)	0.568**	(0.18)	0.476***	(0.11)	0.172**	(0.06)
Literate	-0.072	(0.26)	-0.882	(0.58)	-0.412	(0.28)	0.491**	(0.18)
Black	-2.410***	(0.25)	-2.912***	(0.51)	-2.491***	(0.29)	-1.467***	(0.19)
Asian	0.097	(0.69)	-0.785	(0.98)	0.672	(0.56)	0.137	(0.42)
Brown	-0.786***	(0.21)	-0.769*	(0.31)	-0.657***	(0.13)	-0.404***	(0.09)
Indigenous	-2.154***	(0.52)	-1.060	(0.76)	-2.252***	(0.62)	-1.463***	(0.41)
Residents: 1	0.944*	(0.40)	-0.802	(0.78)	0.971*	(0.43)	1.083***	(0.28)
Residents: 2	1.219**	(0.38)	0.155	(0.70)	0.632	(0.39)	0.534*	(0.27)
Residents: 3	-0.310	(0.42)	-1.048	(0.83)	-0.645	(0.41)	0.183	(0.29)
Residents: 4	-0.639	(0.40)	-1.104	(0.84)	-1.258**	(0.42)	-0.504 ⁺	(0.27)
Residents: 5	-0.806	(0.60)	-0.762	(1.25)	-1.472*	(0.59)	-0.459	(0.37)
Residents: over 5	0.000	(.)	0.000	(.)	0.000	(.)	0.000	(.)
PV Output (log)	0.528	(0.85)	0.355	(1.95)	-0.027	(0.93)	1.458*	(0.72)
Housing type: house	0.987**	(0.32)	0.808	(0.69)	0.969**	(0.37)	0.059	(0.27)
Housing type: condo	0.881**	(0.33)	0.660	(0.70)	0.919*	(0.38)	-0.113	(0.28)
Housing type: apartment	-1.459***	(0.33)	-1.056	(0.69)	-1.422***	(0.38)	-1.700***	(0.27)
Housing type: other	0.000	(.)	0.000	(.)	0.000	(.)	0.000	(.)
Ownership: owned	-1.242***	(0.10)	-1.352***	(0.18)	-1.250***	(0.11)	-0.958***	(0.07)
Ownership: rent	-1.951***	(0.14)	-1.711***	(0.27)	-1.741***	(0.15)	-0.482***	(0.10)
Ownership: others	0.000	(.)	0.000	(.)	0.000	(.)	0.000	(.)
Bathrooms: 1	-0.500*	(0.19)	-0.125	(0.29)	-0.490*	(0.21)	0.136	(0.14)
Bathrooms: 2	0.761***	(0.23)	0.910*	(0.40)	0.794**	(0.24)	1.100***	(0.16)
Bathrooms: 3	0.215	(0.25)	0.641	(0.44)	0.185	(0.26)	0.783***	(0.18)
Bathrooms: over 3	1.753***	(0.26)	2.011***	(0.43)	2.174***	(0.28)	1.689***	(0.18)
Bathrooms: 0	0.000	(.)	0.000	(.)	0.000	(.)	0.000	(.)
Electricity 1	-0.038	(0.41)	0.472	(0.81)	-0.215	(0.42)	-0.322	(0.32)
Electricity 2	0.274	(0.42)	0.931	(0.81)	0.136	(0.41)	0.017	(0.31)
Electricity 3	-0.260	(0.39)	0.260	(0.78)	-0.365	(0.40)	0.000	(0.30)
Electricity 4	-0.548	(0.61)	0.310	(1.03)	-1.019 ⁺	(0.52)	-0.654	(0.45)
Electricity 5	0.000	(.)	0.000	(.)	0.000	(.)	0.000	(.)
Constant	-14.487**	(5.16)	-9.893	(12.10)	-8.244	(5.72)	-16.382***	(4.38)
Observations	303099		303099		303099		303099	
Log Pseudo-Lik.	-210237.10		-4118.98		-1073486.80		-536460.31	

Robust clustered standard errors are reported in parentheses.

⁺ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

with many residents lead to lower PV capacity. Besides, another covariate presenting a different result concerns electricity, the one expressing the proportion of housing units with electricity but no disco responsible for its supply. It is statistically significant with a negative effect on the capacity. This result is expected, because a household must be connected to some disco's network to benefit of the net metering scheme.

Lastly, I discuss the average capacity through Model 9. Regarding the degree of urbanization, the three categories of urban become statistically significant with a positive coefficient. Age also presents significance, for the groups 45-54 and 55-65. Household responsible literate become significant with a positive coefficient. This covariate do not show an important role on the other models analyzed. It leads one to conclude that territories with higher proportion of household with literate reference persons may lead to higher average capacity of residential PV systems. Concerning residents, areas with high proportion of households with 1 resident, become more significant preserving its coefficient sign. Thus, the higher number of residents in household the lower the average capacity. PV output effect turns into significant and positive, meaning that, in average, capacity are larger in zones where PV output is higher. This is the only specification in which this covariate is statistically significant. Houses and condo houses are not significant, although apartment keeps similar effect to the one in Model 2.

Tables 2.5 to 2.7 show a final robustness check in the Appendix A. In this analysis, I modify the territory fixed effects, from the most to the least disaggregated level. This robustness check is realized for the sake of sensibility. The objective is to verify how the coefficients vary as the region level is modified. As the disaggregation level reduces, the within variation of the covariates tends to increase and their effects may alter. Still, the performance of the models increase as the disaggregation level increases. I observe that there are some variables effects do not change considerably. One may conclude that these covariates may be included in other investigations of the same nature, even if they are available in less disaggregated levels. This is the case for housing units, average income, gender, ethnicity, housing type, ownership and housing size.

2.5 Conclusion

In this chapter, I investigate the determinants of residential PV adoption in an emerging country context using social, economic and environmental variables. The analysis is realized, mainly, using a dataset in census sector level with 310,120 observations, 42 covariates and territory fixed effects is applied in the municipality-level. The main results show that 21 covariates are statistically significant and that most of them may be related to income distribution issues in some degree. Therefore, net metering incentive mechanism had a positive influence to boost residential renewable energy generation, mainly PV technology. However, those who benefit from the incentive are wealthier people, which does not make sense in respect to social justice, because those who indeed need to be subsidized in order to reduce the electricity bills and increase the purchasing power are the underprivileged population.

2.6 Appendix A: Territorial robustness check

In this appendix one can find the territorial analysis as a final robustness check in the Tables 2.5 to 2.7.

Table 2.5: Territorial robustness check 1

Dep. Var.:	Model 10		Model 11		Model 12	
# of new PV Projects	Neighbourhood		Subdistrict		District	
Housing Units (log)	0.766***	(0.03)	0.743***	(0.03)	0.746***	(0.03)
Income: average (log)	1.033***	(0.05)	1.042***	(0.05)	1.090***	(0.05)
Urban 1	0.133	(0.08)	0.025	(0.07)	0.021	(0.07)
Urban 2	0.752***	(0.10)	0.624***	(0.09)	0.623***	(0.09)
Urban 3	0.081	(0.09)	-0.044	(0.09)	-0.061	(0.09)
Rural	0.000	(.)	0.000	(.)	0.000	(.)
Age: 25-34	0.283	(0.45)	0.406	(0.43)	0.482	(0.43)
Age: 35-44	-0.234	(0.38)	0.019	(0.36)	0.033	(0.35)
Age: 45-54	-1.640***	(0.38)	-1.642***	(0.36)	-1.583***	(0.36)
Age: 55-65	-0.947*	(0.41)	-1.238**	(0.40)	-1.178**	(0.39)
Age: over 65	-2.209***	(0.39)	-2.129***	(0.38)	-2.155***	(0.39)
Age: under 25	0.000	(.)	0.000	(.)	0.000	(.)
Male	0.520***	(0.09)	0.555***	(0.08)	0.559***	(0.08)
Literate	0.036	(0.28)	-0.014	(0.28)	-0.145	(0.27)
Black	-2.180***	(0.27)	-2.317***	(0.25)	-2.512***	(0.25)
Asian	0.569	(0.70)	0.009	(0.73)	-0.045	(0.73)
Brown	-0.851***	(0.24)	-0.833***	(0.22)	-0.854***	(0.21)
Indigenous	-2.213***	(0.59)	-2.204***	(0.56)	-2.265***	(0.57)
Residents: 1	0.397	(0.42)	1.206**	(0.40)	1.038**	(0.40)
Residents: 2	0.813*	(0.40)	1.558***	(0.37)	1.398***	(0.37)
Residents: 3	-0.520	(0.43)	0.107	(0.42)	-0.117	(0.42)
Residents: 4	-0.745 ⁺	(0.42)	-0.194	(0.41)	-0.423	(0.41)
Residents: 5	-1.108 ⁺	(0.62)	-0.606	(0.61)	-0.653	(0.60)
Residents: over 5	0.000	(.)	0.000	(.)	0.000	(.)
PV Output (log)	3.537**	(1.25)	-0.214	(1.51)	-1.041	(1.28)
Housing type: house	0.824*	(0.34)	0.935**	(0.31)	0.968**	(0.32)
Housing type: condo	0.676*	(0.34)	0.785*	(0.32)	0.870**	(0.33)
Housing type: apartment	-1.351***	(0.34)	-1.376***	(0.32)	-1.465***	(0.33)
Housing type: other	0.000	(.)	0.000	(.)	0.000	(.)
Ownership: owned	-1.362***	(0.11)	-1.197***	(0.11)	-1.214***	(0.11)
Ownership: rent	-2.067***	(0.16)	-2.077***	(0.15)	-2.059***	(0.14)
Ownership: others	0.000	(.)	0.000	(.)	0.000	(.)
Bathrooms: 1	-0.211	(0.19)	-0.487*	(0.20)	-0.512*	(0.20)
Bathrooms: 2	0.874***	(0.23)	0.688**	(0.24)	0.668**	(0.24)
Bathrooms: 3	0.439 ⁺	(0.25)	0.173	(0.25)	0.115	(0.25)
Bathrooms: over 3	1.881***	(0.27)	1.656***	(0.27)	1.615***	(0.27)
Bathrooms: 0	0.000	(.)	0.000	(.)	0.000	(.)
Electricity 1	-0.054	(0.41)	0.039	(0.43)	0.047	(0.43)
Electricity 2	0.173	(0.42)	0.282	(0.44)	0.310	(0.44)
Electricity 3	-0.301	(0.39)	-0.240	(0.41)	-0.200	(0.41)
Electricity 4	-0.429	(0.63)	-0.300	(0.61)	-0.284	(0.62)
Electricity 5	0.000	(.)	0.000	(.)	0.000	(.)
Constant	-31.873***	(7.59)	-9.743	(9.11)	-4.910	(7.74)
Observations	299394		302963		303007	
Log Pseudo-Lik.	-184986.90		-195925.77		-198218.78	

Robust clustered standard errors are reported in parentheses.

⁺ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.6: Territorial robustness check 2

Dep. Var.:	Model 13		Model 14		Model 15	
# of new PV Projects	Metropolitan Region		Microregion		Mesoregion	
Housing Units (log)	0.751***	(0.02)	0.779***	(0.03)	0.776***	(0.02)
Income: average (log)	1.091***	(0.04)	1.086***	(0.05)	1.037***	(0.04)
Urban 1	-0.070	(0.07)	0.120 ⁺	(0.07)	0.098	(0.07)
Urban 2	0.544***	(0.08)	0.829***	(0.09)	0.780***	(0.08)
Urban 3	-0.123	(0.09)	0.136	(0.08)	0.192*	(0.08)
Rural	0.000	(.)	0.000	(.)	0.000	(.)
Age: 25-34	-0.968*	(0.43)	0.323	(0.43)	0.064	(0.43)
Age: 35-44	-0.640 ⁺	(0.34)	0.086	(0.35)	0.112	(0.35)
Age: 45-54	-1.959***	(0.35)	-1.565***	(0.35)	-1.529***	(0.35)
Age: 55-65	-2.215***	(0.36)	-1.340***	(0.38)	-1.272***	(0.37)
Age: over 65	-3.303***	(0.38)	-2.686***	(0.38)	-2.727***	(0.38)
Age: under 25	0.000	(.)	0.000	(.)	0.000	(.)
Male	0.799***	(0.09)	0.559***	(0.08)	0.664***	(0.08)
Literate	0.566**	(0.21)	0.572*	(0.24)	0.808***	(0.22)
Black	-1.949***	(0.23)	-2.561***	(0.24)	-2.685***	(0.23)
Asian	0.450	(0.57)	0.711	(0.52)	1.081*	(0.51)
Brown	-0.393***	(0.08)	-0.949***	(0.18)	-0.889***	(0.15)
Indigenous	-2.087**	(0.73)	-1.929***	(0.48)	-1.986***	(0.52)
Residents: 1	3.270***	(0.37)	0.852*	(0.39)	1.051**	(0.37)
Residents: 2	4.342***	(0.38)	1.402***	(0.36)	1.920***	(0.37)
Residents: 3	2.056***	(0.39)	-0.299	(0.40)	0.024	(0.39)
Residents: 4	1.775***	(0.40)	-0.750 ⁺	(0.38)	-0.422	(0.39)
Residents: 5	1.510*	(0.60)	-0.722	(0.59)	-0.426	(0.59)
Residents: over 5	0.000	(.)	0.000	(.)	0.000	(.)
PV Output (log)	2.243***	(0.24)	1.632***	(0.46)	1.324***	(0.33)
Housing type: house	0.379	(0.29)	0.863**	(0.31)	0.686*	(0.31)
Housing type: condo	0.051	(0.30)	0.697*	(0.31)	0.488	(0.31)
Housing type: apartment	-2.263***	(0.29)	-1.811***	(0.31)	-2.042***	(0.31)
Housing type: other	0.000	(.)	0.000	(.)	0.000	(.)
Ownership: owned	-1.046***	(0.09)	-1.180***	(0.10)	-1.195***	(0.09)
Ownership: rent	-1.252***	(0.13)	-1.588***	(0.13)	-1.501***	(0.13)
Ownership: others	0.000	(.)	0.000	(.)	0.000	(.)
Bathrooms: 1	0.151	(0.15)	-0.311 ⁺	(0.17)	-0.035	(0.16)
Bathrooms: 2	1.114***	(0.19)	1.032***	(0.20)	1.277***	(0.20)
Bathrooms: 3	0.688***	(0.20)	0.423 ⁺	(0.22)	0.747***	(0.21)
Bathrooms: over 3	2.203***	(0.21)	2.005***	(0.23)	2.210***	(0.22)
Bathrooms: 0	0.000	(.)	0.000	(.)	0.000	(.)
Electricity 1	0.570	(0.44)	0.510	(0.44)	0.692	(0.45)
Electricity 2	0.896*	(0.45)	0.891*	(0.44)	1.104*	(0.45)
Electricity 3	0.663	(0.42)	0.331	(0.42)	0.577	(0.43)
Electricity 4	0.107	(0.68)	0.103	(0.67)	0.207	(0.68)
Electricity 5	0.000	(.)	0.000	(.)	0.000	(.)
Constant	-28.533***	(1.65)	-22.658***	(2.86)	-21.370***	(2.14)
Observations	303099		303099		303099	
Log Pseudo-Lik.	-237687.29		-218870.53		-225825.44	

Robust clustered standard errors are reported in parentheses.

⁺ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.7: Territorial robustness check 3

Dep. Var.:	Model 16		Model 17		Model 18	
# of new PV Projects	State		Great Region		Country	
Housing Units (log)	0.775***	(0.02)	0.729***	(0.03)	0.731***	(0.03)
Income: average (log)	0.824***	(0.04)	0.878***	(0.04)	0.908***	(0.04)
Urban 1	-0.055	(0.06)	-0.165**	(0.06)	-0.158*	(0.07)
Urban 2	0.627***	(0.08)	0.490***	(0.08)	0.496***	(0.09)
Urban 3	0.012	(0.08)	-0.203*	(0.08)	-0.211*	(0.08)
Rural	0.000	(.)	0.000	(.)	0.000	(.)
Age: 25-34	-0.419	(0.43)	-1.448***	(0.41)	-2.063***	(0.40)
Age: 35-44	-0.431	(0.35)	-1.649***	(0.32)	-2.094***	(0.32)
Age: 45-54	-1.789***	(0.35)	-2.234***	(0.34)	-2.631***	(0.34)
Age: 55-65	-1.984***	(0.37)	-2.880***	(0.35)	-3.370***	(0.34)
Age: over 65	-2.957***	(0.38)	-3.906***	(0.35)	-4.513***	(0.35)
Age: under 25	0.000	(.)	0.000	(.)	0.000	(.)
Male	0.966***	(0.09)	1.166***	(0.09)	1.190***	(0.09)
Literate	-0.245	(0.19)	0.112	(0.20)	0.250	(0.19)
Black	-3.352***	(0.24)	-1.404***	(0.21)	-2.058***	(0.21)
Asian	0.474	(0.55)	-3.910***	(0.65)	-4.360***	(0.65)
Brown	-0.764***	(0.12)	-0.072	(0.11)	-0.500***	(0.08)
Indigenous	-1.719**	(0.53)	-1.305*	(0.59)	-1.380**	(0.51)
Residents: 1	1.681***	(0.39)	4.221***	(0.37)	4.124***	(0.37)
Residents: 2	3.602***	(0.38)	5.336***	(0.37)	5.509***	(0.37)
Residents: 3	1.200**	(0.40)	2.785***	(0.40)	2.909***	(0.40)
Residents: 4	0.939*	(0.40)	2.530***	(0.40)	2.530***	(0.41)
Residents: 5	0.482	(0.61)	2.000***	(0.61)	2.008***	(0.61)
Residents: over 5	0.000	(.)	0.000	(.)	0.000	(.)
PV Output (log)	5.463***	(0.21)	4.756***	(0.15)	3.898***	(0.15)
Housing type: house	1.023**	(0.31)	1.185***	(0.29)	1.368***	(0.29)
Housing type: condo	0.743*	(0.32)	0.871**	(0.30)	1.014***	(0.30)
Housing type: apartment	-1.945***	(0.32)	-1.687***	(0.30)	-1.516***	(0.30)
Housing type: other	0.000	(.)	0.000	(.)	0.000	(.)
Ownership: owned	-1.335***	(0.09)	-1.156***	(0.09)	-1.085***	(0.09)
Ownership: rent	-0.964***	(0.12)	-1.225***	(0.12)	-1.330***	(0.12)
Ownership: others	0.000	(.)	0.000	(.)	0.000	(.)
Bathrooms: 1	0.348*	(0.16)	0.094	(0.16)	-0.002	(0.15)
Bathrooms: 2	2.039***	(0.19)	1.520***	(0.18)	1.145***	(0.18)
Bathrooms: 3	1.615***	(0.21)	1.488***	(0.20)	1.078***	(0.19)
Bathrooms: over 3	3.102***	(0.22)	2.387***	(0.21)	1.876***	(0.21)
Bathrooms: 0	0.000	(.)	0.000	(.)	0.000	(.)
Electricity 1	0.792 ⁺	(0.46)	0.500	(0.44)	0.454	(0.43)
Electricity 2	1.061*	(0.47)	0.647	(0.45)	0.560	(0.44)
Electricity 3	0.863 ⁺	(0.45)	0.999*	(0.42)	0.907*	(0.41)
Electricity 4	0.095	(0.73)	0.118	(0.68)	-0.079	(0.68)
Electricity 5	0.000	(.)	0.000	(.)	0.000	(.)
Constant	-45.796***	(1.47)	-43.193***	(1.17)	-37.730***	(1.17)
Observations	303099		303099		303099	
Log Pseudo-Lik.	-238487.41		-250595.52		-251812.29	

Robust clustered standard errors are reported in parentheses.

⁺ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

3

Social contagion and PV technology risk aversion among residential customers: Evidences from Brazil

3.1 Introduction

Power systems have been facing difficult and exceptional challenges in the recent years. The verticalized electricity industry - generation, transmission, distribution and supply - is giving place to a new-born complex one. This new framework have the power to affect all links in the electricity industry and encourage new market structures, business models and actors to emerge. Indeed, power systems of the future are likely to look hugely different from the ones in the present.

According to IEA (2019), 70% of global power capacity expansion will come from solar PV and wind and the half of solar PV growth will be based on distributed generation

(DG)¹ systems through 2024. Some of the main reasons may be pointed as the falling costs of PV technology around the globe due to the increase of energy conversion efficiency and the scalable feature, allowing the project customization from huge centralized plants to distributed household-scale ones. Although, IEA (2019) specifies that commercial and industrial undertakings stimulate distributed PV development globally, the progress of residential distributed PV will be also significant.

Previous authors dedicate their studies to investigate empirically the residential PV adoption experience approaching different aspects. Müller and Rode (2013); Bollinger and Gillingham (2012) analyze the peer effects and Rode and Weber (2016) investigate how imitation dynamics occurs spatially in residential PV. De Groote et al. (2016) and Kwan (2012) are interested in the social, economic, environmental and political drivers behind the residential PV adoption decision. Lan et al. (2020) evaluated the efficiency of feed-in tariffs on residential PV diffusion using spatial econometrics and Poruschi and Ambrey (2019) present a dynamic panel data model to analyse the impact of the built environment and feed-in tariffs on the installation of solar rooftop PV. Gautier and Jacqmin (2020) and Moreno Rodrigo de Freitas (2020) investigate how electricity tariffs affect residential PV diffusion under net metering system.

Brazil shows a great solar potential market. Concerning the natural resources, the country presents values from 3 to 6 kWh/m²/day of direct normal irradiation according to ESMAP (2016). Those numbers can stimulate not only DG PV systems investors, but also those interested in centralized plants. Taking into consideration the electricity customer potential, 5,570 municipalities distributed through 26 states and the Federal District composes the country. Brazil has a huge population with about 210 million people and 69 million households. There are more than 84 million electricity consumption unities, in which 75% are residential. Those numbers reflect, not only the importance, but also the potential to carry on empirical studies about the Brazilian household DG PV market.

This chapter contributes to a literature branch that focuses on understanding the influence of socioeconomic drivers on PV market diffusion and technology risk aversion by the residential segment on a municipality level. To my knowledge, this is the first study focusing on explaining heterogeneity in PV technology risk aversion, using the complete in-

¹In a broader sense, one can conceptualize DG, as small-scale power production systems located near the load centers, based on low-carbon technologies, connected to the distribution system or on the consumer side and not dispatched by the local system's operator.

stalled base of PV in a developing country. As this study is realized at a municipality-level, I benefit from a very rich set of socioeconomic characteristics with 5,570 municipalities. This is the first work using that much large data set at such fine level of disaggregation. A similar study was carried out by Kurdgelashvili et al. (2019), with certain caveats. Firstly, differently from my research, the authors did not investigate risk aversion concerning PV technology, but only the imitation process. Secondly, their analyses use a limited sample, because they have as study case the state of California in the county level, which is composed only by 46 counties. In turn, I investigate in the municipality level for the entire Brazilian territory, which is constituted by 5,570 municipalities. It means that my results are more robust, due to the number of observations in the used dataset.

The remainder of this chapter is structured as follows. Section 3.2 explains and brings discussions about technology diffusion studies. Section 3.3 describes the dataset used. Section 3.4 establishes the methodology of the empirical proposal. Section 3.5 presents and discuss the findings. Section 3.6 concludes.

3.2 Technology diffusion

In order to describe new methods to predict the acceptance of new products in a market, Fourt and Woodlock (1960) publish one of the first works about product diffusion. In Mansfield (1961), the author proposes a deterministic and a stochastic version of a model to explain the spread of innovation among firms. In 1962, the first edition of Rogers (2003) is published, in which the author dedicates a whole book to develop a theory on the diffusion of innovation. In short, the author states that the diffusion of innovation follows a normal shape curve, in which adopters can be divided as innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%) and the laggards (16%). Then, the integration of the diffusion of innovation curve will assume a S-shape form. He also makes some connections with social variables specifying that early adopters are better educated, more literate, have higher social status, a greater degree of upward social mobility and are wealthier than later ones.

3.2.1 The Bass model

Based on Roger's theory, a settled methodology in the sphere of economics is proposed in Bass (1969) named as the Bass diffusion model. It states that the instantaneous probability of adoption $f(t)$ follows the dynamics as in equation 3.1:

$$f(t) = \frac{dF(t)}{dt} = (p + qF(t))(1 - F(t)) \quad (3.1)$$

where $F(t)$ is the cumulative proportion of adopters in the population, p is the coefficient of innovation (or external effect), representing the role of innovators in the diffusion process and q is the coefficient of imitation (or internal effect), representing the "word-to-mouth" process. Integrating over time, the total fraction $F(t)$ of the adoption potential at time t is in equation 3.2. Multiplying $F(t)$ by the market potential $m > 0$, one can find the cumulative adoptions $Y(t)$ at time t in equation 3.3. It is important to note that m is a constant parameter in the original model. This premise is not adopted in the present work and it will be explained further in subsection 3.4.1.

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p}e^{-(p+q)t}} \quad (3.2)$$

$$Y(t) = mF(t) = m \left[\frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p}e^{-(p+q)t}} \right] \quad (3.3)$$

The Bass' model parameters p and q must be non-negative (Srinivasan and Mason (1986)). Bass (1969) states that, in a pure innovation scenario ($p > 0, q = 0$), diffusion follows a modified exponential; in a pure imitation scenario ($p = 0, q > 0$), diffusion follows a logistic curve. Besides, $(p + q)$ controls scale and the ratio (q/p) controls the shape, in which $q/p > 1$ is needed for the curve to be S-shaped.

3.2.2 Adopter's technology risk aversion behavior

Since the development of the Bass model, marketers, researchers and policymakers have been using it to predict technology diffusion with a high level of performance. There

are several social contagion mechanisms regarding new technology adoption, for instance, social learning under uncertainty, social-normative pressures, competitive concerns and performance networks effects (Van den Bulte and Stremersch (2004)). Although, some modifications on the original Bass model have been proposed, it is a complex duty to identify which social contagion process is occurring in the diffusion data.

A frequent phenomenon happens in many studies regarding several different types of innovation known as excess inertia or wait-and-see behavior. It happens when an eligible consumer delays the product's purchase raising several reasons for this including being uncertain about its quality and expecting its price to fall (Horsky (1990)). As the new technology is introduced, there is uncertainty associated with its experience- type attributes, due to the inexistence availability of experience information. To the extent that there is a heterogeneity in the population with respect to each individual's reservation price due to income and taste differences, risk averse customers will to pay less for a risky choice. In other words, they tend show a lower valuation of the product than if there were a complete information scenario (Kalish (1985)).

The Bass model coefficients may be used to understand, in which extent adopters are risk averse concerning a given technology. Van den Bulte and Stremersch (2004) carried out a paper in this theme. The q/p ratio express not only the shape of the adoption curve, but also reflects the relative importance of imitative and innovative tendencies. Van den Bulte and Stremersch (2004) states that risk averse population presents high q and low p values. Then, the authors confirm the hypothesis that the q/p ratio is positively associated with uncertainty avoidance, which can also be interpreted as technology risk aversion. Yaveroglu and Donthu (2002) also found similar results.

3.3 Data

The data used in the present work is acquired only from publicly available sources. The first data source is the Brazilian Electricity Agency (ANEEL in Portuguese abbreviation). Since the launch of NR 482 in 2012 and the appearance of DG systems in Brazil, ANEEL collects information about all the DG projects in Brazil. The available data concerns location (coordinates, municipality and state), technology type, date of connexion to the grid, installed capacity and name of the project developer (ANEEL (2020b)). The transparency

of this information is a mandatory requirement for the units to benefit from the net metering system. Data concerning the applied residential electricity tariffs by each distribution company (disco) in Brazil and the discos responsible for the energy supply for each municipality may also be obtained from ANEEL in ANEEL (2020a) and ANEEL (2020c), respectively.

A 1 km X 1 km raster resolution file containing the information about PV production yield data in kWh/kW/day covering all the Brazilian territory may be found in ESMAP (2016).² From there, I am able to extract the average annual PV production yield by each municipality. Another important variable for further calculation is the installation cost per unit at the country-level and was obtained from IDEAL and AHK-RJ (2015, 2016, 2017, 2018) and Greener (2019) in the 2013-2019 period. The demographic data used in the potential market estimation described in Subsection 3.4.1 and as regression explanatory variables detailed in Subsection 3.4.4 is obtained from the demographic census 2010 realized by the Brazilian Institute of Geography and Statistics (IBGE in Portuguese abbreviation) (IBGE (2010)).

3.4 Methodology and empirical strategy

3.4.1 Potential market estimation

The potential market is one of the main parameters of the Bass model. It characterizes the total number of individuals who can afford technically and economically the adoption of a given technology and the number of products that can be sold to them in a specific market. The potential market can be estimated by using the Bass model through observed data. Bass (2004) and Yamaguchi et al. (2013) state that this methodology is problematic, as it could result in significant underestimations. Thus, I propose in this section the following approach to estimate the potential market by external methods based on Konzen (2014).

At first, for each municipality m the total number of housing units HU_m is extracted from the census 2010 database. In general, residential PV systems are installed in a rooftop, so that f_{house_m} is the proportion of housing units considered as house or condo house types. PV adoption is a long-term commitment, because after installed, the PV system cannot be easily removed to be transferred to another housing unit. In other words, only

²The methodology and premises for PV production yield data can be found in ESMAP (2020).

residents having long term plans of staying in the housing unit install a PV system, so it is not applicable to rented housing units. Therefore, f_{own_m} is the proportion of housing units that is owned by their respective residents. The suitability factor f_{suit_m} is also used, as some housing units are not available for PV installation due to the fact that they present disturbance from shadow, chimneys, water tanks, antennas etc. The value considered is 0.85, also used by Konzen (2014), EPE (2019) and Da Silva et al. (2020).

Residential PV technology adoption is considered in the present work as a phenomenon that only wealthier people can afford, so that among all the housing units, only a smaller portion will install PV systems. EPE (2019) follows a premise that the threshold of the housing unit income is over three minimum wages and the same is adopted in f_{inc_m} . Besides, this income class is evolving in time, so that I extracted from CPS-FGV (2012) the average growth rate r_{st} by state st from 1993 to 2009 and set as a constant rate for all time t .³ In Appendix 3.7.1, Table 3.4 brings the r_{st} used in the estimation.

Multiplying all previously mentioned factors by the total housing units HU_m in each municipality m , one should estimate the maximum potential market $mpm_{m,t}$ for each year t , for the period 2013-2019, as in equation 3.4.

$$mpm_{m,t} = HU_m * f_{house_m} * f_{own_m} * f_{suit_m} * f_{inc_m} * (1 + r_{st})^t \quad (3.4)$$

The equation 3.4 estimates a portion of the housing units that would be able to afford a PV project technically and financially. Nevertheless, some previous studies specify that only a fraction will be motivated to invest according to the economic appeal (Navigating-Consulting (2007)). The impetus varies on the individual basis, some consumers are more inclined to adopt with slower financial returns, while the majority is uniquely captivated by shorter payback periods.

There are several ways of assessing a project technically and economically. One of the existing methods is through the simple payback time, i.e., the calculation of how much time is needed for the project's positive cash flow to surpass the initial investment. The major drawback of this method is that it does not take in consideration the present value of money. However, it is a simpler techno-economic assessment method from the residential electricity consumer's point of view, being adopted by previous studies as in Denholm et al.

³The information extracted is related to the growth of ABC income classes.

(2009) and Konzen (2014). Thus, I also use the simple payback period assessment.

Navigating-Consulting (2007) explains that the probability of residential PV adoption follows an exponential distribution depending on the payback period $PBP_{m,t}$ and the sensitivity to payback coefficient SP . The reasoning behind this assumption is that, as payback period tends to zero, the adoption rate tends to 100% and as the payback period increases the adoption rate tends asymptotically to 0%. Multiplying this distribution to the results of equation 3.4, one may find the final potential market $fpm_{m,t}$ as expressed in equation 3.5.

$$fpm_{m,t} = mpm_{m,t} * e^{-SP * PBP_{m,t}} \quad (3.5)$$

The $PBP_{m,t}$ calculation is based on the following method. Firstly, one needs to calculate the annual energy production by a given PV system. Using geographic information systems-GIS analysis tools in *RStudio* (RStudio-Team (2019)) with the *raster* (Hijmans (2020)) and *sf* (Pebesma (2018)) packages, I vectorize the raster file, obtaining the data points of pixel centroids. Next, I extract the data points within each municipality and calculate the average PV production yield. To arrive at the annual energy production yield by municipality, I multiplied by 365, the number of the days in a year. ANEEL (2018) uses a representative capacity of 7.5 kWp for the residential segment and the same premise is adopted in the present work. Then, I multiply it by the annual PV production yield and this result is the total PV production in the first year of the representative PV system for each municipality. The PV system is assumed to have a lifetime of 20 years, suffering a production depreciation in a rate of 1%/year.

Multiplying the representative capacity by the installation costs per unit one may find the total initial investment. Inverters usually present a 10 years lifetime and must be replaced after this period. ANEEL (2018) states that this represents 15% of the initial investment cost, hence I use the same premise.

Next, it is necessary to build the annual cash flow for the PV system project. It is based on the avoided costs comparing to a scenario in which the residential consumption unit do not possess a PV system. To calculate it, one needs the retail price practiced in the local of the installed PV system. It is worth noting that from 5,570 municipalities, 969 present more than one disco acting in their territories. Since, it is not possible to obtain information about the market share within municipalities; those are dropped from the analysis. I build

a R code to calculate the simple payback period for each year and municipality, so that it is possible to calculate the $fpm_{m,t}$.

3.4.2 Imitation and innovation coefficients estimation

The data used is set on a yearly basis. There are many methodologies for the Bass's model estimation, being originally implemented with the Ordinary Least Squares (OLS) estimator. Schmittlein and Mahajan (1982) proposed a new approach using the Maximum Likelihood (ML) estimator outperforming the OLS method. Srinivasan and Mason (1986) show that Non-Linear Least Squares (NLS) method is superior over ML and OLS estimators for $F(t)$ estimation also used by Jain and Rao (1990). Other approaches as Hierarchical Bayes method and the Augmented Kalman filter are reported in Lenk and Rao (1990) and Xie et al. (1997), respectively, achieving satisfying prediction capabilities. Nonetheless, all these methods present a drawback concerning a lower prediction performance if only pre-peak sales data is available for estimation. To overcome these inconveniences, Venkatesan and Kumar (2002) and Venkatesan et al. (2004) propose the genetic algorithms (GA) estimation method, testing against the methods previously mentioned and proving its superiority. Hence, I apply GA to estimate $\hat{\theta}_m = [\hat{p}_m \quad \hat{q}_m]$ according to the objective function found in equation 3.6, where $N_{m,t}$ is the observed cumulative adoptions by municipality m and year t . The results of $\hat{\theta}_m$ estimation serve to build the dependent variable of the present study \hat{q}_m/\hat{p}_m . I build a R code to estimate $\hat{\theta}_m$ based on the GA package (Scrucca (2013, 2017)). More details on the estimation of the Bass model using GA and the premises adopted are provided in Appendix 3.7.2.

$$\hat{\theta}_m = \operatorname{argmin} \sum_{t=1}^T \left(\frac{N_{m,t}}{fpm_{m,t}} - F_{m,t}(\theta_m) \right)^2 \quad (3.6)$$

3.4.3 Determinants for coefficients of residential PV technology risk aversion

Further, I apply a cross-sectional regression approach to investigate the impact of demographic census variables on \hat{q}/\hat{p} as in equation 3.7.

$$\hat{q}_m/\hat{p}_m = \alpha + \beta X_m + \mu_{mc} + \varepsilon_m \quad (3.7)$$

where α is a constant term and β measure the influence (i.e. marginal effect) of their associated explanatory variable on the dependent variable, keeping other explanatory variables constant. ε_m is the normally distributed error term, representing the net effect of all other unobservable factors that might influence the dependent variable. I also include fixed dummies μ_{mc} in order to capture unobserved heterogeneities across microregions. X_m is the vector representing the determinants of interest for each municipality m .

As described further in Subsection 3.5.1, the dependent variable \hat{q}/\hat{p} is highly asymmetric with a great proportion of zero values observation. The zero-inflated property of the dependent variable could create potentially large biases in parameter estimates when using traditional OLS estimation techniques (Santos Silva and Tenreyro (2006)). Hence, the main estimations 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 well compared with other estimators (Santos Silva and Tenreyro (2011)), proving that the PPML approach gives consistent estimates regardless of how the data are distributed. Therefore, PPML shows great advantages as an estimator for the spatial analysis of new technologies diffusion in emerging markets. One could find further details on the Poisson regression in Winkelmann (2008).

3.4.4 Covariates regression data

The dataset used to realized the regressions defined previously comes from the demographic census 2010. From there, I extract demographic variables at the municipality-level to investigate how they influence on residential PV technology risk aversion index divided in five groups: **urbanization**, **economic**, **people** and **housing**. Table 3.1 presents the descriptive statistics of the independent variables considering only the remaining census sectors analyzed in this work.

The **urbanization** group is composed by variables that are related to the process of ur-

Table 3.1: Descriptive statistics of the independent variables

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Median	Pctl(75)	Max
Housing Units (log)	2,841	8.10	1.15	5.48	7.24	7.94	8.69	14.58
Housing Density (log)	2,841	1.83	1.51	-3.79	1.01	1.87	2.61	8.34
Urban	2,841	62.60	21.66	4.51	46.16	62.97	80.80	100.00
Income: up to 1 mw	2,841	69.27	15.83	16.88	58.32	73.23	82.90	91.93
Income: 1-2 mw	2,841	17.30	10.23	1.81	8.48	14.26	25.48	51.54
Income: 2-3 mw	2,841	4.29	3.56	0.00	1.48	3.11	6.29	20.26
Income: 3-5 mw	2,841	2.62	2.38	0.00	0.80	1.83	3.82	16.34
Income: 5-10 mw	2,841	1.29	1.41	0.00	0.34	0.84	1.78	16.58
Income: over 10 mw	2,841	0.51	0.71	0.00	0.00	0.30	0.74	10.35
Rental Price up to 1 mw	2,841	97.16	5.58	28.45	96.39	99.99	100.00	100.00
Rental Price 1-2 mw	2,841	2.55	4.92	0.00	0.00	0.00	3.30	58.86
Rental Price 2-3 mw	2,841	0.19	0.70	0.00	0.00	0.00	0.00	10.00
Rental Price over 3 mw	2,841	0.10	0.75	0.00	0.00	0.00	0.00	21.00
Man	2,841	66.64	7.64	31.54	61.63	66.59	71.68	88.83
White	2,841	41.61	22.87	1.45	23.20	35.16	58.38	99.03
Age: 25-34	2,841	19.23	3.76	7.05	16.73	19.07	21.50	36.64
Age: 35-44	2,841	21.63	2.01	14.42	20.29	21.55	22.95	31.11
Age: 45-54	2,841	19.90	2.18	12.99	18.29	19.84	21.43	31.87
Age: 55-64	2,841	15.60	2.26	5.68	14.17	15.58	16.99	26.04
Age: over 64	2,841	17.47	4.20	2.50	14.75	17.62	20.34	30.61
Bachelor	2,841	3.14	2.12	0.11	1.63	2.59	4.09	21.70
Master	2,841	0.06	0.11	0.00	0.00	0.00	0.09	1.63
PhD	2,841	0.02	0.05	0.00	0.00	0.00	0.02	0.99
Bedrooms: 2	2,841	48.09	10.88	0.00	42.20	47.70	54.29	100.00
Bedrooms: 3	2,841	16.02	8.65	0.00	10.27	15.46	21.25	65.04
Bedrooms: 4	2,841	1.35	2.07	0.00	0.00	0.60	2.04	26.47
Bedrooms: 5	2,841	0.09	0.43	0.00	0.00	0.00	0.00	7.92
Bedrooms: over 5	2,841	0.02	0.17	0.00	0.00	0.00	0.00	4.00
Ownership: Own and Paid	2,841	74.60	11.07	26.15	67.03	75.35	83.22	96.38
Ownership: Own and Purchasing	2,841	2.79	3.77	0.00	0.32	1.04	3.98	29.07
Nuclear Arrangement	2,841	67.37	4.88	42.11	64.20	67.73	70.92	81.97
Extended Arrangement	2,841	19.08	4.66	8.72	15.75	18.19	21.68	45.91
Composed Arrangement	2,841	2.01	1.16	0.00	1.25	1.76	2.49	13.71

banization as the number of *housing units*, *housing density* and *urban*, defined as the proportion of housing units located in urban areas. The **economic** group contains the average *income*, the proportion of the housing units distributed as *income* range and the proportion of housing units belonging to *rental price* ranges. Income and rental prices ranges are measured as the equivalent of the quantity of minimum wages.⁴ The classes with no income or no declaration are omitted from the analysis.

Next, the **people** group gathers the characteristics of the housing units reference person, who is responsible for the decision-making, and the population. The variable *man* is defined as the proportion of housing units that the reference person is male gender. The ethnicity is used as *white*, meaning the proportion of housing units having a white person as reference. The *age* classes represent the proportion of reference persons belonging to the given age range. The range lower than 25 years old is dropped from the regressions. The population's maximum level of instruction is tested in *bachelor*, *master* and *Phd*.

Housing characteristics are used in the **housing** group. I use the number of *bedrooms* as a proxy for housing unit size, skipping the housing units with one bedroom from the investigation. Housing *ownership* is the proportion of housing units that are: *own and paid* - owned by the resident and the instalments payment are finished; *own and purchasing* - owned by the resident and the instalments payment are not finished; and *rented* - the resident rents his housing unit from a landlord. Household **arrangements** are divided in: *nuclear* - conventional family composed of couples with or without children and men or women without spouses with children; *extended* - version of nuclear defined by the presence of a person whose relationship with the reference person of the household is that of "another relative", *composed* - the same definition as nuclear, but including a non-relative person in the arrangement and *single person*, being this last omitted from the regressions.

3.5 Results and discussions

3.5.1 Bass model parameters

In this Subsection, I analyse the outcomes of the Bass model parameters estimation in the municipality-level described previously in Section 3.4. It is worth noting that, in the estimation procedure, I can only estimate 2,494 municipalities from a total of 5,570 because:

⁴In 2010, the minimum wage in Brazil was 540 BRL.

(i) some municipalities were excluded from the analysis because more than one disco operates within its territory; (ii) lack of data for the potential market estimation; and (iii) some municipalities do not present PV installation within its territory. Moreover, I explain further the building process of the \hat{q}_m/\hat{p}_m ratio that represents the PV technology risk aversion by residential customers and is used in the regression results as a dependant variable in Subsection 3.5.2.

Table 3.2 presents the descriptive statistics of Bass model coefficients. For the case where no subsetting rule is applied the imitation coefficient \hat{q}_m shows well behaved estimations concerning its descriptive statistics, tending to follow a gaussian distribution. Both of measures of central tendency, the mean and median results, are close to each other, presenting a unimodal distribution. The skewness and kurtosis outcomes are adjacent to the gaussian ones 0 and 3, respectively. Contrarily, the innovation coefficient \hat{p}_m presented a more extreme results, tending towards an exponential distribution, being excessive right skewed and leptokurtic. The \hat{q}_m/\hat{p}_m ratio ends up with a less sharp, but still right skewed and leptokurtic distribution. The error metrics sum of square errors (*SSE*), mean absolute deviation (*MAD*) and the coefficient of determination (R^2) presented a wide range, needing the application of a subsetting rule on the municipalities that will be analyzed.

Table 3.2: Descriptive statistics

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Median	Pctl(75)	Max	Skewness	Kurtosis
Estimated without subsetting rule										
\hat{q}_m	2,494	0.64196	0.28327	0.00014	0.45743	0.64504	0.84058	1.84949	-0.1016	2.8325
\hat{p}_m	2,494	0.00342	0.00955	0.00016	0.00073	0.00105	0.00200	0.13394	7.6012	78.0281
\hat{q}_m/\hat{p}_m	2,494	766.71	686.67	0.00000	227.33	620.61	1,140.43	4,513.28	1.5046	6.2848
SSE	2,494	0.02605	0.07130	0.00001	0.00182	0.00623	0.01810	0.96134	6.88607	65.59572
MAD	2,494	0.03219	0.03221	0.00084	0.01251	0.02250	0.03853	0.33749	3.17056	18.3656
R^2	2,494	0.73628	0.19885	-1.69133	0.63984	0.75473	0.88918	0.99933	-2.39853	18.74658
Estimated with subsetting rule: $R^2 > 0.8$										
\hat{q}_m	1,029	0.74166	0.24212	0.00039	0.56808	0.75621	0.90461	1.71434	-0.05161266	2.953286
\hat{p}_m	1,029	0.00194	0.00253	0.00035	0.00082	0.00109	0.00202	0.03591	5.194696	45.85629
\hat{q}_m/\hat{p}_m	1,029	731.02	507.87	0.02157	274.12880	717.61040	1,042.54200	3,124.92000	0.836459	4.090699
SSE	1,029	0.01409	0.02768	0.00001	0.00143	0.00453	0.01363	0.27112	5.030155	38.67985
MAD	1,029	0.02598	0.02113	0.00084	0.01135	0.01965	0.03359	0.14179	1.904622	8.047479
R^2	1,029	0.90152	0.05205	0.80003	0.86064	0.90339	0.94384	0.99933	-0.1446382	2.012402
Estimated with subsetting rule: $R^2 > 0.8$ including inserted zero values										
\hat{q}_m	2,841	0.26862	0.38514	0.00000	0.00000	0.00000	0.62052	1.71434	0.9774479	2.415137
\hat{p}_m	2,841	0.00070	0.00179	0.00000	0.00000	0.00000	0.00089	0.03591	6.944617	83.95331
\hat{q}_m/\hat{p}_m	2,841	264.77360	465.68150	0.00000	0.00000	0.00000	375.28020	3,124.92000	1.932457	6.687541

Still in Table 3.2, one may find the Bass model coefficients estimations concerning only those municipalities that presented the coefficient of determination higher than 0.8, 1,029 in total. The results show smoother statistics for the Bass model coefficients, the \hat{q}_m/\hat{p}_m ratio and the error metrics. 1,812 municipalities do not present residential PV adoption, so that they receive zero value on Bass model coefficients and the \hat{q}_m/\hat{p}_m ratio. I gather them to the $R^2 > 0.8$ subset municipalities to build the final dataset to be analyzed. The final \hat{q}_m/\hat{p}_m ratio presents a highly right skewed and leptokurtic distribution with about 63.8 % of zero value observations.

3.5.2 Determinants of the coefficient of residential PV technology risk aversion

Table 3.3 compiles the regression results having the \hat{q}_m/\hat{p}_m ratio as the dependant variable to represent PV technology risk aversion by the residential segment. From Model 1 to 4, I build regressions only with the explanatory variables belonging to each of the urbanization, economic, people and housing groups. In Model 5, I run the full model gathering all the explanatory variables applicable to the present work.

Table 3.3: Regression results

Dep. Var.:	Model 1	Model 2	Model 3	Model 4	Model 5
\hat{q}/\hat{p}	Urbanization	Economic	People	Housing	Full Model
Housing Units (log)	0.277*** (0.04)				0.426*** (0.05)
Housing Density (log)	-0.202*** (0.05)				-0.146* (0.06)
Urban	0.014*** (0.00)				0.012*** (0.00)
Income: up to 1		-0.000 (0.01)			-0.000 (0.02)
Income: 1-2		0.042** (0.02)			0.022 (0.02)
Income: 2-3		0.019 (0.03)			0.014 (0.03)
Income: 3-5		0.028 (0.04)			-0.008 (0.04)
Income: 5-10		0.054 (0.05)			0.066 (0.05)

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Table 3.3 – *Continued from previous page*

Dep. Var.: \hat{q}/\hat{p}	Model 1 Urbanization	Model 2 Economic	Model 3 People	Model 4 Housing	Model 5 Full Model
Income: 10+		-0.106 (0.07)			-0.159 ⁺ (0.08)
Rental Price: up to 1		0.036*** (0.01)			0.025*** (0.01)
Rental Price: 1-2		0.027* (0.01)			-0.017 (0.01)
Rental Price: 2-3		-0.023 (0.05)			-0.001 (0.06)
Rental Price: 3+		-0.026 (0.06)			-0.010 (0.05)
Man			-0.022*** (0.01)		0.009 (0.01)
White			0.021*** (0.00)		0.020*** (0.01)
Age: 25-34			0.015 (0.04)		-0.088 ⁺ (0.05)
Age: 35-44			0.046 (0.04)		-0.039 (0.04)
Age: 45-54			0.023 (0.04)		-0.076 ⁺ (0.04)
Age: 55-64			-0.020 (0.04)		-0.063 (0.05)
Age: over 64			0.018 (0.03)		-0.004 (0.04)
Bachelor			0.054* (0.02)		-0.067* (0.03)
Master			-0.178 (0.38)		-0.137 (0.40)
PhD			-1.102 ⁺ (0.59)		-0.693 (0.61)
Bedrooms: 2				-0.003 (0.00)	-0.002 (0.01)
Bedrooms: 3				0.012* (0.01)	0.001 (0.01)
Bedrooms: 4				0.003 (0.02)	0.002 (0.02)
Bedrooms: 5				0.049 (0.06)	0.007 (0.08)
Bedrooms: 5+				-0.016 (0.16)	0.125 (0.14)
Ownership:				-0.020**	-0.000
Own and Paid				(0.01)	(0.01)
Ownership:				0.002	0.000
Own and Purchasing				(0.01)	(0.01)

Continued on next page

Table 3.3 – *Continued from previous page*

Dep. Var.: \hat{q}/\hat{p}	Model 1 Urbanization	Model 2 Economic	Model 3 People	Model 4 Housing	Model 5 Full Model
Nuclear				-0.005 (0.02)	0.018 (0.03)
Extended				0.088*** (0.02)	0.082** (0.03)
Composed				0.028 (0.04)	0.081 (0.06)
Constant	3.292*** (0.29)	1.688 (1.46)	4.634 (3.02)	6.247*** (1.49)	0.433 (4.08)
Observations	2794	2794	2794	2794	2794
Log Pseudo-Lik.	-407559.82	-407419.49	-429512.71	-426289.05	-370638.42

Robust clustered standard errors in parentheses.

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Distinct causes make less clear the analysis of the determinants related to the coefficient of PV technology risk aversion by the residential segment. Firstly, the coefficients of innovation and imitation needed to build the \hat{q}_m/\hat{p}_m ratio are considered to be static regarding time, although the used explanatory variables are dynamic. Next, I am not able of employing panel and time series methods, since the diffusion parameters present a cross-sectional sort. At last, I must be moderate on the interpretation, because some of the used explanatory variables are correlated.

Firstly, consider the covariates related to the urbanization process. In Model 1, all three included variables are statistically significant. Housing units and urban covariate present a positive effect on PV technology risk aversion; however housing density has a negative influence. The significance and signs of their effects are kept in Model 5. More precisely, the results suggest that, on one hand, the more housing units or the higher the proportion of housing units located within urban areas, the more risk averse is the residential segment. On the other hand, as housing density increases, residential customers are more risk loving concerning PV adoption.

Next, I explore the economic variables group. It is composed by the household distribution within income and rental price ranges calculated as the amount of minimum wages (mw). In Model 2, the only statistically significant variable regarding income is in the range of 1 to 2 minimum wages, with a positive sign. For the rental price, both ranges, up to 1 and 1 to 2, show a positive effect on PV technology risk aversion. In the full model,

due to multicollinearity issues, income 1-2 and rental price 1-2 drop in significance. The income range over 10 mw becomes mildly positive significant. These outcomes may reveal a risk appetite feature among wealthier people and risk aversion for underprivileged ones.

Now consider the people group of covariates. In Model 3, the only explanatory variables presenting statistical significance are man and PhD, with a negative sign; and white and bachelor presenting a positive. In the complete configuration in Model 5, man and PhD drop in significance and the age ranges 25-35 and 45-54 become significant with a negative effect. Still, bachelor keeps its statistical significance, but changes its sign. It suggests that people with superior degrees may be more risk loving concerning PV technology. The cause may be interpreted as that they understand better the risks and return because they are better informed. Another possibility is that they may present an environmental consciousness due to their level of instruction, so that they know that self-producing electricity through PV systems may help reduce their carbon footprints. Concerning age, Kellstedt et al. (2008) states that older people have less concern for global warming and environmental issues than younger populations and this support my findings.

Lastly, I analyse the housing characteristics group. In Model 4, three variables are statistically significant: bedrooms 3; own and paid; and extended arrangement. Nevertheless, this last is the unique keeping its significance in the full Model 5. Extended arrangement households are those in which other relatives live with the nuclear family (couple/single mother with kids). The reason related to the fact that other relatives live with the nuclear family may be that they cannot afford their own housing unit, so that they must suffer from low-income issues and then, risk averse.

Appendix C in Section 3.7.3, brings the robustness check results in Table 3.5. In Models 6 and 7, I run regressions using the socioeconomic variables on the coefficients of imitation and innovation, respectively, as dependent variables. The purpose of this analysis is to figure out which covariates are related to each of the imitation and/or innovation processes. In general lines, the robustness check ratifies the main results. Still, I observe that some variables are only associated to one of both processes previously mentioned. The income range from 1 to 2 minimum wages is significant and positive regarding imitators. It is in accordance with the main results, because lower income households are risk averse and they imitate risk lovers innovators. The three youngest age groups, 25-34, 35-44 and 45-54 are significant and positive concerning innovators. This result support the main findings

in which younger people are risk lovers concerning PV technology, due to environmental awareness. Next, the level of education revealed that bachelor is significant and negative for imitation, master is significant and negative for innovation and PhD is significant and positive for innovation coefficients. It means that population with bachelor and PhD studies are risk lovers and, surprisingly, population master studies are risk averse concerning PV adoption. The two classes of ownership are significantly and negatively associated to the innovation process, meaning that household owners may adopt PV systems, but they are conservative on PV investment. Extended arrangement housing units are considered risk averse about PV technology according to the main results. This is confirmed as it presents a positive and significant effect on the imitation coefficient.

3.6 Conclusion

In this chapter, I examine the association between certain socioeconomic covariates and PV market diffusion in the municipality level. I conduct a two-stage empirical analysis. At first, I use the Bass technology diffusion model to estimate the innovation and imitation coefficients. For that, I build the q/p ratio to represent a risk aversion index to each respective municipality's adoption rate over time. In the second stage, I run regressions based on the PPML estimator, due to the non-gaussian nature of the dependent variable, to investigate associations between the risk aversion index and different socio-demographic and economic covariates. The results show evidences of the association of PV technology risk aversion and households socioeconomic characteristics. This behavior may be based on several assumption as regulatory uncertainty, technology information and easy to understand rules for average customers etc.

3.7 Appendix

3.7.1 Appendix A: ABC classes growth rate

Table 3.4: ABC class growth rate

State	Rate	State	Rate
Rondônia	4.7%	Alagoas	3.91%
Acre	3.01%	Sergipe	4.41%
Amazonas	4.23%	Bahia	5.49%
Roraima	3.00%	Minas Gerais	4.81%
Pará	3.61%	Espírito Santo	4.79%
Amapá	4.59%	Rio de Janeiro	2.15%
Tocantins	9.21%	São Paulo	2.1%
Maranhão	8.78%	Paraná	4.45%
Piauí	9.35%	Santa Catarina	3.36%
Ceará	6.91%	Rio Grande do Sul	2.13%
Rio Grande do Norte	6.00%	Mato Grosso do Sul	4.23%
Paraíba	6.15%	Mato Grosso	5.4%
Pernambuco	5.19%	Goiás	4.65%
		Distrito Federal	2.42%

3.7.2 Appendix B: Estimation of diffusion models using GA

Genetic Algorithms (GA) is a stochastic parallel search algorithm based upon Darwin's theory of evolution. In this work, I use the R package called *GA* from Scrucca (2013, 2017). The following pseudocode was adapted from Venkatesan et al. (2004). The parameters that are not set are used as default in the package implementation and may be found in the reference previously indicated. I set *seed* = 1 for the sake of reproducibility.

Solution string: (p, q)

Fitness function:

$$SSE = \frac{1}{T} \sum_{t=1}^T [x(t) - \hat{x}(t)]^2 \quad (3.8)$$

where $x(t)$ = actual cumulative adoption rate in respect to the calculated potential market and $\hat{x}(t) = F(t)$.

Step 1: Generate 1,000 random real-valued candidate solution strings in the interval $[0,10]$ to create generation $i = 1$.

Step 2: Select candidate solution vectors for iteration $i + 1$ from solution strings in iteration i . Solution vectors with a lower SSE have a higher probability of being selected for iteration $i + 1$.

Step 3: Perform crossover and mutation on the candidate solution vectors to generate a solution set for iteration $i + 1$.

Step 4: Compute fitness value for solution vectors and the optimal solution string in iteration $i + 1$.

Step 5: Proceed to Step 2 if the optimal solution string has changed in the last 500 iterations; else terminate. 10,000 is the maximal iterations.

3.7.3 Appendix C: Further regressions for robustness check

Table 3.5: Robustness check

Dep. Var.	Model 6		Model 7	
	\hat{q}		\hat{p}	
Housing Units (log)	0.379***	(0.04)	0.297***	(0.06)
Housing Density (log)	-0.169***	(0.04)	-0.165*	(0.07)
Urban	0.013***	(0.00)	0.017***	(0.00)
Income: up to 1	-0.000	(0.01)	-0.030	(0.02)
Income: 1-2	0.025 ⁺	(0.01)	-0.018	(0.02)
Income: 2-3	0.009	(0.02)	-0.028	(0.04)
Income: 3-5	0.017	(0.03)	0.014	(0.06)
Income: 5-10	0.012	(0.04)	-0.020	(0.07)
Income: over 10	-0.049	(0.05)	0.134	(0.11)
Rental Price: up to 1	0.022***	(0.01)	0.030***	(0.01)
Rental Price: 1-2	-0.010	(0.01)	0.002	(0.02)
Rental Price: 2-3	0.020	(0.04)	-0.012	(0.05)
Rental Price: over 3	0.043	(0.04)	0.071	(0.05)
Man	-0.001	(0.01)	-0.015	(0.01)
White	0.018***	(0.00)	0.014 ⁺	(0.01)
Age: 25-34	-0.041	(0.04)	0.153*	(0.07)
Age: 35-44	0.016	(0.03)	0.174**	(0.06)
Age: 45-54	-0.029	(0.03)	0.129*	(0.06)
Age: 55-64	-0.012	(0.03)	0.076	(0.06)
Age: over 64	0.007	(0.03)	0.076	(0.05)
Bachelor	-0.050*	(0.02)	0.031	(0.05)
Master	-0.347	(0.29)	-1.371**	(0.47)
PhD	-0.195	(0.38)	1.350*	(0.68)
Bedrooms: 2	-0.002	(0.00)	0.002	(0.01)
Bedrooms: 3	0.003	(0.00)	0.015 ⁺	(0.01)
Bedrooms: 4	0.006	(0.01)	0.020	(0.02)
Bedrooms: 5	0.038	(0.06)	0.104	(0.10)
Bedrooms: over 5	0.123	(0.11)	0.196	(0.26)
Ownership: Own and Paid	-0.004	(0.01)	-0.017 ⁺	(0.01)
Ownership: Own and Purchasing	-0.011	(0.01)	-0.061***	(0.02)
Nuclear Arrangement	0.025	(0.02)	-0.032	(0.03)
Extended Arrangement	0.053**	(0.02)	-0.006	(0.03)
Composed Arrangement	0.040	(0.05)	-0.085	(0.08)
Constant	-9.240**	(3.15)	-18.691***	(5.60)
Observations	2794		2794	
Log Pseudo-Lik.	-1142.99		-13.13	

Robust clustered standard errors in parentheses.

⁺ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Part III

General conclusion

Although indispensable to the contemporary way of living and economy, power systems are experiencing complex and remarkable challenges in recent years. The traditional vertically integrated power systems are changing towards a smarter system with a high presence of renewable technologies, distributed generation, greater energy efficiency and electric vehicles. Solar PV is the technology with the highest share among residential DG systems, due to several reasons among them: falling costs, increase of energy conversion efficiency and scalability features.

Brazil launched the Normative Resolution 482 in 2012 allowing prosumers to connect their DG systems to the distribution networks and benefit from the net metering incentive scheme. Modifications on the original resolution helped Brazil to boost the DG participation in its mostly based on hydropower electricity matrix. Due to its idiosyncrasies, residential PV is the most promising niche in the DG Brazilian market. By the end of 2019, more than 100,000 households had installed a PV system. Some modifications on the current regulation may impact the prosumer's return on investment and slow down the speed of adoptions.

In Chapter 1, 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 4,995 municipalities over the period of 2013-2017 is employed. Since the explanatory variable showed high content of zero-valued observations I use the PPML estimator to run the regressions.

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 play an important role on the residential decision to install PV system as well. 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 main model structure is modified, as in the findings of Kwan (2012). The latter shows a statistical strong negative effect, as expected. This outcome means that if country's energy planners want to encourage residential PV adoption, they 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 Chapter 1 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 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" phenomenon in the analysis, Chapter 1 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 behavior.

In Chapter 2, I investigate the determinants of residential PV adoption in an emerging country context using social, economic and environmental variables. The analysis is realized using a dataset in census sector level with 310,120 observations and 42 covariates. I apply territory fixed effects in the municipality-level. This is one of the first studies analysing the residential PV adoption in a national territory extension outside the US-Europe axis, with a rich dataset in such fine level of disaggregation (on average 185 households). Again, as the dependent variable shows high content of zero-valued observations I used the PPML estimator.

Regarding the main model, the findings in Chapter 2 are the following. Firstly, in the preferred model, the housing units elasticity is 0.76, being as high as 0.89 considering only the two-year period 2016-2017, and as low as 0.48 in unconditional elasticity (without controlling for other covariates). These results show that the number of residential PV projects amplifies as the number of housing units increase.

Secondly, the unconditional income elasticity is as high as 1.23, arriving at 1.39 in the three-year period 2013-2015. De Groot et al. (2016) found similar results, suggesting that in their case study occurred the Matthew effect, in other words, wealthier households takes advantage of subsidies overmuch. The same effect occurs in Brazil.

PV systems need open vertical spaces to be installed, otherwise their performance may be drastically reduced, due to shadowing. Parallely, as mentioned previously, residential PV adoption is a phenomenon of wealthier households. In Brazil, then, urban areas present higher average household income. Therefore, residential PV adoption in Brazil happens more frequently in urban zones considered as undeveloped areas of town or village.

A fourth main finding is that three people characteristics also reveal to be important. Older household reference persons are less likely to install PV systems. Male gender presents positive influence on PV adoption. Regarding ethnicity, those other than white are less likely to adopt, which may reflect the social structural features of Brazilian society, since PV adoption is tied to richer people behavior.

The fifth main finding is related to housing units characteristics. Housing type proves the *a priori* hypotheses considering the presence of a rooftop at the housing unit, in which houses and condo houses impact positively and apartments negatively on residential PV adoption. Rented housing units have a negative effect and housing unit size also play an important role.

In sum, the results of Chapter 2 show that the net metering incentive mechanism had a positive influence to boost residential renewable energy generation, mainly PV technology. However, those who benefit from the incentive are wealthier people, which does not make sense in the aspect of social justice. In fact, those who indeed need to benefit from subsidies to reduce electricity bills are underprivileged people. Besides, it is proved that those who adopt PV residential, richer people, are the same who start the vicious circle, receiving cross subsidies from non adopters, again, low-income residents. Therefore, net metering is a good mechanism to encourage renewable energy technology adoption among residential consumers in emerging DG markets. Nevertheless, as soon as the market is set, the rules must be reviewed to avoid greater distortions and restore the social optimum.

Social contagion and customer innovation risk aversion are of specific interest to researchers, marketers and policymakers. In Chapter 3, I examine the relationship between certain socioeconomic determinants and PV market diffusion in the municipality level. I

conduct a two-stage empirical analysis. At first, I use the Bass technology diffusion model to estimate the innovation and imitation coefficients, building, then, the q/p ratio to represent a risk aversion index to each respective municipality's adoption rate over time. In the second stage, I run regressions based on the PPML estimator, due to the non-gaussian nature of the dependant variable, to investigate associations between the risk aversion index and different socio-demographic and economic covariates in each municipality.

Concerning the first-stage analysis, the imitation coefficient estimation is close to a gaussian distribution, differently from the innovation coefficient, which presents a sharply non-gaussian distribution. Thus, the ratio between these two parameters, the risk aversion index distribution, neither produces a normal distribution dependent variable. In an attempt to have it closer to a gaussian distribution, those municipalities presenting a coefficient of determination lower than 0.8 are excluded from the analysis, which indeed succeeds. Gathering with the municipalities with no residential PV installations and inserting a zero value for the q/p ratio, ends up with about 63.8% of zero valued observations.

In the second-stage analysis, some important determinants are found to be related to PV technology risk aversion by the residential segment. Under the urbanization group, all of them seems to play an important role. Investigating the economic group, the hypothesis of underprivileged people are more risk averse than wealthy ones holds. Age, ethnicity and level of education are also important. The familiar arrangement explains partially the models results as well.

In sum, the results of Chapter 3 show evidences of the PV technology risk aversion association with some socioeconomic characteristics of dwellings. This behavior may be based on several assumption as regulatory uncertainty, technology information and easy to understand rules for average customers etc. These outcomes may serve as a literature to energy planners who intend to count on PV distributed generation systems to compose their energy matrix. In this way, they may plan to solve some target issues to reduce this risk aversion behavior and then obtain faster responses after a mechanism is endorsed.

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Distributed Energy Resources in an Emerging Country Context: Three Essays on
Residential Photovoltaic Adoption in Brazil

Abstract

The traditional vertically integrated power systems are changing towards a smarter ones with the high presence of renewable technologies, distributed generation (DG), greater energy efficiency and electric vehicles. Solar PV is the technology with the highest share among residential DG systems, due to several reasons among them: falling costs, increase of energy conversion efficiency and scalability features. The present thesis presents an investigation on the dynamics of residential PV adoption in Brazil.

In the first chapter, 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 4,995 municipalities over the period of 2013-2017 is employed. Since the explanatory variable shows a high content of zero-valued observations, I use the PPML estimator to run the regressions. The main result is 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.

In the second chapter, I investigate the determinants of residential PV adoption in an emerging country context using social, economic and environmental variables. The analysis is realized using a dataset in census sector level with 310,120 observations, with 42 covariates. Territory fixed effects are applied in the municipality-level. The main results show that 21 covariates are statistically significant and that most of them may be related to income distribution issues in some degree. Therefore, net metering incentive mechanism had a positive influence to boost residential renewable energy generation, mainly PV technology. However, those who benefit from the incentive are wealthier people, which does not make sense in respect to social justice, because those who indeed need to be subsidized in order to reduce the electricity bills and increase the purchasing power are the underprivileged population.

Finally, in the third chapter, I examine the relationship between certain socioeconomic covariates and PV market diffusion in the municipality level. I conduct a two-stage empirical analysis. At first, I use the Bass technology diffusion model to estimate the innovation and imitation coefficients. For that, I build the q/p ratio to represent a risk aversion index to each respective municipality's adoption rate over time. In the second stage, I run regressions based on the PPML estimator, due to the non-gaussian nature of the dependant variable, to investigate associations between the risk aversion index and different socio-demographic and economic covariates. The results show evidences of the association of PV technology risk aversion and households socioeconomic characteristics. This behavior may be based on several assumption as regulatory uncertainty, technology information and easy to understand rules for average customers etc.

Résumé

Les systèmes électriques traditionnels à intégration verticale évoluent vers un système plus intelligent avec une forte présence des technologies renouvelables, de la production distribuée (PD), d'une plus grande efficacité énergétique et des véhicules électriques. L'énergie solaire photovoltaïque est la technologie la plus répandue parmi les systèmes de production décentralisée résidentiels, et ce pour plusieurs raisons : baisse des coûts, augmentation de l'efficacité de la conversion énergétique et caractéristiques d'évolutivité. La présente thèse présente une enquête sur la dynamique de l'adoption du photovoltaïque résidentiel au Brésil.

Dans le premier chapitre, j'étudie comment les tarifs de l'électricité, structurés sous forme de redevances volumétriques, affectent l'adoption du photovoltaïque résidentiel dans le cadre d'un système de comptage net au Brésil, pays en développement et marché émergent de la production décentralisée. Une régression bidirectionnelle des données d'un panel à effets fixes couvrant 4 995 municipalités sur la période 2013-2017 est utilisée. Comme la variable explicative a montré un contenu élevé d'observations à valeur nulle, j'utilise l'estimateur PPML pour effectuer les régressions. Le principal résultat est que pour chaque centième de hausse des tarifs en réel Brésilien, il y aura une expansion d'environ 5,3 % des nouveaux projets PV résidentiels l'année suivante.

Dans le deuxième chapitre, j'étudie les déterminants de l'adoption du photovoltaïque résidentiel dans le contexte d'un pays émergent en utilisant des variables socioéconomiques et environnementales. L'analyse est réalisée, principalement, en utilisant un ensemble de données au niveau du secteur de recensement avec 310 120 observations, 42 covariables et l'effet fixe du territoire est appliqué au niveau municipal. Les principaux résultats montrent que 21 covariables sont statistiquement significatives et que la plupart d'entre elles peuvent être liées à des questions de distribution des revenus dans une certaine mesure. Par conséquent, le mécanisme d'incitation au comptage net a eu une influence positive pour stimuler la production résidentielle d'énergie renouvelable, principalement la technologie PV. Cependant, ceux qui bénéficient de l'incitation sont les personnes les plus riches, ce qui n'a pas de sens en matière de justice sociale, car ceux qui doivent effectivement réduire les factures d'électricité et augmenter le pouvoir d'achat sont les populations défavorisées.

Enfin, dans le troisième chapitre, j'examine la relation entre certaines covariables socioéconomiques et la diffusion du marché photovoltaïque au niveau des municipalités. Je mène une analyse empirique en deux étapes. Dans un premier temps, j'utilise le modèle Bass sur la diffusion de technologies pour estimer les coefficients d'innovation et d'imitation. Pour cela, je construis le rapport q/p pour représenter un indice d'aversion au risque du taux d'adoption de chaque municipalité respective au fil du temps. Dans un deuxième temps, j'effectue des régressions basées sur l'estimateur PPML, en raison de la nature non gaussienne de la variable dépendante, pour étudier les associations entre l'indice d'aversion au risque et différentes covariables socio-démographiques et économiques. Les résultats montrent des preuves de l'association entre l'aversion au risque de la technologie PV et les caractéristiques socio-économiques des ménages. Ce comportement peut être basé sur plusieurs hypothèses telles que l'incertitude réglementaire, les informations technologiques et des règles faciles à comprendre pour les clients moyens, etc.