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Determinants of distributed PV systems in Brazil

by

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Abstract

In this thesis determinants of distributed PV uptake in Brazil are estimated over a period from 2012 to 2019. To provide a deeper inside into the distributed PV market, a municipality-based panel regression is used to estimate determinants of PV consumer units and installed potential. The results indicate that most PV systems are located in the South and Southeast of the country, where PV potential is lowest. This suboptimal distribution can be accounted to regional inequality, electric tariff distortions, and a revision of the legal foundation of distributed generation in 2016.

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List of abbreviations

ANEEL	Brazilian Electricity Regulatory Agency	Agência Nacional de Energia Elétrica
CIP	Contribution to Public Lightning	Contribuição para Custeio do Serviço de Iluminação Pública
CNPJ	National registry of legal entities	Cadastro Nacional da Pessoa Jurídica
COFINS	Contribution for Social Security Financing	Contribuição para o Financiamento da Seguridade Social
CPF	Individual Registration Number	Cadastro de Pessoas Físicas
CU	Consumer unit	
DG	Distributed generation	
EEG	Renewable Energy Sources Act	Erneuerbare-Energien-Gesetz
EMCI	Energy Mix Concentration Index	
EPE	Energy research office	Empresa de Pesquisa Energética
FE	Fixed effects	
IBGE	Brazilian Institute of Geography and Statistics	Instituto Brasileiro de Geografia e Estatística
ICMS	Tax on the circulation of goods and services	Imposto sobre a Circulação de Mercadorias e Serviços
IHS	Inverse hyperbolic sine	
IPI	Tax on industrialized products	Imposto sobre Produtos Industrializados
NICU	Newly installed consumer unit	

NIP	Newly installed potential	
PIS	Social Integration program	Programas de Integração Social
PV	Photovoltaic	
TSEE	Social tariff	Tarifa Social de Energia Elétrica
TUSD	Use of Transmission System	Tarifa de Uso dos Sistemas Elétricos de Distribuição

1 Introduction

The future of the electricity supply in Roraima, a state in Northern Brazil, has been debated over the last years. The Energy research office EPE (2017, 2020b) notes that due to its remote location in the Amazon rainforest, the state is connected to the Venezuelan grid instead of the Brazilian national grid. While contracts guarantee that Venezuela must provide Roraima with electricity until 2021, the outbreak of the Venezuelan political, economic, and energy crisis in 2016 affects electricity supply in Roraima. Pietrosemoli & Rodriguez-Monroy (2019) identify mismanagement of Venezuelan primary sources as the cause of imbalances in electricity supply resulting in frequent blackouts. For this reason, the Venezuelan government terminated electricity supply to Roraima in March 2019 (Soares, 2019). Since then Roraima depends entirely on thermal emergency aggregates, generating electricity from fossil fuels. To cover electricity consumption, 700 to 1,100 million liters of diesel are burned per day (Oliveira, 2020). Kander et al. (2015) and Smil (2016) consider this development as worrisome since CO_2-emissions generated by burning fossil fuels are connected to global warming and climate change. Considering that Roraima is the least populated state in Brazil with 450.000 inhabitants in 2010 (Sidra 2020) and obtains a share of merely 0.2% of Brazils total electricity consumption in 2018 (EPE, 2019), this development would not exert a significant effect on CO_2-emissions. However, increased electricity generation from fossil fuels can also be observed on the national scale.

Historically, electricity supply in Brazil has been secured by hydroelectric power plants. Castilho (2017) and the EIA (2019a, 2019b) observe that Brazil is the 2nd biggest producer of hydroelectric energy in the world. Until 2002 the share of hydroelectric potential accounted for more than 80% of its massive consumption of 350 TWh per annum. Pepermans et al. (2003) and Silva et al. (2016) point out that hydroelectric generation is renewable, cost-efficient, and low in carbon emission. However, remaining hydro potential is limited and hydroelectric generation is highly dependent on rainfalls. Indeed, draughts resulted in two major supply crises in 2001 and 2015, causing electricity cutoffs throughout the country. According to Rüther & Zilles (2011), and Dezem (2014) the Brazilian government expanded the capacity of thermal power plants since 2001 to increase the resilience of electricity supply to variations in rainfall.

Though this reduces the intensity of the second supply crisis, thermal capacity proved insufficient in preventing it.

Even though the supply crises demonstrated the shortcomings of hydroelectric generation new projects are under discussion. This includes plans to secure electricity supply in Roraima. According to Costa (2019) and Paes (2019) the Brazilian government plans to construct a hydroelectric power plant or a 750km long transmission from Manaus. Both projects criticized based on ecological concerns, land conflicts with the indigenous population, cost intensity and prolonged construction times. Consequentially, electricity generation would remain carbon intensive for several years.

Castilho (2017), IRENA (2016), and the EPE (2017) propose distributed generation (DG) as a cost-efficient alternative to secure energy autonomy in Roraima, and remote areas in general. The Brazilian Electricity Regulatory Agency (ANEEL, 2015) defines DG as generation by individuals and legal entities from renewable sources, with a maximum capacity of 5MW. According to ANEEL hydro, biomass, solar, and wind are considered as renewable primary sources.

From its legalization in 2012 until December 2019, 227,000 consumer units (CU) with a potential of 2.15 GW were installed in Brazil (ANEEL, 2020b). The most popular are photovoltaic (PV) installations, accounting alone for 92% of installed potential. According to Scarabelot et al. (2019) and Schmidt et al. (2014), distributed PV are considered as a reliable alternative source to diversify and decarbonize the Brazilian electricity matrix. Moreover, construction periods are short and PV installations are flexible in location, what reduces the risk of land conflicts.

Though several studies discuss solar generation in Brazil in general (Ferreira et al., 2018; Silva et al., 2016; Rüther & Zilles, 2011; Carstens & Cunha, 2019; Schmidt et al., 2016), few studies focus particularly on distributed PV. This can be accounted to the novelty of the topic, as DG was only legalized in 2012. Studies focusing primarily on distributed PV were conducted by Luna et al. (2019), Scarabelot et al. (2019), Schneider et al. (2019). Luna et al. examine the legal foundation of distributed PV, while Scarabelot et al. focus their study on technicalities behind the balancing of generation and consumption of distributed PV units. Schneider et al. focus their analysis on solar cooperatives, a subgroup of distributed PV.

The only study estimating the determinants of distributed PV uptake on the municipality level is conducted by Assunção & Schutze (2017). However, their study leaves plenty of room for extension. First, their data set is limited to the period from 2012 until mid-2017. The number of PV CU increased since then by a factor of 14 (ANEEL, 2020b). Further, Assunção & Schutze do not examine changes over time in their study. In addition, they only use four explanatory variables namely GDP, population, electric tariffs, and solar irradiation in their study. Finally, they only analyze determinants of PV CU but not of installed potential.

The aim of this thesis is to close this gap in economic literature, by estimating underlying determinants of PV uptake on the municipality level for both newly installed CU (NICU) and newly installed potential (NIP) over time. Two questions will be addressed:

(1) What are the determinants of distributed PV uptake on the municipality level?

(2) Are there substantial differences between determinants of NICU and NIP?

To tackle these questions, a monthly panel on the municipality level is constructed for the period from 2012 to 2019. Data on the outcome variables NICU, NIP, as well as on the control variables electric tariffs, previously existing CU, and potential, is provided by ANEEL (2019,2020b). In addition to this, data from LABREN (2017), the Brazilian Institute of Geography and Statistics IBGE (2019, 2020a, 2020c), Sidra (2020), and the EPE (2020a), provide information on radiation, population density, electrification, unemployment, electricity consumption, and average household income.

The novelty of this study is that it also analyzes determinants of installed PV potential in Brazil. Furthermore, the panel structure of the data set allows to estimate how PV uptake varies across municipalities and time. Control variables studied by Assunção & Schutze (2017) are adjusted and policy dummies, electricity consumption, unemployment, electrification rates, existing potential, and existing CU are added as explanatory variables. Moreover, the present study analyzes data from 2012 until the end of 2019. To the authors best knowledge this data set has never been included in an empirical study before.

The remainder of this thesis is structured as follows. The 2nd chapter provides an overview over existing literature and empirical findings, while the 3rd chapter focusses on the Brazilian electricity sector. Chapter 4 and 5, present the data and estimation model used in the empirical analysis. The following 6th chapter includes a discussion of estimation results as well as limitations of the analysis, sensitivity tests, policy advice and an outlook for distributed PV in Brazil. In the final chapter, findings from the study are summarized.

2 Review of existing literature

In this chapter, summarizes findings from existing literature on distributed PV, and empirical results on determinants of PV systems. Section 2.3 compiles information on the design of PV policy and its effect on PV uptake.

2.1 Distributed PV systems

According to Ferreira et al. (2018) and Kannan & Vakeesan (2016) PV installations are the most suitable renewable energy source in developing countries, due to their efficiency, accessibility, and capacity. This applies especially to countries located close to the equator like India and Brazil, which have the highest rates of solar irradiation. Apart from this, variations in the output of PV system can be advantageous to balance supply and consumption. In countries depending on hydro-electric generation, Schmidt et al. (2016) and Carstens & Cunha (2019) observe that PV generation is highest during dry periods while hydro-electric generation is higher during wet season and after heavy rainfalls. Furthermore, distributed PV are highly variable in location and can even be installed on roof tops. This has positive implications for land conflicts since no additional land needs to be used to set up PV installations.

Scarabelot et al. (2019) and Rüther & Zilles (2011) note that PV generation varies to a high extent throughout the day. The high generation during the middle of the day is advantageous in places with need for air conditioner. Since both demand and PV generation are highest around noon, distributed PV located on commercial and residential buildings can contribute to peak shaving during hours of high demand.

Especially for small scale consumers, Pepermans et al. (2003) and Rüther & Zilles (2011) identify reduction of transmission costs as a major advantage of DG compared to centralized generation. Due to the high share of transmission and distribution costs in small-scale consumers electric bills, distributed PV can reduce total electricity costs by about 40%.

Figure 1: Global average PV module price in US$/Wp 2000-2016

Source: Adapted from Lafond et al., 2017.

*The unit $/Wp on the y-axis indicates that the price in US$ refers to installed capacity.

In connection to this, Luna et al. (2019) identify the rapid price decline in PV modules as the underlying factor behind the competitiveness of PV installations with other primary sources. Figure 1 illustrates the global average costs of PV systems in US$/W between 2000 and 2016. Until 2008 the costs of PV modules remained above 3.5 US$/W. Between 2008 and 2012 the price for PV modules decreased by 80% to only 0.77 US$/W.

Cook (2011) and Zhang et al. (2011) consider rural electrification as a crucial factor behind economic development and for poverty alleviation. Lacks in rural electrification occur primarily in developing countries, since private providers are discouraged from investing in remote areas due to low consumption and prolonged recovery times for investment. IRENA (2016) and Silva et al. (2016) suggest that solar energy is the most cost-efficient measure for electrification in remote areas not connected to the national grid, for example in mountainous regions in the Andes and the Amazon rainforest. Since these regions rely usually on fossil fuels for electricity generation, distributed PV uptake can contribute to a reduction in CO_2–emissions.

2.2 Empirical findings

Empirical studies on determinants of distributed PV uptake were conducted all over the world. Borenstein (2017) and Graziano & Gillingham (2015) study in US states, while Zhang et al. (2011) investigates PV uptake in Japan. There exist also several studies on European countries. Baginski & Weber (2019) and Winter & Schlesewsky (2019) study PV systems in Germany. Gautier & Jacqmin (2020) base their analysis on PV systems on Wallonia. Moreover, Ozkan et al. (2018) analyze PV system determinants in the UK. Another interesting study was conducted by Briguglio & Formosa (2017) on PV uptake in Malta. Due to its location in the middle of the Mediterranean Sea, Malta offers the opportunity to investigate particularities of PV uptake in isolated electric systems. Finally, Aklin et al.'s (2017) study on PV uptake in rural India offers a quite different perspective compared to studies based on data from industrialized countries. This study is of special interest since Ferreira et al. (2018) observe that India and Brazil are very similar in terms of insolation rates and the presence of several isolated areas within the country.

Findings from the studies listed above are compared to those of Assunção & Schutze (2017). According to their estimation results, radiation only becomes significant when controlling for distributors concession areas. Low PV uptake in the regions with the highest radiation can be explained by significantly lower income and electric tariffs in the Northern regions of Brazil. According to their estimations, a 10% increase in electric tariffs and GDP raises PV uptake by 7% and 4%, respectively. 10% higher population per municipality is estimated to increase PV uptake by 0.4%. Corresponding to Assunção & Schutze (2017), Zhang et al. (2011) find no significant effect of irradiation on PV uptake. In contrast to this, Ozkan et al. (2018), Baginski & Weber (2019) as well as Winter & Schlesewsky (2019) detect a positive effect of solar irradiation on PV uptake. Baginski & Weber estimate that a 10% increase in radiation raises installed potential by 2.3%.

Assunção's & Schutze's (2017) finding that electric tariffs are a main determinant of PV adoption corresponds to findings of Borenstein (2017), Graziano & Gillingham (2015) and Gautier & Jacqmin (2020). The latter detect a strong relationship between electric tariffs and the adoption of PV systems in Wallonia. An increase in the electricity tariff by 0.01€/kWh is associated with an increase in the adoption of PV systems by 8%. Correspondingly, Graziano

& Gillingham (2015) find that the number of CU rises by 0.3 if the electric tariff increases by $1.

Assunção & Schutze (2017) control for GDP to estimate the effect of income on distributed PV uptake. Anyhow, Nolan et al. (2016) find that due to growth inequality, changes in the financial funds of households are better reflected by median household income. This control is also preferred by Aklin et al. (2017) and Borenstein (2017). According to their findings richer households are more likely to invest in distributed PV since initial investment costs exceed the means of most poor households.

Like Assunção & Schutze (2017), Gautier & Jacqmin (2020), and Graziano & Gillingham (2015) also control for population size. However, Gautier & Jacqmin only detect an insignificant effect. Other authors also consider the availability of space per household or individual as a determinant of PV uptake. According to Winter & Schlesewsky (2019) the area of municipalities should be considered since less roof space per capita is available in highly populated areas. This corresponds to Briguglio & Formosa (2017) who observe that the availability of roof space is a key factor behind PV uptake in Malta, and Graziano & Gillingham, detecting higher PV uptake in small and medium sized communities.

Closely connected to this but not considered by Assunção & Schutze (2017), is the importance of residential consumption for PV adaption. Baginski & Weber (2019) and Ozkan et al. (2018) identify consumption as a main determinants of PV uptake. Correspondingly, Borenstein (2017) observes that a progressive electric tariff regime promotes investment in distributed PV among high income households in California, since higher consumption levels increase the financial benefits from PV installations.

Ozkan et al. (2018) and Graziano & Gillingham (2015) find evidence for neighborhood effects. The presence of PV systems in the neighborhood has a positive effect on the physical infrastructure and knowledge about the technology. According to their findings, neighborhood effects speed up PV uptake in the short run and the saturation of the PV market. For this reason, neighborhood effects evaporate over time.

Briguglio & Formosa (2017), find that higher unemployment has a negative effect on PV uptake in Malta. A 1% increase in unemployment is associated with a 0.2% decrease in the share of households owning PV systems. Moreover, Scarabelot et al. (2019) detect a link between unemployment and residential electricity consumption, since unemployment increases the time spent at home. This has a stronger effect on electricity consumption compared to a greater number of household members.

Electrification rates also affect the amount of installed PV potential. Ozkan et al. (2015) and Baginski & Weber (2019) find that lower electrification rates increase installed PV potential. The latter estimate that PV uptake increases by 2.2% if the share of detached households rises by 10%. This corresponds to Pepermans et al.’s (2003) findings that distributed PV provide a cheaper source for electrification than connection to the electric grid.

Education has according to Ozkan et al. (2015) and Briguglio & Formosa (2017) a positive effect on PV uptake. However, education is according to Lam (1999) highly correlated with household income in Brazil. The inclusion of education could therefore reduce the explanatory power of household income.

Average age and environmental behavior produce less consistent estimates across countries. Empirical findings of Gautier & Jacqmin (2020) and Briguglio & Formosa (2017) on average age point into opposite directions. While it rises PV uptake in the Wallonia, PV uptake among older households is lower in Malta. Similarly, environmental behavior exerts according to Zhang et al. (2011) a positive effect on PV uptake, while Briguglio & Formosa (2017) detect an insignificant effect. Moreover, Gautier & Jacqmin (2020) and Baginski & Weber (2019) detect no significant effect of the share of green party voters on PV uptake in Belgium and Germany.

2.3 Importance of policy regulation for PV adaption

Luna et al. (2019) and Rüther & Zilles (2011) note that reaching cost efficiency of PV might not be sufficient to guarantee their large-scale adaption. Additional policies to promote PV are usually required since several technological, economic, commercial, regulatory, institutional, cultural, ideological barriers, and a lack of knowledge among the population might discourage potential investors.

Cook (2011) points out that policy makers tend to subsidize electricity tariffs of poor people. The burden of the subsidies is often placed on other consumers. Cook warns that this can generate suboptimal outcomes. First, tariff subsidies financed by other consumers might over burden those who pay for them. Moreover, market distortion caused by tariff adjustments can result in a non-optimal allocation of assets. Finally, artificially low tariffs can discourage energy saving behavior. This applies also to feed-in tariffs, allowing consumers to sell their excess electricity on the electricity market. Rüther & Zilles (2011) and Luna et al. (2019) point out, that feed in tariffs should only serve to bridge the time until economic viability of PV system is reached. Otherwise, subsidies for owners of PV systems would pose a financial burden on other consumers, and lost tax revenue would limit the scope of government spending.

Failures in the design of incentive systems can even increase social inequality, demonstrated by the example of Germany. Winter & Schlesewsky (2019) consider the Renewable Energy Sources Act (EEG), issued in 2000, as highly efficient in promoting uptake of distributed PV in Germany, but also as a source of increasing inequality. According to the EEG, grid operators must purchase renewable energy and producers of renewables receive feed-in tariffs if production exceed consumption. This policy caused a rapid expansion in installed PV capacity from 2.9 GW in 2006 to 42.3 GW in 2017. Though the feed-in tariff was reduced from 0.52 €/kWh to 0.12€/kWh over the same period, the massive increase in PV installations raised the EEG-levy by more than a factor 3. Since producers of renewable energy and heavy industries are excepted from the levy, the burden is placed on non-generating consumers. Import to note in this context is that distributed PV are mainly installed in the rich South of the country, due to higher solar irradiation and income. The feed-in tariff functions consequentially as a cash-transfer from poor to rich households and regions.

Besides of this, Pepermans et al. (2003) detect an ambiguous effect of PV systems on energy security. Energy security refers to diversity of the electric mix and supply security. On the one hand, greater variety of primary sources can improve energy security. On the other hand, an expansion of DG can reduce energy security since the output of PV modules is highly variable. According to Tamimi et al. (2013) this is only the case for centralized PV installations. Distributed PV a lower impact on grid stability, since a large fraction of the generated electricity is consumed on site and never injected into the electric grid.

In connection to this, the design of the compensation systems matters for energy security. Gautier & Jacqmin (2020) demonstrate that the net-metering system in Wallonia limits PV capacity installed by individual households. This is the case since consumers under a system of net-metering system, insert generated electricity into the electric grid and are compensated with the same amount at a later point in time. In difference to a feed-in tariff, consumers are prohibited to sell electricity exceeding their own consumption. Individuals will consequently only invest in the amount of PV potential needed to cover their own consumption. This has positive implications for grid stability as only a small share of the generated electricity will be inserted into the electric grid. However, the downside of net-metering is that the overall increase in solar energy is limited. If a country aims to decarbonize its energy matrix, implementing a feed-in tariff is a more appropriate measure.

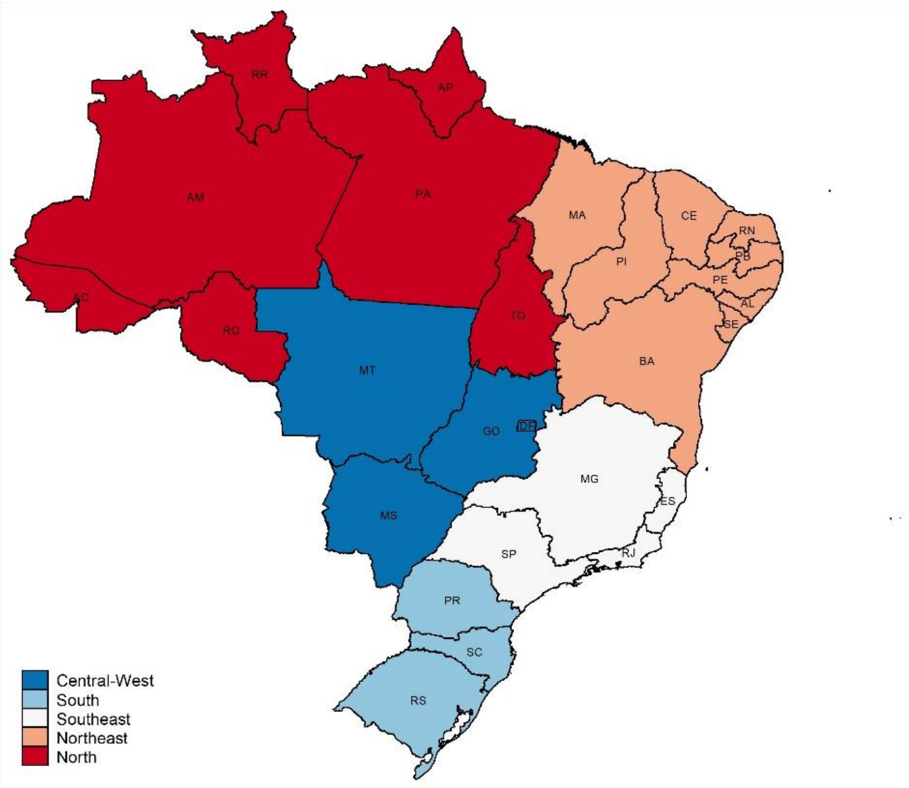
A rather exceptional example for PV expansion is Kenya. According to Kammen & Jacobsen (2013), 75% of rural electrification is provided by distributed PV even in the absence of government subsidies. However, the presence of low-quality modules, characterized by high module failure, limited durability, and unreliable power provision, hinder a further expansion of the sector. As mostly rural clients fail to distinguish between high- and low-quality providers, investment uncertainty emerged on the Kenyan PV market. This calls for governmental institutions to ensure product quality and reduce uncertainties in the DG market.

Borenstein's (2017), Aklin et al.'s (2017), and Cook's (2011) findings suggest that PV uptake among low income households is substantially lower. While, maintenance costs of PV installations are relatively low, high upfront costs pose a barrier for investment in distributed PV. To provide poor households with the financial possibility to invest in PV, initial investment rather than maintenance costs should be subsidized. In accordance to this, Briguglio & Formosa (2017) report that the Maltese government adopted a policy in 2013, which guarantees households a one-time payment of up to 2500€ for new PV installations. Furthermore, Graziano & Gillingham (2015) and Schneider et al. (2019) suggest that removing bureaucratic hinders for shared and community-based generation can foster growth of solar PV in densely populated and underprivileged areas since these generation modalities enable consumers to participate in larger investment projects, exceeding their individual means.

3 Brazilian electricity market

This chapter focusses on characteristics of the Brazilian electricity market and DG. The historical development of the electricity market is discussed in section 3.1. Section 3.2 focusses on the electric tariff rate. The final two section are focused on the evolution and legal foundation of DG.

Figure 2: Regional division of Brazil



Source: USP, 2020; IBGE, 2020b.

To provide an overview, over the states and regions in Brazil, figure 2 illustrates the regional division of the IBGE, dividing Brazil's 27 states into five greater regions, based on geographical, economic, social, and political characteristics (Duran, 2013). A list over the states located in each region, and the number of municipalities is provided in table A2 in the appendix. A complete list over Brazil's 5,570 municipalities is available at the IBGE (2020b).

3.1 Historical development

3.1.1 Early development

According to Castilho (2017), hydro electricity generation dominated Brazilian electricity supplies since electrification started in 1879. Thermoelectric plants were constructed as backup capacities, and in locations were no hydroelectric potential was available. Pepermans et al. (2003) note that at this time electricity generation was dominated by DG, since available technologies did not allow for large plants or transmission grids. Though DG was the prominent generation modality, the electricity sector was ever since highly concentrated. Concession areas of distributors stretched over several states, and some distributors acted even as electricity generators.

Technological improvements and increasing demand for electricity incentivized an extension of transmission networks during the second half of the 20th century. In this context, the construction of the Itaipu dam played an important role. According to Castilho (2017) the Itaipu dam is 2nd largest hydroelectric plant in the world, providing 12% of Brazil’s electricity. While it is located in the South most consumers live in the Southeastern region. Therefore, the construction of the Itaipu dam made an integration of regional networks in the South and Southeast necessary. While integration in the south of Brazil occurred quite early, regional grids in the North and Northeast were only integrated in the 1990s. Furthermore, electrification in the North remains incomplete until today as there exist several isolated networks in the Amazon rainforest. As mentioned above this includes the entire state of Roraima.

Castilho (2017) and Carstens & Cunha (2019) report, that the privatization in the 1990s reduced the concentration in the electric sectors, allowed new actors to enter the market, and contributed to a further extension of the national grid. Even after the privatization distributors hold a preferential position. Distributors in most Northern and Northeastern states face no competition since their concession areas comprise entire states. In the southern regions, concession areas are substantially smaller and increasing competition between distributors can be observed, as up to 6 distributors operate in the same municipality (ANEEL, 2016a).

3.1.2 Supply crises in 2001 and 2015

The biggest disadvantage of hydroelectric generation is its dependency on climatic conditions such as rainfall. According to Silva et al. (2016) and Rüther & Zilles (2011), the supply crisis in 2001 was caused by a massive drought coupled with rising electricity consumption. Furthermore, due to delays in the construction of transmission lines newly constructed plants were not connected to the national grid. This worsened the supply shortage and resulted in blackouts throughout the country.

Silva et al. (2016) and Carstens & Cunha (2019) note that the Brazilian government reversed the privatization process after 2001 to regain control over the sector. The government incentivized the construction of thermal emergency units and transmission lines to prevent electricity rationing in the future. As shown in table 1, this reduced the share of hydroelectric generation from 82.9% in 2000 to 69.7% in 2012 and doubled the share of fossil fuels to 18.9%. Also, biomass and wind energy grew rapidly over this period, gaining importance on the national level. In contrast, solar potential remained insignificant, with an installed capacity of merely 3 MW. Changes between 2012 and 2019 are discussed in section 3.4.

Table 1: Installed capacity by primary source in MW and shares in installed capacity

Primary Source	**Installed Capacity MW**			**Share in installed capacity**		
	2000	2012	2019	2000	2012	2019
Fossil fuels [a)]	7,966	22,855	26,267	10.8%	18.9%	15.4%
Nuclear	1,966	2,007	1,990	2.7%	1.7%	1.2%
Biomass [b)]	2,657	9,922	14,992	3.6%	8.2%	8.8%
Hydro	61,063	84,294	109,092	82.9%	69.7%	64.1%
Solar [c)]	0	3	2,485	0.0%	0,0%	1,5%
Wind	22	1,894	15,364	0.0%	1.6%	9.0%
Total	**73,674**	**120,975**	**170,189**	**100%**	**100%**	**100%**

Source: IRENA, 2020.

[a)] Fossil fuel includes other non-renewables.

[b)] Bioenergy consists of biogas, liquid biofuels, renewable municipality waste, solid biofuels.

[c)] Includes grid connected and off-grid PV systems.

According to Pepermans et al. (2003), diversification of primary sources is highly important regarding energy security. A measure for diversification of electricity generation was developed by Rubio-Varas & Muñoz-Delgado (2019). Their Energy Mix Concentration Index (EMCI) is measured as the sum of squares of shares of primary sources in the electric mix. The EMCI can take values between 0 and 1, where 0 indicates completely diversified electric supplies while 1 indicates complete concentration. Brazil's EMCI dropped from 0.7 to 0.53 between 2000 and 2012, indicating substantial improvement in diversification of electric supply.

Dezem (2014), Wurmeister (2015), and Silva et al. (2016) consider the greater diversification of electricity supply as a crucial factor helping to prevent blackouts, when another supply crisis occurred in 2015. The crisis was again triggered by a sharp decline in hydroelectric potential, caused by a draught period starting in 2012. The massive increase in thermal capacity contributed to a stabilization of electric supply.

Though it helped to prevent most electricity cut offs, Silva et al. (2016) consider the rising share of fossil fuels in the electricity mix as problematic. First, reliance on fossil fuels threaten the achievement of climate targets since the burning of fossil fuels emits a lot of CO_2. Second, dependency on fossil fuels imports rises since national supplies of natural gas and coal are insufficient. Moreover, import costs for fossil fuels caused a massive increase in the electric tariff by as much as a factor of 10 compared to pre-crisis levels. Third, plant quality is a major concern. Most Brazilian thermal plants were only constructed to provide backup capacity, in case that hydroelectric potential is insufficient. As observed by Soares (2019), exclusive reliance on thermal emergency aggregates results in blackouts whenever aggregates must be maintained. For this reason, massive investment in thermoelectric plants are necessary such that they can provide baseload capacity.

Carstens & Cunha (2019) point out, that the second supply crisis coincides with a political, economic, and financial crisis. Furthermore, economic, and financial instability discourage investment in the entire Brazilian economy. A lack of investment in the electricity sector increases the risk of another supply crisis. Cook (2011) suggests, that insufficient private investment in the electricity sector can be compensated by encouraging DG. Since DG units are financed by small-scale individual investments, they reduce the need for large-scale private and governmental investments. Moreover, investment in renewable energy has even the potential to boost employment and economic growth. According to Silva et al. (2016) a 1% increase in the share of renewable energy in electricity consumption can increase the Brazilian GDP by 0.2%. Furthermore, Carstens & Cunha find that an expansion of the PV market can create approximately 20 to 30 jobs per MW through direct and indirect channels.

3.2 Electric tariff design

According to Silva et al. (2016) and Assunção & Schutze (2017), the Brazilian electricity market remains highly regulated until today. This is indicated by several public enterprises operating in the electricity sector, and the great influence of ANEEL on the electric tariff rate. The components of the final tariff rate paid by consumers are illustrated in formula (1). The formula is retreived from Assunção & Schutze.

$$\text{Final tariff} = \left\{\frac{\text{Tariff}_{\text{ANEEL}}}{1-(\text{PIS}+\text{COFINS}+\text{ICMS})}\right\} + \text{CIP} \tag{1}$$

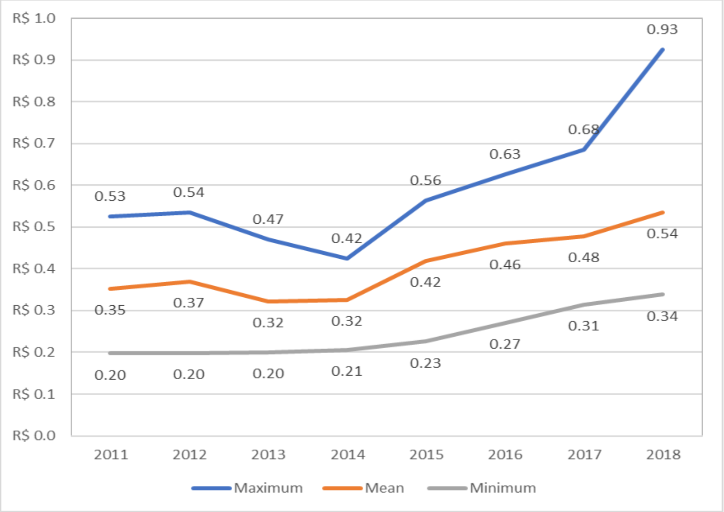
The first component of the Final tariff rate is the electric tariff set by ANEEL $\text{Tariff}_{\text{ANEEL}}$. This tariff rate varies across concession areas, according to electricity generation costs, the number of consumers, the extension of the distribution network, and market density (Castilho, 2017). In addition to this the final tariff is determined by charges and taxes set on the country, state, and municipality level. Charges for the Social Integration program *PIS* and the Contribution for Social Security Financing *COFINS* are determined by the federal government. The Tax on the circulation of goods and services *ICMS* is charged on the state level, while the Contribution to Public Lightning *CIP* is set on the municipality level. For this reason, Luna et al. (2019) observe that the electric tariff differs across all states and municipalities.

As illustrated in formula (1), taxes have a great influence on the final tariff rate paid by consumers. Castilho (2017) finds that taxes and charges account for as much as 45% of electricity tariffs. The share of generation costs is with 36% comparably low, due to the great availability of hydropotential. Since $\text{Tariff}_{\text{ANEEL}}$ is designed to cover operational and investment costs, the share of distribution costs amounts to 17%.

The favorable position of electricity producers and distributors as well as the high share of taxes are the reason why electric tariffs in Brazil are among the highest in the world. According to Castilho (2017) and Assunção & Schutze (2017), the great share of distribution costs in final tariffs is an indicator for the market power of distributors and producers. The authors consider the current tariff system as problematic since the governmental guarantee to cover operational and investment costs provides little incentives for providers to keep operational and investment costs low.

Furthermore, small consumers are generally oppressed in the Brazilian electric market. Castilho (2017) observes that charges and taxes vary across consumption classes. Lower taxes and charges for the industrial sector are compensated by higher charges for the residential and commercial sector. In addition to this, Silva et al. (2016) note that consumers with a consumption below 500 kW per month face formal restrictions, hindering them to purchase electricity directly form electricity producers. Therefore, they depend on their local distributors to source electricity.

Figure 3: Residential tariff B1 in R$/kWh 2011-2018



Source: ANEEL (2019).

Figure 3 illustrates the residential tariffs of subgroup B1 between 2011 and 2018. Since 2014, the average electric tariff increased significantly from 0.32 R$/kWh to 0.54 R$/kWh. Important to note is the rapid increase in the maximum tariff rate, rising from only 0.42 R$/kWh to 0.93 R$/kWh between 2014 and 2018. Over the same period, variations on the national level increase by a factor 3 to 0.67 R$/kWh. ANEEL (2016a) suggests that the rise in variation can be accounted to the market entry of several new distributors in the aftermath of the supply crisis.

Furthermore, the general upward trend can be explained by the fact that the electric tariff is designed to cover distributors operational costs. Castilho (2017) and Silva et al. (2016) point out that electric tariffs vary for this reason by changes in the electricity mix. The drop in the share of hydroelectric generation resulted in a massive increase in electric tariffs after the 2015 supply crisis, since generation from fossil fuels is more cost intensive.

In addition to this a law issued in 2015, provided distributors with greater freedom to adjust electric tariff rates. Since distributors used this law in their favor to a different extent, the 2015 reform exerted even an regional tariff patterns. Electric tariff rates were reduced in the South, São Paulo, and the Northeastern region (figure B9 and B10). Since then, electric tariff rates in rich stated like São Paulo and Santa Catarina, belong to the lowest in Brazil. In contrast to this, the poorest state Maranhão, faces one of the highest electric tariff rates after the reform. Cook (2011) finds that demand for electricity is inelastic, since it is considered as a basic good. Consumers can therfore not reduce their electricity consumption to a high extent when electric tariffs increase. Consequentially, the 2015 reform deteriorates income inequality in Brazil, since the population of the poorest state has to spend an increasing fraction of their disposable income on electricity.

3.3 Legal foundation of distributed generation

ANEEL (2015) legalized the micro- and minigeneration of electric energy in their normative resolution ANEEL n°482/2012 on April 17th in 2012 to diversify the Brazilian electricity matrix. This change in law allows individuals and legal entities to generate their own electric energy up to a maximum capacity of 1MW. Owners of DG systems are compensated through net-metering.Therefore, they receive energy credits for their surplus electricity which is injected into the electric grid. According to ANEEL n°482/2012, energy credits can only be used within the same concession area by holders of the identic Individual Registration Number (CPF) or National Registry of Legal Entity (CNPJ). Furthermore, energy credits lose their validity after 36 months.

As discussed in the previous section, a policy was issued in 2015, strengthening the position of distributors in the electric market. This policy should not be confounded with ANEEL nº687/2015, a revision of ANEEL n°482/2012. According to Luna et al. (2019), ANEEL nº687/2015 was motivated by the economic, political, and electricity supply crisis and came into force on March 1st, 2016. The aim of this policy was to secure investment in renewable energy, in the absence of large centralized investment projects.

Table 2 summarizes the main components of ANEEL n°482/2012 and adjustments made in ANEEL nº687/2015. First, the maximum size of DG units was readjusted. The maximum value for microgeneration was reduced from 100 kW to 75 kW, while the limit of minigeneration was extended to 5 MW. Second, the validity of energy credits was extended to 60 months. The biggest difference is that ANEEL nº687/2015 allows DG producers to share energy credits among registered units, in form of remote self-consumption, shared generation, and condominiums. According to Schneider et al. (2019) the latter two are of great importance since they enable individuals who lack funds or possibilities to invest in DG by themselves, to participate in DG projects financed by a group of individuals.

Table 2: ANEEL n°482/2012 and ANEEL nº687/2015

	ANEEL n°482/2012	**ANEEL nº687/2015**
Microgeneration	≤ 100 kW	≤ 75 kW
Minigeneration	100 kW to 1,000 kW	75 kW to 5,000 kW
Net metering	a. Surplus energy is transferred to local distributor b. Owner of the same CPF or CNPJ compensated with energy credits	a. Can be used for remote self-consumption, shared generation, or condominiums
Energy credits	a. Valid for 36 months b. Valid in the same concession area	a. Validity extended to 60 months b. Valid in the same concession area
Remote self-consumption	No	Holder of the same CPF or CNPJ can use energy credits on different properties
Shared generation	No	Members of a consortium or cooperative share energy credits
Condominiums – Multiple CU	No	DG units can be owned by joint owners, electricity is divided among owners in self-defined shares.

Source: Luna et al. (2019), ANEEL (2015). Assunção & Schutze (2017).

Though ANEEL nº687/2015 improved the conditions for individual investors in DG, the Brazilian net-metering raised critique among scholars. Already before ANEEL n°482/2012 was implemented, Rüther & Zilles (2011) recommended to introduce a feed-in tariff as the most promising measure to boost the share of renewable primary sources in the electricity mix.

Accordingly, Luna et al. (2019) consider the fact that consumers are still prohibited to sell their excess electricity on the electric market as the main shortcoming of DG in Brazil.

To further boost the adoption of distributed PV system in Brazil, the Brazilian government introduced additional tax incentives, listed in table 3. Most subsidies are limitted over time, including the ICMS exemption for PV equipment. Important to note is that this subsidy has even a regional component. Until 2017, all states except for Espírito Santo, Amazonas, Paraná and Santa Catarina joined this program.

Table 3: Tax incentives for distributed PV Systems

Time period	**Tax/Charge**	**Remarks**
Since 06/2010	Tax on industrialized products (IPI)	Exemption on electric energy
04/2011 - 12/2021	Tax on Circulation of goods (ICMS)	Exemption on equipment and components of PV installations (Except for Espírito Santo, Amazonas, Paraná, Santa Catarina)
Since 10/2015		Exemption on self-generated electricity if installed potential <1MW
Since 10/2015	Social Integration program (PIS)	Exemption on self-generated electricity if installed potential <1MW
Since 10/2015	Contribution for Social Security Financing (COFINS)	Exemption on self-generated electricity if installed potential <1MW
Until 12/2017	Use of Transmission System (TUSD)	80% reduction of TUSD for 10 years if installed potential ≤30MW
Since 01/2018		50% reduction of TUSD for 10 years if installed potential ≤30MW
08/2015-12/2016	Import duty	Reduction of Import duty on PV equipment from 14% to 2%

Source: Luna et al. (2019). Assunção & Schutze (2017). Carstens & Cunha (2019).

3.4 Decentralized generation

As mentioned above, the change in installed capacity between 2012 and 2019 (table 1) is discussed in this section. This is motivated by the importance of DG, for the evolution of renewable sources during this period. Comparing installed capacity of different primary sources in 2012 and 2019 shows, that the electricity mix was even more diverse at the end of this period. An increasing share of biomass, wind, and solar potential improved the EMCI to 0.45. Among new renewables, biomass, and wind play an important role on the national level. Today, both sources obtain shares close to 9% in installed capacity. Though the share of solar capacity remains comparably low at 1.5%, its share rose from only 3 MW in 2012 to nearly 2.5 GW in 2019.

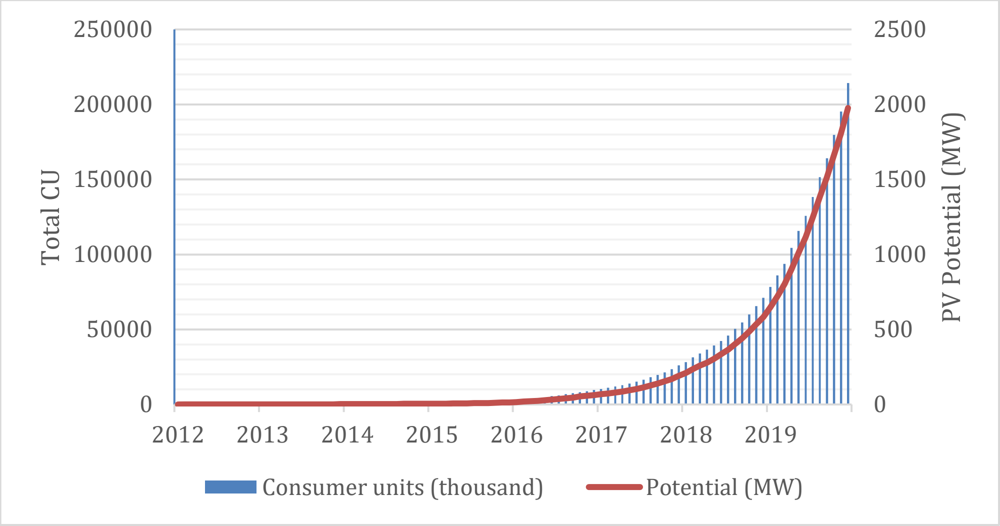
Table 4: Installed DG capacity (MW) by primary source

Primary Source	2012	2013	2014	2015	2016	2017	2018	2019
Solar	0.5	1.9	4.4	14.1	63.2	190.2	583.2	1,976.3
Biomass	0	0	0.1	2.2	12.0	24.2	40.1	66.4
Hydro	0	0	0.8	0.8	5.8	43.5	67.1	96.7
Wind	0	43.9	44.0	44.0	49.1	54.2	98.3	98.3
Total	**0.5**	**2.0**	**5.4**	**17.3**	**86.1**	**268.2**	**700.7**	**2,149.7**

Source: ANEEL, 2020b.

Table 4 illustrates the evolution of installed DG capacity by primary source between 2012 and 2019. Installed capacity increased rapidly over this period, to 2.15 GW in 2019. Coinciding with the implementation of ANEEL nº687/2015 in 2016, solar energy held the leading position among DG primary sources. The exponential growth in both PV CU and installed potential is even illustrated in figure 4. In 2019, the capacity of distributed PV amounted to nearly 2 GW, what corresponds to 92% of installed DG capacity. Exceptional is that distirbuted PV even play a relevant role in total solar capacity. At the end of 2019, distributed PV installations contributed with 87% to the entire solar capacity in Brazil. Other DG sources obtained solely shares below 1% of total capacity.

Figure 4: Distributed PV - CU and installed potential (MW) 2012-2019



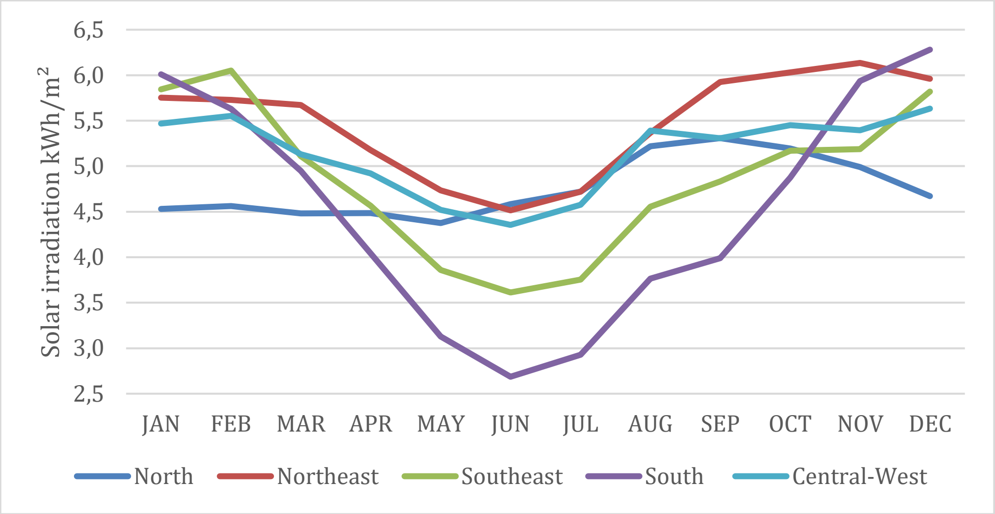
Source: ANEEL, 2020b.

3.4.1 Advantages of distributed PV in Brazil

Brazil has several advantages regarding distributed PV uptake. As identified by Rüther & Zilles (2011), Silva et al. (2016), and Ferreira et al. (2018), the first one is Brazil's location close to the equator, providing it with great potential for solar energy. According to figure B3, solar irradiation is especially high in the Northeast and Central-West, where daily average irradiation exceeds 5 kWh/m². In addition to solar irradiation, high electric tariffs ensure economic viability of PV systems, and large reserves of high-quality quartz provide Brazil with a comparative advantage in the production of PV modules.

Yearly variation in average daily solar irradiation are illustrated in figure 5. Depending on the distance to the equator, irradiation differs throughout the year. While it is highest in the South during summer, the region has the lowest average radiation during winter, with less than 3 kWh/m² in June. As discussed in section 2.1, tropical countries including Brazil benefit from the seasonality of PV, since variations in PV generation correspond to variations in electric consumption throughout the year.

Figure 5: Average daily solar irradiation by region in kWh/m²



Source: LABREN (2017).

Though ANEEL (2016b) mandates distributors to attend all households within their concession areas, universal electrification has only been reached in urban areas. Figure B5 reveals that electrification in the North and Northeast of Brazil remains incomplete. IRENA (2016) notes that this can be accounted to a lack of financial incentives for distributors to connect scarcely populated areas, with low consumption to the electric grid. This explains why electrification rates in the richer and densely populated southern regions are significantly higher, while electrification in parts of the North and Northeast remains below 40%. According to Rüther & Zilles (2011), Schmidt et al. (2014), and the World Bank (2000), the lack of electrification in the North of Brazil, can be considered as another application possibility for distributed PV since it is the cheapest option for electrification in remote areas.

3.4.2 Factors hindering distributed PV uptake

According to Luna et al. (2019) and Ferreira et al. (2018), installations costs amount approximately to 10,000 R$/kW depending on local conditions, irradiation, installation surface and technology. Total costs are about 25% lower in areas with high insolation since less PV capacity is sufficient to cover electric consumption. This is advantageous since high radiation ensures lower installation costs in poor Northeastern states. However, differences in installation costs are insufficient to compensate for income differences. Figure B4 illustrates average household income on the state level. Income in the southern regions exceeds income in the

North and Northeast by a factor of 2. According to the Prydz & Wadwha (2019), income differences on the municipality level in Brazil correspond to those between low-middle and high income countries. This entails that there exist massive differences in financial funds across Brazil. In 2010, income in the richest municipality, Santana de Parnaiba (São Paulo), was 14 times higher compared to the poorest municipality Marajá do Sena (Maranhão). In the latter, average yearly household income amounted to merely R$ 5,208 in 2010, this corresponds to US$2.865 (XE, 2020).

In addition to this Assunção & Schutze (2017) and Luna et al. (2019) criticize that artificially lower tariffs rates reduce PV uptake among low income households. Charges and taxes in the Northeastern region are reduced to lower the financial burden on poorer consumers in this region. To compensate for the costs of this subsidy, consumers in the Southern parts of the countries are charged more. Furthermore, ANEEL (2020a) introduced the Social Tariff (TSEE) in 2002, to reduce electricity costs of low income households. The TSEE reduces electricity costs by up to 65% depending on their consumption level. For indigenous families, the policy is even more generous. For households consuming less than 30 kWh/month, electricity provision is free. This tariff design actively de-incentivizes investment in the highly insolated Northeast and among low income households, while households in the less insolated Southeast are encouraged to invest in distributed PV.

Silva et al. (2016), Carstens & Cunha (2019), and Ferreira et al (2018) propose that costs for PV installations could be reduced by establishing a solar industry in Brazil. Anyhow, the relatively small market size of the Brazilian PV market, high competitivity on the international market as well as a lack of investment due to the economic and financial crisis, harms investment in solar cell manufacturing in Brazil. According to Ferreira et al., entering the international market in solar manufacturing is only possible if the state engages in industry protection policies, creating a closed national market for solar panel manufacturers.

Moreover, Ferreira et al. (2018), Rüther & Zilles (2011), and Carstens & Cunha (2019) identify a lack of financing and knowledge among potential users and investors as a main factor harming PV uptake. Furthermore, limited knowledge transfer, international cooperation, and diffusion among different actors in the solar sector harm technological improvement. To further incentivize the development of the solar sector, public awareness of this technology should be increased, and knowledge exchange between different interest groups in the solar sector should be encouraged.

4 Data

This chapter provides an overview over base of the data set as well as dependent and independent variables included in the regression.

4.1 Panel base

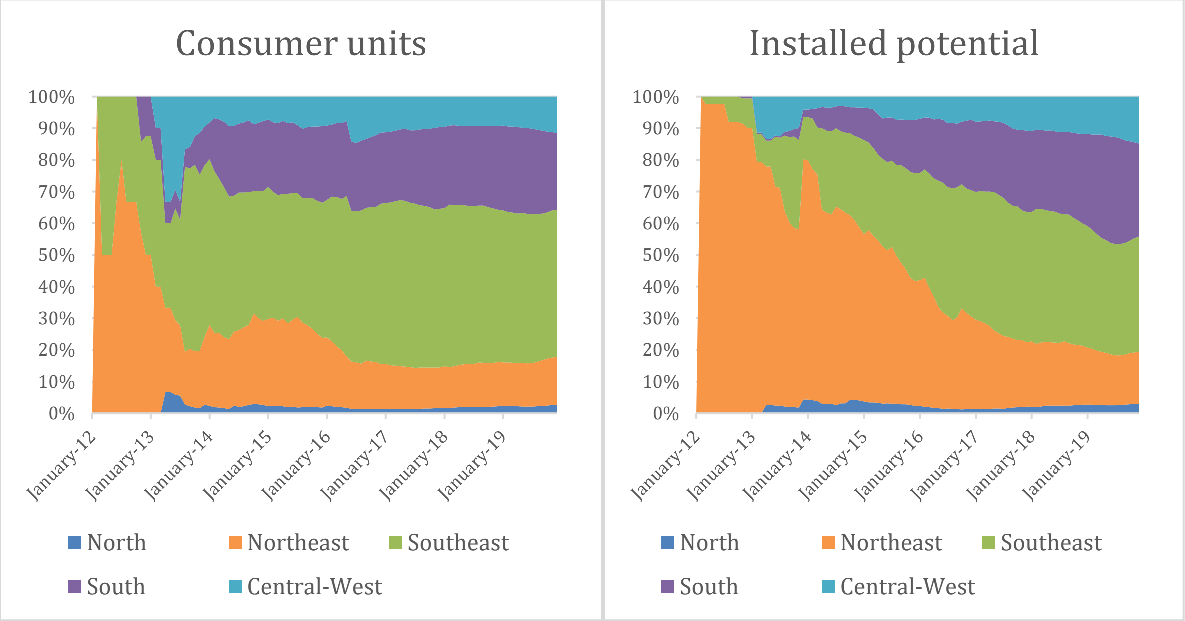
The data set used in the analysis is based on a monthly panel data. Information on the 5,570 municipality is sources from the IBGE (2020b). For each municipality monthly observations over the period from 2012 until 2019 are created. The total number of observation amounts therefore to 534,720. Dependent and independent variables are assigned to municipality-month cells, based on their temporal and spatial characterisitcs.

4.2 Outcome Variables

Since findings from existing literature suggest that effects of independent variables on CU and installed PV potential differ in some regards, both NICU and NIP are calculated as outcomes to provide a deeper insight into the Brazilian PV market. Data on outcome variables is sourced from ANEEL (2020b). The data set provides information on the connection date, location, generation source, consumer subgroups, generation modality, and distributors. Out of the 229,505 registered installations on December 31st, 2019, 15,155 were excluded from the final data set since their location could not be assigned to a municipality or electricity was generated from another primary source.

While figure 4 illustrates that PV CU and installed potential showed a very similar growth pattern, this is not the case for their regional distribution, presented in figure 6. High variations in the regional share of CU during early years can be accounted to the fact that the total number of CU was very low. Regional shares were therefore highly sensitive to newly installed CU. However, with an increasing number of CU regional shares stabilized already since 2014 to their current distribution pattern. In the end of 2019, 36% of CU were located in the Southeast followed by the South with shares of 24%.

Figure 6: Regional shares in CU and installed PV potential 2012-2019



Source: ANEEL, 2020b.

Regarding installed potential the regional development was quite different. Until ANEEL nº687/2015 came into force in March 2016, most of installed potential was found in the Northeast. Since then, changes in the incentive system caused a shift in installed potential towards the South and Southeast. In December 2019, 29% and 46% were located in the South and Southeast, respectively. The remaining regions are rather underrepresented. The Northeast and Central-West hold shares of around 15% in both CU and installed potential, while only 3% of distributed PV systems are located in the North. To account for regional differences PV uptake, regional controls are included in the estimation.

Table 5 illustrates the shares of generation modalities in CU and installed potential. Own CU have the highest share in both consumer units and installed potential, with a share of two thirds and 80.7% respectively. Other generation modalities became only available after ANEEL nº687/2015 was implemented in March 2016. Among new generation modalities, remote consumption is the most popular one, occupying a share of 31.8% and 18.5% in CU and installed potential, respectively. With shares below 1% in CU and installed potential, shared consumption and condominiums remain rather an exception.

Table 5: Distributed PV - Generation modalities

Modality	CU	Potential
Own CU	67.4%	80.7%
Remote consumption	31.8%	18.5%
Shared consumption	0.66%	0.76%
Condominiums	0.11%	0.04%

Source: ANEEL, 2020b.

Table 6 provides an overview over the share of different consumer categories in CU and installed potential, as well as the average capacity of PV installations in kW. According to Luna et al. (2019) and Scarabelot et al. (2019), residential and commercial consumers face the highest electric tariff rates, and therefore have the highest incentives to invest in distributed PV. This is in line with the data presented in table 6. The residential sector has the highest share of consumer units with nearly 70%, followed by the commercial sector with a share of 20.8%. The combined share of the industrial, rural, and public sector in CU is only about 10%.

Table 6: Distributed PV – Consumer categories

Category	CU	Installed potential	Average capacity (kW)
Residential	68.7%	39.0%	5.2
Commercial	20.8%	39.7%	17.6
Industrial	2.65%	8.61%	30.0
Rural	7.31%	11.0%	13.8
Public	0.52%	1.67%	29.6

Source: ANEEL, 2020b.

[a)] Public sector includes public authorities, services, and lightning.

Differences in average capacity of PV installations across consumer categories explain, why the shares in installed potential do not resemble the shares in CU. Since the average capacity of PV installations in the commercial sector is more than 3 times larger compared to the residential sector, the share of both classes in consumer units is nearly identical. The greatest average capacity can be found in the industrial and public sector with values of approximately 30 kW.

An explanation for this is Gautier's & Jacqmin's (2020) observation that individuals under a net metering system will only install PV potential according to their own consumption. This sets an upper limit on installed potential by CU. Further, it explains differences in installed capacity across consumer groups. According to data from the EPE (2020), electric consumption varied to a high extent across consumer classes. While an average Brazilian household consumed 1932 kWh in 2018, consumption of an industrial company was more than 160 times higher.

4.3 Control Variables

According to Angrist & Pischke (2008:47-48), control variables can turn into bad controls if they are determined after outcomes. In this case, the outcome might be a determinant of control variable and vice versa. To avoid this problem, constant variables are taken from the years 2010 and 2011, while data on time variant factors (consumption, unemployment, and the electric tariff rate) is take form the previous year. The only control variable that is determined after the start of the observation period in 2012 is solar radiation, which is based on data from 2015 (LABREN, 2017). Though this fulfills the criteria of a bad control variable regarding the timing observation, it appears unlikely, that distributed PV installed in Brazil until 2015 have a significant effect on solar irradiation rates. Since several data sets are combined, values for some control variables are missing on the municipality level. These are replaced by state-month average values.

Data on averaged daily solar irradiation is sourced from LABREN (2017). As illustrated in figure 4, solar irradiation varies throughout the year. However, as discussed in section 2.1 irradiation and electric consumption are positively correlated in tropical countries. Yearly average radiation rates are included in the data set, since it is assumed that variations in generation are balanced by fluctuations in consumption.

ANEEL (2016a, 2019) provides information on electric tariffs in R$/kWh and on distributor attendance by municipality. In about 12% of the municipalities there exist multiple distributors. In this case the electric tariff from the biggest distributor is chosen as a control. This seems reasonable since distributors cannot deviate in prices to a high extent when they are competing in the same market. For example, in 2018 three distributors operated in Saquarema (Rio de

Janeiro). While tariff rates varied on the national level by 273%, variation within the municipality amounted only to 8%. Corresponding to Assunção's and Schutze's (2019) study the low voltage B1 residential tariff rate is used as a control here. This is motivated by the fact that most CU and installed potential is owned by residential and commercial consumers, who face similar tariff rates. For the same reason, annual residential consumption data, provided by EPE (2020a) is used as a measure for electricity consumption.

Census data is conducted on a decennial basis by the IBGE (2020c, 2020d). For the estimation, data is used from the latest available version in 2010. The household survey provides information on several socio-economic characteristics from all Brazilian municipalities, including electrification rates and average annual household income.

While the smallest Brazilian municipalities do not even comprise 1 km², the largest, Altamira (Pará), has 160.000 km². This is comparable to the area of Tunisia (Worldometers, 2020). To account for differences in area when comparing the population size of different municipalities, the population density is preferred as a control variable here. Data on population density per km² is a combination of the 2010 municipality area from the IBGE (2020a) and 2011-population estimates sourced from SIDRA (2020).

The IBGE (2020c) also provides yearly average unemployment rates by states. Due to changes in the calculation method and data availability, data for the year 2011 is not available. Since unemployment rates is one of the variables changing over time, data from the previous year are used as control variables. The year 2012 is therefore omitted when unemployment is included in the analysis.

To account for neighborhood effects, existing CU and existing potential for each municipality are calculated from the data set. Existing CU is the cumulated number of CU installed in a municipality i before period t. Correspondingly, existing potential is the total PV potential installed in a municipality i before period t.

$$Existing\ CU_{it} = \sum_{t\prime=1}^{t-1} NICU_{it\prime} \qquad Existing\ potential_{it} = \sum_{t\prime=1}^{t-1} NIP_{it\prime}$$

Based on table 3, a set of policy dummies is included to control for policy incentives for PV installations over time and space. A complete overview over the policy dummies, including temporal and territorial limitations is included in table A1. The dummies will take on the value 1 if it applies for a municipality i during period t, and 0 otherwise. No policy dummy is added for IPI exemptions since this policy is valid throughout the entire observation period. Though, this is also the case for the ICMS exemption on PV equipment, this incentive policy does not apply to all states. The ICMS dummy will take on the value 1 for all states except Espírito Santo, Amazonas, Paraná, and Santa Catarina.

Though they are discussed shortly in section 2.2, age, education and environmental behavior are not used as controls here. For environmental behavior, no reliable data is available. Age was also excluded, to not overload the model, and education is highly correlated with household income. As mentioned above, correlation between education and household income attenuates the estimated effect of household income.

4.4 Descriptive statistics

Table 7: Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
NICU	534,720	0.40	3.7	0	1,111
NIP	534,720	3.70	38.1	0	8,580
Existing CU	534,720	4.26	34.2	0	2548
Existing potential	534,720	35.98	302	0	23,147
Electrification rate	534,720	97.08	5.8	30.11	100
Household income	534,720	18,908	8,265	5,208	73,756
Daily solar irradiation	534,720	5.04	0.4	3.59	6.06
Population density	534,720	109.08	575.83	0.132	13,044
Electric tariff	534,720	0.486	0.122	0.209	0.856
Electricity consumption	534,720	1,844	442.37	1,195	3,887
Unemployment rate	467,880	9.10	3.16	2.94	20.54

Table 7 presents descriptive statistics on the control and outcome variables included in the estimation. All control variables, except for existing CU and existing potential, are presented as maps in Appendix B. Variation in the maps is lower compared to the descriptive statistics, since the maps illustrate the average of control variable on the state level. Important here are also the units in which the variables are measured. Compiled information on variable sources, units and observation frequency is compiled in table 8.

According to Solar Schools (2020), there exists a crucial difference between W and Wh. W is a unit of power, measuring how much energy is produced or consumed over a time period. Wh is an amount of energy. For example, a 10W lamp consumes 10Wh if it is switched on for an hour and 20Wh if it burns for 2h. The units kW, MW, GW, refer to 1,000 W, 1 million W, and 1 billion W.

Table 8: Compiled information on dependent and independent variables

Variable	Unit	Territory	Frequency	Time	Source
NICU	#	Municipality	Monthly	2012-2019	ANEEL (2020b)
NIP	kW	Municipality	Monthly	2012-2019	ANEEL (2020b)
Existing CU	#	Municipality	Monthly	2012-2019	ANEEL (2020b)
Existing potential	kW	Municipality	Monthly	2012-2019	ANEEL (2020b)
Electrification rate	%	Municipality	Constant	2010	IBGE (2020c)
Household income	R$/Year	Municipality	Constant	2010	IBGE (2020c)
Population density	Inhabitants/km²	Municipality	Constant	2010 2011	IBGE (2020a) SIDRA (2020)
Daily solar irradiation	kWh/m²	Municipality	Constant	2015	LABREN (2017)
Electric tariff	R$/kWh	Concession area	Yearly	2011-2018	ANEEL (2019)
Electricity consumption	kWh	State	Yearly	2011-2018	EPE (2020a)
Unemployment rate	%	State	Yearly	2012-2018	IBGE (2019)

To provide an example for the daily, monthly, and yearly generation of a PV module, a CU has a capacity of 1kW, and generates electricity for 8h a day. Daily generation of the CU is therefore 1kW*8h=8kWh. During a 30-day month, energy generation amounts to 240 kW and annual generation is 2,880 kWh or 2.88 MWh.

How does this relate to average residential consumption? Average residential consumption in the data set amounts to 1,844 kWh. Assuming again that a CU generated electricity for 8h per day, an installed PV capacity of 0.63kW is sufficient to make an average household energy self-sufficient.

5 Empirical Model

This chapter introduces the empirical model for the estimation of distributed PV determinants. In addition to this, it is explained how the estimated effects must be interpreted.

5.1 Empirical model

The data set used for the estimation is a monthly panel regression on the municipality level, over the period from 2012 to 2019. The outcome variables NICU and NIP are estimated as a function of the control variables introduced in the previous chapter, policy dummies, year fixed effects (FE) and region FE. As in Aklin et al. (2018) and Assunção & Schutze (2017), variables are log transformed. According to Bellemare & Wichman (2019) this has the advantage, that log transformed variables reduce heteroskedasticity. This means, that the effect of outliers on the estimation results is reduced. However, the utilization of log transformations is problematic when zero values are included in the data set, since the logarithm of zero is undefined. For this reason, scholars tend to drop zero observations from the data set in this case. Similar to Assunção & Schutze (2017), the data set used here, has a high share of zero values on the outcome variables. In the present case, 90% of the data set would be lost in this way.

To resolve this problem, Assunção & Schutze use an inverse hyperbolic sine (IHS) transformation. According to Bellemare & Wichman (2019) this transformation method became popular in applied econometrics since it allows to contain zero and negative observations, while it behaves like a logarithm for large values. The IHS of a variable Y is calculated as follows:

$$IHS(Y) = \operatorname{arcsinh}(Y) = \ln\left\{Y + \sqrt{(Y^2 + 1)}\right\} \tag{2}$$

In case that Y=0:

$$IHS(0) = \ln\left\{0 + \sqrt{(0^2 + 1)}\right\} = ln\left\{\sqrt{1}\right\} = \ln(1) = 0 \tag{3}$$

By utiliziing the IHS transformation the original variable value is not affected to a large extend, but the function is defined for zero values of variables. Because of these properties, both dependent and indenpendent regression variables are IHS transformed instead of using a simple log transformation.

$$IHS(NICU_{it}) = a + \beta_1 IHS(Ex\_CU_{it}) + \beta_2 IHS(E_i) + \beta_3 IHS(R_i) + \beta_4 IHS(T_{it}) + \beta_5 IHS(I_i) + \beta_6 IHS(U_{it}) + \beta_7 IHS(D_i) + \beta_8 IHS(C_{it}) + \beta_9 P_{it} + \rho_i + \tau_t + \varepsilon_{it} \tag{4}$$

Equation (4) estimates determinants of NICU in municipality *i* in period *t*. $NICU_{it}$ is estimated as a function of exisiting CU Ex_CU_{it}, electrification E_i, solar irradiation R_i, the electric tariff T_{it}, household income I_i, unemployment U_{it}, population density D_i, and residential consumtion C_{it}. All these variables are IHS transformed. In addition to this, Policy dummies P_{it}, region fixed effects (FE) ρ_i, and year FE τ_t and an error term ε_{it} are included in the model.

$$IHS(NIP_{it}) = a + \beta_1 IHS(Ex\_Pot_{it}) + \beta_2 IHS(E_i) + \beta_3 IHS(R_i) + \beta_4 IHS(T_{it}) + \beta_5 IHS(I_i) + \beta_6 IHS(U_{it}) + \beta_7 IHS(D_i) + \beta_8 IHS(C_{it}) + \beta_9 P_{it} + \rho_i + \tau_t + \varepsilon_{it} \tag{5}$$

Similar to equation (4), equation (5) is used to estimate determinants of NIP in a municipality i during period t NIP_{it}. Apart from the different outcome varibles, the only difference is that instead of existing CU, existing potential Ex_Pot_{it} is controlled for in the estimation to account for neighborhood effects. Both equations (4) and (5) are estimated with a random effects panel regression including robust clustered standard errors.

5.2 Interpretation of estimated effects

According to Assunção & Schutze (2017) the estimates can be interpreted as follows. A 1% change in the independent variable, corresponds to a $\hat{\beta}$% change in the dependent varibale, given that all other variables are held constant. Regarding estimation precision, Bellemare & Wichman (2019) point out, that greater values of IHS-transformed variables will generate more stable estimates. They demonstrate this by deriving the elasticity of estimations with IHS-transformed dependent and independent variables. The elasticity or estimated effect of an independent varible x on an outcome y can be written as:

$$\xi_{yx} = \hat{\beta} \cdot \frac{\sqrt{y^2+1}}{y} \cdot \frac{x}{\sqrt{x^2+1}} \tag{6}$$

According to Bellemare & Wichman (2019) $\hat{\beta}$ will be a consistent estimator for the elasticity ξ_{yx}, in case that y and x are sufficiently large. In this case the terms $\lim_{x\to\infty}\frac{x}{\sqrt{x^2+1}}$ and $\lim_{y\to\infty}\frac{\sqrt{y^2+1}}{y}$ will converge towards 1. On the contrary, if values of x and y significantly smaller than 1, $\hat{\beta}$ will be biased. For this reason, it is also of importance in which unit variables are measured. For example, if a varible has a value of 10kW it generates a better estimate, compared to the case when it is measured in MW, since it will only have a value of 0.01MW in this case.

Policy dummies are not log transformed. For this reason, they have to be interpreted differently than other control varibales. According to Benoit (2011), the estimated effect of a policy dummy on the outcome variable has to be interpreted as exponential of the coefficient $\hat{\beta}$.

$$\xi_{yP} = e^{\hat{\beta}} \tag{7}$$

If $\hat{\beta} = 0.5$, the exponential of the estimated effect is 1.648. If the policy applies, the outcome variable will be raised by 65%. For values of $|\hat{\beta}|$ significantly smaller than 1, this equaltion can be simplified to $\xi_{yP} \approx 1 + \hat{\beta}$ since $e^{\hat{\beta}} \approx 1 + \hat{\beta}$. For example, if $\hat{\beta} = 0.05$, $\xi_{yP} \approx 1 + 0.05 \approx 1.05$. The policy P increases the outcome Y in this case by 5%.

6 Empirical Analysis

This chapter focusses on regression results, limitations of the study, policy implications, and future development of the distributed PV sector. Section 6.1 discusses regression results for NICU and NIP. In section 6.2 limitations of the analysis are discussed. The following section includes a sensitivity analysis. Section 6.4 focusses on alternative sources, while section 6.5 provides policy advice and an outlook for the distributed PV sector.

6.1 Regression results

Regression results are discussed seperately for NICU and NIP. Furthermore, policy dummies are jointly discussed in section 6.1.3.

6.1.1 Newly installed consumer units

The regression results for NICU are presented in two separate tables. Table 9 presents the regression results when control variables are considered as single determinants of NICU. The main regression results for NICU, including year FE, region FE and policy dummies are presented in column 5 of table 10. In the previous columns, policy dummies, year and region FE are added individually to the control variables. The statistical significance of estimates is reported as p-values. If not explicitly stated, estimates are significant at the 1% level. Furthermore, the magnitude of estimates is discussed for 10% increases in independent variables.

Taking control variables as individual determinants, provides estimates highly consistent with the maps in appendix B. Existing CU, electric tariff rates, household income, population density, and consumption have as expected a positive effect on NICU.

The most important determinant of NICU is the already existing number of CU in a municipality. A 10% increase in existing CU raises NICU by 3.34%. This estimate is stable throughout the different model specifications. This result corresponds to Aklin et al. (2018) and

Graziano & Gillingham (2015) who also detect a positive effect of existing CU in the neighborhood on PV uptake.

Household income and higher population density increase NICU according to the estimation results. As single determinants household income raises NICU by 3%, while population density raises NICU by 0.78%. Including all controls, the effects drop to 0.6% and 0.11%, respectively, but stay highly significant and positive. This result does not correspond to findings from German studies suggesting that higher population density reduces PV uptake (Winter & Schlesewsky, 2019; Baginski & Weber, 2019). What must be considered here, is that according to the World Bank (2020), the population density in Germany is about 10 times higher than in Brazil. The simultaneous positive effect of household income and population density is highly consistent with Aklin et al. (2017), who find that in rural India PV uptake is lower in poor and remote villages. As illustrated in figure B1, B4 and figure B6, this applies especially to the Northern region, where household income, population density and PV uptake are all below the national average.

Regarding individuals' controls, changes in the electric tariff exert the largest effect on NICU. A 10% increase in the electric tariff is associated with a 16.56% rise in NICU. The estimated effect drops to 0.62% when controls are included and converges towards zero and loses statistical significance through the inclusion of year FE. This result contrasts findings from Assunção & Schutze (2017), detecting a 7% increase. As discussed in section 3, tariff distortions caused by the reform in 2015, might be a reason why the estimated effect converges towards zero. This topic will be further discussed in the sensitivity analysis in section 6.2.

As expected, consumption is estimated to increase NICU by 0.42% as a single determinant. When all controls are included, the effect drops to 0.27%. Though the direction of the estimated effect corresponds to findings in empirical literature, the magnitude of the estimates is relatively small and only statistically significant at the 10% level. Baginski & Weber (2019) estimated that the effect of consumption on PV uptake is 10 times larger in Germany.

Results for electrification, radiation and unemployment as single determinants are inconsistent with empirical findings from other studies. An exception is the negative effect of radiation on NICU corresponding to Assunção & Schutze (2017). As explained above, lower income in Brazil hinders PV uptake in remote areas. Electrification rates are to a high extend determined by household income as well as population density, since distributors have economic incentives to attend primarily rich and densely populated areas due to higher consumption levels.

Radiation and unemployment turn into the expected direction when controls are included. Main findings correspond well to Baginski & Weber (2019). While 10% higher electrification is estimated to decrease NICU by 1.6%, Baginski & Weber estimate the effect to 2.2%. Regarding radiation, they find a 2.3% increase in NICU, while the result here is 1.66%. However, the results disagree with Assunção's & Schutze's (2017) findings, suggesting that radiation only raises PV uptake in Brazil when distributor areas are controlled for. In this study the inclusion of control variables is sufficient to reverse the effect into its expected direction. Differences in estimated effects can be explained by variations in the data set and the choice of control variables.

In contrast to other authors, Carstens & Cunha (2019) consider the fact that most PV systems are installed in areas with low radiation, as not problematic. They argue that solar potential is generally high in an international comparison. According to Winter & Schlesewsky (2019) solar irradiation in Germany is only at about 3,2 kWh/m² per day in the most insolated areas. Even in the municipality with the lowest solar irradiation in Brazil average irradiation amounts to 3,59 kWh/m².

As discussed above unemployment, consumption and electric tariffs point in the expected direction if all controls are included. However, the estimate of the electric tariff drops towards zero and loses statistical significance. This can be accounted to the fact that all variables changing over time are highly sensitive to the inclusion of year FE. As in column (5) where all controls are included, the inclusion of year FE in column (3) attenuates the estimates towards zero.

When unemployment is taken as the single determinant of CU, a 10% increase in unemployment raises NICU by about 6%. This result opposes empirical findings detecting a negative effect on unemployment on PV uptake discussed in section 2.2. It can however be explained by rising unemployment after the outbreak of the financial crisis in 2014 and higher PV uptake during later years (IBGE, 2019). When other controls are included the estimated effect of unemployment on NICU turns negative and falls to 0.5%. Though the magnitude is smaller, this result corresponds to Briguglio & Formosa (2017), estimating a 2% decrease in PV uptake.

Table 9: Individual controls – NICU

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Existing CU	0.331***							
	(0.004)							
Electrification		0.685***						
		(0.047)						
Radiation			-0.378***					
			(0.035)					
Electric tariff				1.656***				
				(0.035)				
Household income					0.302***			
					(0.010)			
Unemployment						0.597***		
						(0.013)		
Population density							0.078***	
							(0.004)	
Consumption								0.042*
								(0.023)
Constant	-0.022***	-3.469***	1.016***	-0.778***	-3.017***	-1.536***	-0.164***	-0.100
	(0.001)	(0.248)	(0.083)	(0.016)	(0.102)	(0.033)	(0.013)	(0.130)
Observations	534,720	534,720	534,720	534,720	534,720	467,880	534,720	534,720
Number of Municipalities	5,570	5,570	5,570	5,570	5,570	5,570	5,570	5,570
Policy?	No	No	No	No	No	No	No	No
Year FE?	No	No	No	No	No	No	No	No
Region FE?	No	No	No	No	No	No	No	No

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 10: Main regression results - NICU

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing CU	0.341***	0.339***	0.333***	0.341***	0.334***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Electrification	-0.242***	-0.229***	-0.216***	-0.145***	-0.160***
	(0.027)	(0.026)	(0.024)	(0.021)	(0.021)
Radiation	0.347***	0.290***	0.286***	0.142***	0.166***
	(0.028)	(0.027)	(0.029)	(0.026)	(0.026)
Electric tariff	0.062***	0.197***	0.047	0.109***	0.053
	(0.017)	(0.021)	(0.032)	(0.018)	(0.034)
Household income	0.027***	0.023***	0.044***	0.059***	0.060***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Unemployment	-0.112***	-0.074***	-0.026***	-0.135***	-0.050***
	(0.007)	(0.009)	(0.009)	(0.008)	(0.012)
Population density	0.012***	0.013***	0.010***	0.009***	0.011***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Consumption	0.001	0.061***	0.031**	0.017	0.027*
	(0.010)	(0.011)	(0.013)	(0.011)	(0.014)
ANEEL2015		-0.034***			-0.022***
		(0.003)			(0.003)
ICMS equipment		0.038***			0.020***
		(0.006)			(0.006)
Tax exemptions		-0.027***			0.001
		(0.003)			(0.002)
TUSD		-0.017***			-0.033***
		(0.004)			(0.011)
Import duty		0.015***			-0.002
		(0.002)			(0.001)
Constant	0.393***	-0.019	-0.152	0.024	-0.206
	(0.143)	(0.140)	(0.136)	(0.139)	(0.146)
Observations	467,880	467,880	467,880	467,880	467,880
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	Yes	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.1.2 Newly installed potential

Regression results for NIP are presented in table 11 and 12. The design of these tables corresponds to table 9 and table 10. Since results of NICU and NIP are quite similar, this section will primarily deal with deviations in regression results. Single determinants of NIP are about twice as large compared to NICU estimates. The difference in the magnitude of estimates is even greater when control variables are included. In this case, estimates are up to four times larger compared to corresponding estimates in table 10. The only exception are existing CU and existing potential which have approximately the same magnitude of 3.4%, in case that the independent variable rises by 10%.

Similar to estimation results in table 10, control variables changing across time are highly sensitive to the inclusion of year FE. In table 10, estimates converge towards zero but remain except for electric tariffs statistically significant. When year FE are included in table 12, both estimates loose their significance and the electric tariff even switches pre-signs. In case of consumption this effect is even stronger. As a single determinant, a 10% increase in consumption is associated with a 1.56% increase in NIP. In column 5 of table 12 this effect is nearly perfectly reversed. A 10% increase in consumption reduces NIP by 1.55%. This counterintuitive observation opposes empirical findings of Borenstein (2017), Baginski & Weber (2019) and Aklin et al. (2018) who all detect a positive effect of higher consumption levels on PV uptake. Again, the electric tariff reform in 2015, discussed in section 3.2, serves as an explanation. According to Cook (2011) artificially lower electric tariffs simultaneously raised consumption and disincentivized investment in distributed PV.

Table 11: Individual controls - NIP

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Existing potential	0.353***							
	(0.004)							
Electrification		1.340***						
		(0.090)						
Radiation			-0.785***					
			(0.063)					
Electric tariff				3.340***				
				(0.059)				
Household income					0.568***			
					(0.016)			
Unemployment						1.202***		
						(0.022)		
Population density							0.138***	
							(0.006)	
Consumption								0.156***
								(0.038)
Constant	-0.015***	-6.768***	2.106***	-1.567***	-5.652***	-3.089***	-0.254***	-0.604***
	(0.001)	(0.473)	(0.147)	(0.028)	(0.163)	(0.057)	(0.021)	(0.215)
Observations	534,720	534,720	534,720	534,720	534,720	467,880	534,720	534,720
Number of municipalities	5,570	5,570	5,570	5,570	5,570	5,570	5,570	5,570
Policy?	No	No	No	No	No	No	No	No
Year FE?	No	No	No	No	No	No	No	No
Region FE?	No	No	No	No	No	No	No	No

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 12: Main regression results - NIP

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing potential	0.343***	0.330***	0.316***	0.343***	0.316***
	(0.004)	(0.004)	(0.005)	(0.004)	(0.005)
Electrification	-0.563***	-0.577***	-0.547***	-0.431***	-0.472***
	(0.051)	(0.052)	(0.048)	(0.044)	(0.044)
Radiation	0.563***	0.575***	0.412***	0.280***	0.356***
	(0.053)	(0.052)	(0.057)	(0.052)	(0.052)
Electric tariff	0.476***	0.646***	0.034	0.538***	-0.002
	(0.033)	(0.044)	(0.066)	(0.036)	(0.072)
Household income	0.182***	0.187***	0.275***	0.231***	0.273***
	(0.014)	(0.014)	(0.014)	(0.015)	(0.015)
Unemployment	-0.135***	-0.130***	-0.009	-0.163***	-0.006
	(0.013)	(0.017)	(0.017)	(0.015)	(0.025)
Population density	0.038***	0.044***	0.032***	0.036***	0.041***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
Consumption	-0.017	0.047**	-0.114***	-0.001	-0.155***
	(0.021)	(0.023)	(0.026)	(0.023)	(0.029)
ANEEL2015		-0.073***			-0.029***
		(0.005)			(0.005)
ICMS equipment		0.033***			0.015
		(0.011)			(0.012)
Tax exemptions		-0.046***			0.005
		(0.006)			(0.004)
TUSD		-0.142***			-0.301***
		(0.007)			(0.022)
Import duty		0.017***			0.000
		(0.005)			(0.003)
Constant	-0.186	-0.540*	-0.420	-0.716***	-0.094
	(0.270)	(0.281)	(0.274)	(0.277)	(0.298)
Observations	467,880	467,880	467,880	467,880	467,880
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	YES	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.1.3 Policy dummies

Policy dummies are discussed jointly as determinats of NICU and NIP in this subsection. In table 13, policy dummies are also presentated as single determinants of NICU and NIP. As explained in section 5, estimates can only be interpreted as changes in varible values if estimates are significantly smaller than 1. Otherwise they have to be interpreted as $\xi_{yP} = e^{\widehat{\beta}}$. Similar to other regression results, the estimated effect of policy dummies on NIP exceed those on NICU by a factor two. Regarding the ICMS exemption on PV equipment the effect of NIP is four times larger.

When policy dummies function as single determinants the direction and magnitude is determined by the timing of the policies. On the one hand, ANEEL 2015 and the tax exemptions on generated electricity are implemented in 2016 and 2015, respectively. As illustrated in figure 4, both CU and installed potential grew rapidly from this period onwards. Therefore, ANEEEL 2015 raises NICU and NIP by 32% and 77% respectively. Tax exemptions which were issued slightly earlier excert a slightly lower effect with 30% and 69%.

On the other hand, policies issued during early periods, are estimated to have a negative effect on PV uptkae, since NICU and NIP were lower during early years. The TUSD and import duty reductions are estimated to reduce NICU and NIP. For the TUSD, the estimated reduction in NICU and NIP are greatest 35% and 58% respectively.

Regarding ICMS exemptions on equipment, PV uptake is higher in states, where the policy is not applied. This corresponds to table A2, illustrating that especially PV uptake in Santa Catarina and Paraná, where the policy does not apply, are among the states with the highest PV uptake in Brazil.

In the last column of table 10 and 12 most estimated lose their statisitical significance. This can be accounted to inclusion of year FE and that except for ICMS equipment, all policy dummies are defined over time periods. However, ANEEL 2015 and TUSD have a significant negative effect on NICU and NIP. For ANEEL 2015 this effect is very small reducing NICU and NIP by 2.18% and 2.86% respectively. TUSD has a significantly stronger negative effect reducing NICU by 3.25% and NIP by 26%. The only varibale exerting a significant positive effect is ICMS equipment raising NICU by 2%. For NIP the effect is insignificant.

Table 13: Individual determinants - Policy dummies

VARIABLES	CU					NIP				
ANEEL2015	0.281***					0.571***				
	(0.006)					(0.011)				
ICMS equipment		-0.021**					-0.082***			
		(0.009)					(0.016)			
Tax exemptions			0.259***					0.526***		
			(0.006)					(0.010)		
TUSD				-0.431***					-0.875***	
				(0.008)					(0.015)	
Import duty					-0.111***					-0.227***
					(0.002)					(0.004)
Constant	0.007***	0.159***	0.004***	0.464***	0.161***	0.013***	0.356***	0.007***	0.943***	0.327***
	(0.000)	(0.008)	(0.000)	(0.009)	(0.004)	(0.001)	(0.015)	(0.001)	(0.016)	(0.006)
Observations	534,720	534,720	534,720	534,720	534,720	534,720	534,720	534,720	534,720	534,720
Number of municipalities	5,570	5,570	5,570	5,570	5,570	5,570	5,570	5,570	5,570	5,570

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.2 Limitations of the study

There exist hurdles limiting the internal and external validity of the estimated effects. As mentioned above, unemployment data broken down by state is only available for the years 2012-2018, due to changes in data collection methods. Since time variant controls are always used from the previous year, missing unemployment data for the year 2011 result in an exclusion of the year 2012 from the regression when unemployment is controlled for.

Second, the observation period comprises the years of the electric supply, economic and financial crises as well as the 2015 electric tariff reform. These caused changes in individual investment behavior and had large impacts on household income due to soaring unemployment rates. Since household income is only measured before the observation period, changes in income during the crisis might hit regions to a different extent, affecting investment behavior. This could affect regression results during later years.

Furthermore, Angrist & Pischke (2008:84) note that the occurrence of measurement errors must be considered. Random measurement errors in control variables result in an attenuation of estimated effects towards zero, weakening the regression results.

Moreover, statistical significance is determined by the size of the data set. Lin et al. (2013) and Engsted (2009) point out that several econometricians focus on statistical significance alone when interpreting estimation results. The p-value used to determine statistical significance drops quickly to zero when samples have more than 10.000 observations. For this reason, it is important, to analyze the magnitude of the estimated effect to determine if estimated effects are also economically significant.

Since, residential consumers are the largest group among distributed PV investors, their electric tariffs and residential consumption are used as base lines. For other consumption classes, this choice might not reflect determinants for NICU and NIP for other consumer classes.

Finally, the design of the econometric model might be problematic. Bell & Jones (2015) note, that linear random effects models in different to FE models have the disadvantage, that unobserved variables cannot be controlled for. This could result in an omitted variable bias. According to Angrist & Pischke (2008:84-86) this occurs if an unobserved variable simultaneously affects dependent and independent variables. To avoid this problem, Angrist & Pischke (2008:165pp.) suggest that FE model can control for municipality specific effect which are constant across time. However, the disadvantage of FE estimation is that all constant terms are dropped form the estimation. Consequentially, utilizing a FE model would not allow to estimate the effect of constant variables such as solar irradiation, household income, electrification, and population density, some of the most important determinants of PV installations.

6.3 Sensitivity analysis

To determine the drivers of the estimated effect in section 6.1, the data set is splitted and re-estimated in this section. First, it is divided into two periods, before and after ANEEL nº687/2015 went into force in March 2016. As explained in chapter 3, changes in DG legislation caused a massive rise in PV uptake and improved adaption possibilities. In addition to temporal variations, figure 6 suggests that regional variations in PV uptake exist as well. For this reason, regressions were run separately for Brazils five greater regions in section 6.2.2. In addition to this, the panel regression in run as a FE model to determine whether regression results are affected by an omitted variable bias.

6.3.1 Temporal division

The data set is divided in the temporal division into the early period, before ANEEL nº687/2015 was implemented and the later period when ANEEL nº687/2015 was enforced. Regression results are presented in tables C1 and C2 for the early and C3 and C4 for the later period. The design of the tables corresponds to tables 10 and 12, containing the main regression results for NICU and NIP. According to these results, the direction of the estimated effects for the early period before March 2016, is similar to those of the later period, but differs in magnitude. Estimated effects during the later period exceed those of the earlier one by about up to a factor of 10, and the main regression results by a factor of 2.

As argued above, small estimated parameters of electric tariffs, consumption, and unemployment can be accounted to the inclusion of year FE. Here, counterintuitive results can be tracked down to smaller time periods. For example, the counterintuitive result that consumption reduces NIP is driven by the later period, where the effect on electricity consumption on PV uptake is clearly negative. A 10% increase in consumption decreases NIP by 5.14%. In difference to the main regression result, this effect turns even significantly negative for NICU during the later period. As discussed above, this can be accounted to tariff distortions caused by the 2015 reform, discussed in more detail in section 3.2.

A negative correlation between unemployment and PV uptake emerges only during the later period. An increase in unemployment by 10% is associated with a reduction in NICU by 1.13% and in NIP by 3.69%. During the earlier period, estimates are positive but have with 0.05% and 0.12% a very small magnitude. Estimates are therefore only significant at the 10% level. As shown in figure 6, the positive effect of unemployment on NICU and NIP during the early period can be traced back to the predominant location of PV system in the Northeast, the region with the highest unemployment rate (figure B8).

Regarding electric tariffs, the estimated effect of a 10% increase in the electric tariff raises NICU by 0.4% and NIP by 1.04% before ANEEL nº687/2015 went into force. During the later period, the effect is reversed. In this context, it is also important that the tariff system was restructured at the end of the early period. Some of the poorest states with low radiation rates now face the highest electric tariff rates in Brazil, but due to a lack of financial funds also lack the possibility to invest in PV installations. This can partially explain why NIP is estimated to drop by 8.85% if the electric tariff rises by 10%.

6.3.2 Regional division

Regression results separated by region are presented in table C5 and C6. The estimates for each region correspond to column (5) in table 10 and 12, respectively. As in previous estimations, results for NICU and NIP for individual regions are similar but determinants of NIP are about 3 times larger. In several cases, estimated effects for the North and the Central-West lack statistical significance. Lin et al. (2013) find, less observations reduces estimation precision. This explains lower statistical significance since both regions have less municipalities and consequentially also less observations compared to the others.

Estimates for the time invariant control variables electrification, household income, population density, and radiation as well as exisiting CU and existing potential all have the expected pre-sign. More interesting are the results for the factors changing across time. The first one is the counterintuitive observation, that unemployment in the main regression has only a very small negative effect on NICU and an insignificant effect on NIP. During the earlier period, the effect is even significantly positive. This association is primarily driven by the Southeast where a 10% increase in unemployment increases NICU and NIP by 3.5% and 6.6%, respectively.

In the main regression, the electric tariff has an insignificant effect on PV uptake. The temporal division demonstrates that the electric tariff exerts a positive effect on NIP uptake during the first but not during the second period. When the data set is divided by region, this unexpected result can be traced back to the Central-West, where a 10% increase in the electric tariff is associated with a reduction in NICU by 3.78% and NIP by 14.07%. In all other regions an increase in the electric tariff boosts PV uptake, as predicted by Gautier & Jacqmin (2020) and Graziano & Gillingham (2015).

Contradictory results for the Central-West by driven by very high PV uptake in the Federal District. According to table A2 and A3 the Federal district consists of a single municipality, with 1,748 CU, while the remaining municipalities in the region have only 50 CU on average. Figure B1, B2, B8 and B9 illustrate that while PV uptake was significantly higher in the Federal District, unemployment was exceptionally high, while electric tariff rates were among the lowest in a national comparison.

Regarding consumption, the counterintuitive observation that higher consumption reduces NIP is driven by the Northeast and Southeast. A 10% increase in consumption reduces NIP by 1.62% in the Northeast and 2.75% in the Southeast. These results can be accounted to very low residential consumption combined with high PV uptake in Minas Gerais and in the Northeast.

6.3.3 Municipality fixed effects

To check whether unobserved variables exert a significant effect on the estimation results, the regression for NICU and NIP are run including municipality FE. The results are presented in table C7 and C8 in the appendix. As discussed above, all independent variables which are constant across municipalities and time, are omitted from the regression. This applies to electrification, radiation, household income, population density, as well as to the ICMS exemption on PV equipment.

The only statistically significant difference to the main estimation results in tables C7 and C8, is that the effect of consumption on NICU rises in magnitude and becomes statistically significant at the 1% level. A 10% increase in residential consumption is associated with a 2.18% in NICU. All other changes in regression results lack statistical significance. Based on these numbers there exists no evidence for an omitted variable bias in the main estimations caused by the utilization of a random effects model.

6.4 Other renewable energy sources

Though Brazil is considered as one of the countries benefitting from seasonal variations in PV generation, Scarabelot et al. (2019) observe that this does not account for variations throughout the day. While PV potential is highest at daytime, consumption exceeds generation during the early evening. For this reason, increasing reliance on distributed PV calls for increased attention how supply and demand can be balanced. In areas with grid connection, a lack of solar potential at nighttime can be compensated by other primary sources such as wind, biomass, and small hydro plants. In isolated systems this topic is of even greater importance. The EPE (2016) and Schmidt et al. (2016) propose that electricity generation during nighttime can be secured either by storage units or hybrid generators combining fossil fuel and PV based generation. Since hydroelectric potential still accounts for most of installed capacity, new renewables are even discussed as complements to centralized hydro plants.

Among alternative sources, Schmidt et al. (2016) and Silva et al. (2016) discuss small hydroelectric and run-on-river plants. Beneficial is that they cause lower initial investments costs compared to large hydroelectric plants. Further, their environmental impact is significantly lower, since they only require a small or even no flooded area. Anyhow, since reservoirs are limited or completely absent, electricity supply cannot be adjusted and is even more affected by seasonal variations in rain falls. This might further reduce supply security. In addition to this, the location of several plants in the same basin reduces the potential of individual plants. Finally, a shift from large-scale to small-scale hydro generation rises electricity costs due to scale effects.

According to Silva et al. (2016), Schmidt et al. (2016), and IRENA (2016), wind potential is anti-seasonal with hydroelectric generation. Electricity generation of windfarms is highest during dry season when hydroelectric potential is low. The adoption of wind farms can therefore contribute to balancing electricity supply throughout the year. In comparison to solar potential, wind potential is even available at nighttime.

Silva et al. (2016) point out that Brazil has the second largest biomass capacity and holds a share of 25% of worldwide ethanol fuel production. In addition to this, it benefits also from anti seasonality with hydro generation (IRENA, 2016). However, biomass is based to more than 70% on sugar cane. For this reason, most of biomass capacity is seasonally bound to its harvest periods. Moreover, biomass is after fossil fuels the most expensive source for electricity generation. Consequentially, biomass is not suited to provide base load capacity but rather to take on a complementary role in electricity generation.

According to Rüther & Zilles (2011), Pepermans et al. (2003), and Silva et al. (2016), cogeneration units, simultaneously generating electricity and heat should be considered. This would be beneficial since electricity is mainly used to heat water in the Brazilian residential sector, and up to a third of energy can be saved through cogeneration. In this way, up to 46 TWh of residential consumtion could have been saved in 2018 (EPE, 2020a). However, the adaption of this technology is similar to other new renewables harmed by a lack of awareness among Brazilian consumers and officials.

6.5 Policy advice and future outlook

6.5.1 Policy advice

To further incentivize distributed PV, Carstens & Cunha (2019) and Scarabelot et al. (2019) consider additional financial incentives on the federal, state, and municipality level, as necessary. Furthermore, policy makers should stimulate knowledge exchange between different actors in the sector to improve technologies and institutional structures in the solar sector.

According to Schneider et al. (2019), it is also highly important to improve pre-conditions for alternative generation modalities. Shared generation has the advantage, that costs and benefits of DG installations can be shared among several individuals. This allows individuals with low income or without real estate possessions to benefit from DG. However, shared consumption units face several financial and regulatory barriers. For this reason, there were only 448 registered shared PV units registered in December 2019 (ANEEL, 2020b). Low presence of shared generation on the national level has the disadvantage that neither policy makers, the financial sector, nor consumers are sufficiently informed about this modality. Consequentially, it is of great importance to remove financial and regulatory barriers for shared generation, and to spread knowledge on alternative generation modalities, to make DG accessible for wider parts of the population.

As mentioned in section 2.3, tariff distortions can lead to non-optimal allocation of PV units. To determine how differences in electric tariffs affect PV adoption, Assunção & Schutze (2017) estimate a counterfactual model. While holding all other estimate values constant, they calculate how many CU were located in each municipality, given that electric tariffs were equal throughout the country. These estimates are compared to the actual estimation results. Their results reveal that municipalities with artificially low tariffs have too few CU compared to municipalities where tariff rates are above average. For this reason, it would be beneficial to equalize electric tariff rates throughout the country, to prevent a non-optimal allocation of CU. Since the 2015 electric tariff reform caused a significant fraction of the electric tariff distortions, it should be abolished.

Non-optimal allocation of PV systems can also be traced back to incentives provided by grid operators. Pepermans et al. (2003) observe that grid operators have incentives to discriminate against DG since it reduces their own revenue. Luna et al. (2019) point out that distributor incentives for PV adoption can be found primarily among distributors operating in the Southern region and in São Paulo, where PV uptake is highest in general. To even out these effects, policy makers should implement laws, which encourage other distributors to offer similar incentives for PV uptake among their consumers.

According to Briguglio & Formosa (2017), a subsidy for installation costs of PV systems was introduced in Malta to encourage households to invest in PV. Since income inequality remains a major hinder for PV uptake, a similar policy should be considered in Brazil. In connection to this, Rüther & Zilles (2011) and Luna et al. (2019) recommend the introduction of tax incentive for non-profit organizations, the inclusion of renewable energy requirements in housing projects, and incentives for rural electrification in the DG legislation. Further, they propose the introduction of a feed-in tariff to increase the absolute size of the sector.

6.5.2 Future outlook

One main incentive for PV uptake is the transmission tax exemption on self-generated electricity for owners of distributed DG systems. According to Globo Rural (2019) and the Agência Senado (2019), ANEEL revised the normative resolution to abolish this subsidy for systems installed after the 30th December 2019. For already existing units, costs for grid utilization will be imposed only in 2030. The announcement caused a short-term increase in PV uptake, but is expected to harm PV uptake in the long and medium run. Cabral (2019) notes that ANEEL and the government justify this step by increasing costs for this subsidy, reaching R$ 400 million in 2019. Further, they point to other countries which also removed subsidies for PV installation, when the solar sector reached maturity.

The Spanish experience demonstrates that the abolishment of subsidies can cause a collapse in the solar energy sector even in areas with high radiation. Couture (2013) notes that Spain was the first country to adopt feed-in tariffs. Until the outbreak of the global financial crisis in 2008 its PV policy was one of the most generous in the world. After the outbreak of the crisis the government stepwise repealed all subsidies for solar installations. Owners of solar systems were forced to connect their PV installations to the electric grid and selling of additional electricity was prohibited. Furthermore, a 7% retroactive tax on renewable energy generation was imposed. Rucinsky and Rodriguez (2013) and Couture, find that these adverse policies made PV systems for most small-scale producers unviable and motivated them to deinstall existing installations. Moreover, the collapse of the PV sector endangered even energy security in Spain, since the country imports 80% on its energy needs. This unfavorable development motivated the Socialist party to remove bureaucratic restrictions imposed on the solar sector when they seized political power from the conservative party in 2018. Combined with the price decrease for PV modules the sector achieved significant growth rates during recent years (UNEF, 2019; Léton, 2019).

Even if the abolishment of the subsidy is only temporary as in the Spanish case, it is expected to have fatal consequences for the solar sector. Carstens & Cunha (2019) note that growth of renewable energy sources creates employment opportunities. Barriers to the growth of this sector could therefore result in lower economic growth, which is of special importance after the economic and financial crisis. Furthermore, investment in DG is disincentivized, what also endangers supply security. In connection to this, the Agência Senado (2019) cites the University of California, Los Angeles economics professor Rodrigo Ribeiro Antunes Pinto who points out that Brazil only generates about 1% of its electricity from solar energy. California continues to subsidize PV installation, despite 13% of its electricity originates from this source. The relative size of the PV sector is therefore an insufficient motivation for the abolishment of PV subsidies.

Nonetheless, the abolishment of the distributed PV subsidies appears to be driven rather by ideological than by economic considerations. According to Proaño (2018) the abolishment of the subsidy can be rather accounted to the neoliberal course of the Bolsonaro government, which leaves little room for environmental protection. Based on neoliberal believes market interventions like subsidies are harmful for economic growth. Consequentially, predictions on the future development of distributed PV are highly uncertain and rather pessimistic under the Bolsonaro administration.

The unresolved electricity crisis in Roraima provides additional evidence that the Brazilian government is rather motivated by ideogical than by economic considerations. According to Oliveira (2020), the costs for electricity generation in Roraima amounted to R$ 1.6 billion. This exceeds costs of the imported electricity from Venezuela by 72%. The additional costs of R$ 1.1 billion for Roraima’s electric consumption are shared among consumers in Roraima and those in other states. This imposes a far higher burden on Brazilian consumers compared to the R$ 400 million paid for distributed PV subsidies in the entire country.

Total electricity consumption in Roraima amounted to 942,000 MWh in 2018 (EPE, 2020a), while total distributed PV capacity in Brazil amounted to 1,976 MW in December 2019 (table 4). It is assumed again that the sun shines for 8h per day. If this assmption holds, a sixth of distributed PV capacity is sufficient to cover electricity consumption in Roraima.

$$\frac{Distributed\ PV_{2019}}{Electricity\ demand_{RR}} = \frac{1{,}976.3\ MW*8h*365}{942{,}000\ MWh} = \frac{5{,}770{,}796\ MWh}{942{,}000\ MWh} = 6.12 \qquad (8)$$

Currently there exist only 75 distributed PV units in Roraima with a capacity of 0.9 MW (table A3). This leaves plenty of room for an extention of distributed PV installations. Though the EPE (2017) points out that distributed PV in isolated system must be backed up with storage units or thermal generators, since they do not generate electricity at night time, equation 8 suggests that electric generation in Roraima could become cheaper, more environmental friendly and secure if higher shares of distributed PV were incorporated. Furthermore, a higher share of distributed PV in the electricity mix would reduce the electricity costs of all consumers in Brazil. If the government was aiming to relieve consumers from high electricity tariffs, they should incentivize DG in Roraima instead of removing basically all financial incentives for this technology.

7 Conclusion

The aim of this thesis was to identify underlying factors of PV uptake in Brazil, and whether there exist substantial differences in the determinants of NICU and NIP. According to the regression results, neighborhood effects, radiation, household income, and population density have a significant and positive effect on PV uptake. On the contrary, higher electrification rates reduce PV uptake. All these results are consistent with findings from empirical literature and confirm the obstacles for cleaner energy sources.

Regarding factors varying across time, results are less consistent and highly sensitive to the inclusion of year FE. Electric tariffs lose their expected positive effect when year FE are included. Similarly, unemployment looses its statistically significant negative impact on NIP. As a determinant of NICU, the estimated effect of unemployment remains negative and significant, but the effect drops close to zero. In the present study, residential consumption is estimated to exert a significant negative effect on NIP, contradicting findings from empirical literature. This unexpected result can be accounted to tariff distortions in Brazil, caused by a reform of the tariff system issued in 2015. This reform generated artificially low tariff rates in some of the richest states, which simultaneosly boosted electric consumption and disincentivized PV uptake.

Because distortions in the electric tariffs lead to non-efficient consumption behavior and affect the allocation of PV installations, distortions in electric tariffs should be removed. Furthermore, installation costs of PV systems should be subsidized to enable low income households to invest in distributed PV. In connection to this, PV uptake is particularly beneficial in remote areas since it provides a cost efficient and sustainable alternative to generation from fossil fuels. Regarding the legal base of DG, policies should be adjusted to incentivize DG from other primary sources than solar energy. This is of high importance to create a diverse electricity mix which is required to prevent future electricity supply crises.

As in previous work, regional income inequality is identified as a cause of higher PV uptake in the less insolated South of the country. However, this is not considered as problematic in Brazil, since solar radiation in the least insolated municipalities is still very high in an international comparison. Critical regarding the development of the distributed PV sector is rather the adverse government policy, abolishing subsidies for installations constructed after 2019.

Because of the novelty of the subject and recent developments in the field, there remains need for future research. On the one hand, research on other primary sources should be conducted to identify reasons why present DG policies are insufficient to incentivize DG from non-solar sources. Furthermore, the Census 2020 is expected to become available soon. This data allows to investigate how electrification was affected by the legalization of DG. Additionally, research on shared generation should be undertaken, since this generation modality allows larger proportions of the population to participate in DG. Of special interest, is the change in law since 2020, in which subsidies for newly installed PV units were abolished. This has the potential to harm future development of the DG sector, renewable energy, and endanger energy security as well as the achievement of climate goals.

The findings of the study have important implications for other highly insolated low- and middle-income countries and for electrification of isolated networks. Distributed PV can grow rapidly even under a net metering system, providing less economic incentives compared to a feed in tariff. Furthermore, the negative association of electrification and distributed PV suggests that distributed PV systems serve as an alternative to grid connection.

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Appendix A

Table A1: Policy dummies

Description	**Name**	**Time**		**States**
		Start	**End**	
ANEEL nº687/2015	p_AN2015	March 2016	December 2019	All
ICMS Excemption ICMS on PV equipment	p_ICMS	All		All, except for Espírito Santo, Amazonas, Paraná, Santa Catarina
Tax excemption on self-generated electricity (ICMS, PIS & COFINS)	p_tax	Oktober 2015	December 2019	All
80% reduction of TUSD for 10 years	p_TUSD	April 2012	December 2017	All
Reduction of Import duty on PV equipment from 14% to 2%	p_import	August 2015	December 2017	All

Table A2: Regions and state codes

Region	Code	State	# Municipalities
North	RO	Rondônia	52
	AC	Acre	22
	AM	Amazonas	62
	RR	Roraima	15
	PA	Pará	144
	AP	Amapá	16
	TO	Tocantins	139
Northeast	MA	Maranhão	217
	PI	Piauí	224
	CE	Ceará	184
	RN	Rio Grande do Norte	167
	PB	Paraíba	223
	PE	Pernambuco	185
	AL	Alagoas	102
	SE	Sergipe	75
	BA	Bahia	417
Southeast	MG	Minas Gerais	853
	ES	Espírito Santo	78
	RJ	Rio de Janeiro	92
	SP	São Paulo	645
South	PR	Paraná	399
	SC	Santa Catarina	295
	RS	Rio Grande do Sul	497
Central-West	MS	Mato Grosso do Sul	79
	MT	Mato Grosso	141
	GO	Goiás	246
	DF	Federal District	1

Source: IBGE, 2020b.

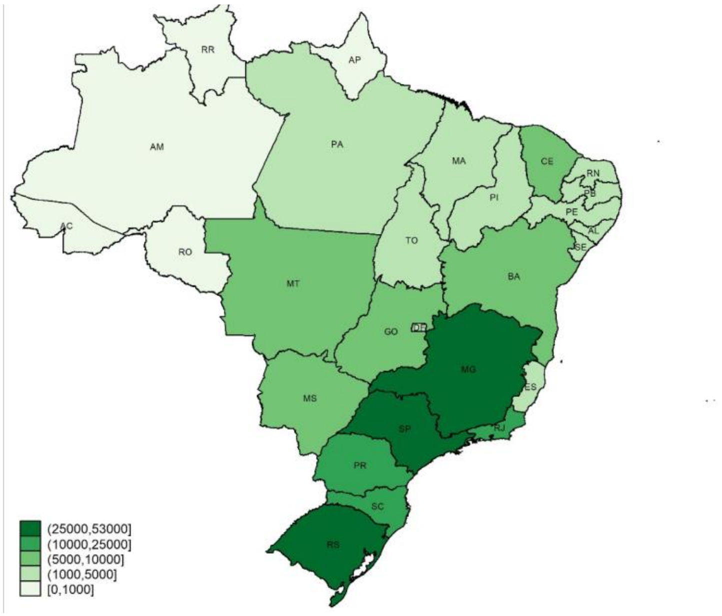
Table A3: CU, installed potential and average capacity in Dec. 2019

State	Consumer units	Potential MW	Average capacity kW
Rondônia	404	4.37	10.83
Acre	179	2.46	13.76
Amazonas	618	5.98	9.67
Roraima	75	0.90	12.00
Pará	2,164	20.56	9.50
Amapá	189	2.64	13.96
Tocantins	2,071	22.39	10.81
Maranhão	3,086	30.68	9.94
Piauí	2,922	29.15	9.97
Ceará	5,314	65.98	12.42
Rio Grande do Norte	3,056	37.94	12.41
Paraíba	4,468	38.46	8.61
Pernambuco	4,545	46.86	10.31
Alagoas	1,458	12.65	8.67
Sergipe	1,199	11.58	9.66
Bahia	6,621	51.62	7.80
Minas Gerais	52,938	371.52	7.02
Espírito Santo	4,073	38.04	9.34
Rio de Janeiro	10,699	77.33	7.23
São Paulo	31,456	230.66	7.33
Paraná	11,473	206.12	17.97
Santa Catarina	13,834	115.85	8.37
Rio Grande do Sul	26,664	259.96	9.75
Mato Grosso do Sul	6,519	61.47	9.43
Mato Grosso	8,473	128.04	15.11
Goiás	8,104	80.25	9.90
Federal District	1,748	22.87	13.09

Source: ANEEL, 2020b.

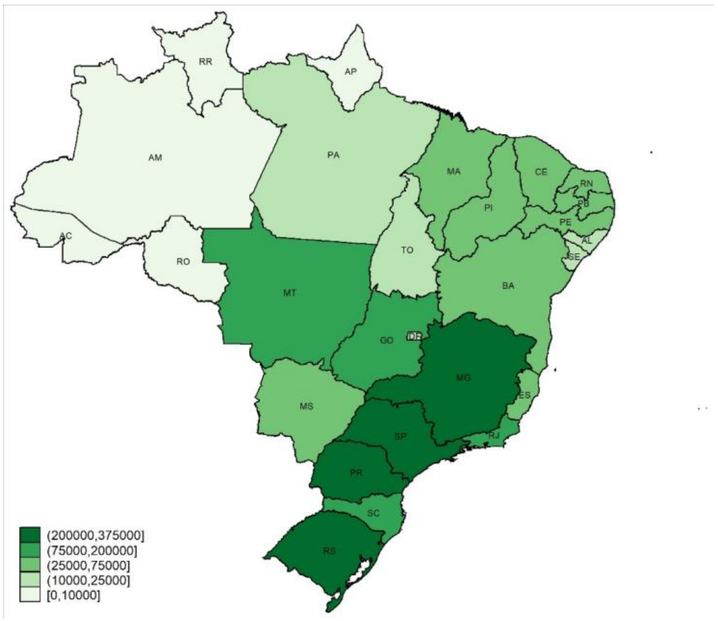
Appendix B

Figure B1: Distributed PV - Consumer units Dec. 2019



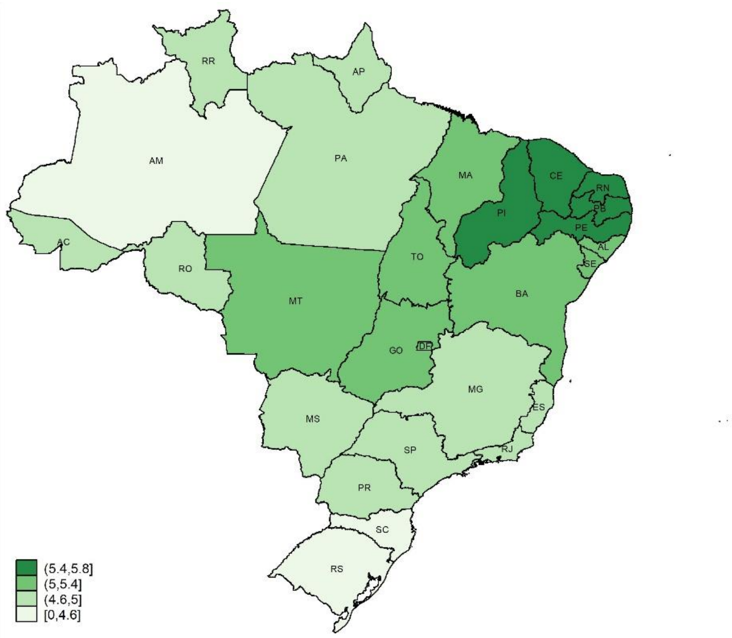
Source: ANEEL, 2020b.

Figure B2: Distributed PV - Potential in kW Dec. 2019



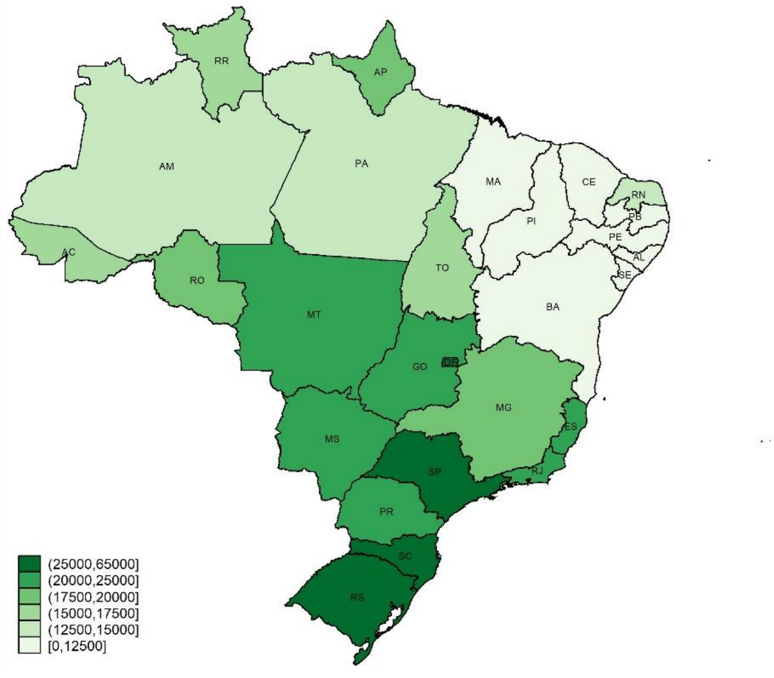
Source: ANEEL, 2020b.

Figure B3: Daily solar irradiation in kWh/m²



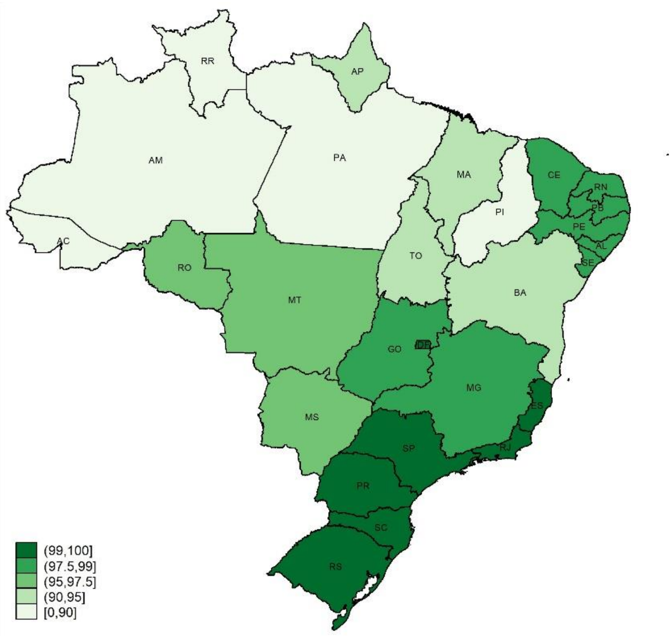
Source: LABREN, 2017.

Figure B4: Average household income in 2010 in R$



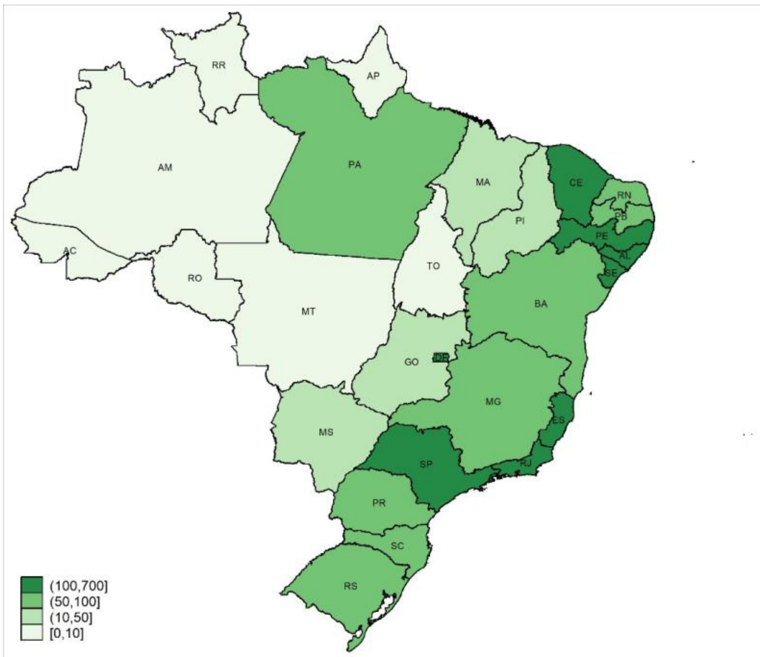
Source: IBGE, 2020c.

Figure B5: Percentage electrification rate in 2010



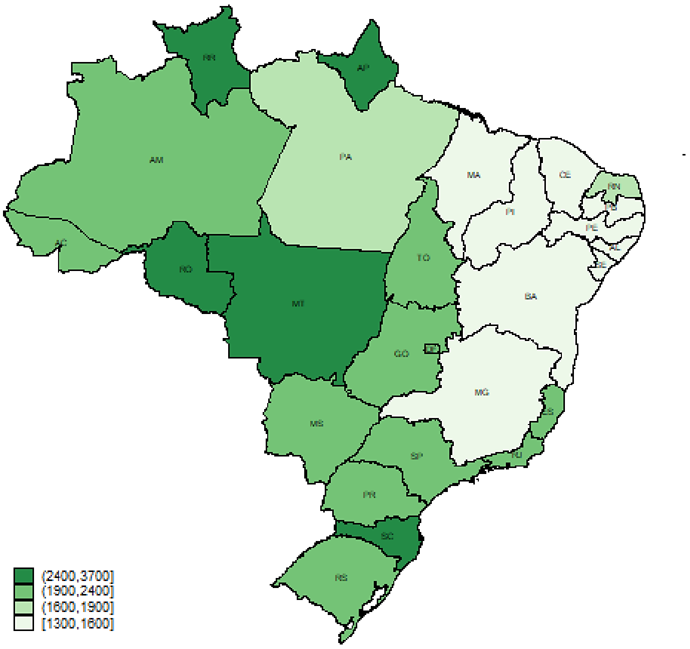
Source: IBGE, 2020c.

Figure B6: Population density in inhabitants per km²



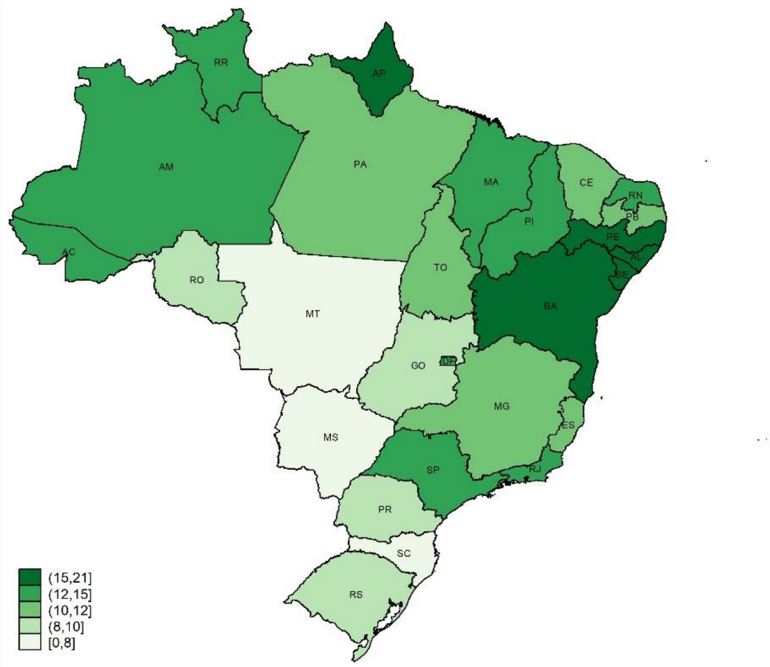
Source: IBGE, 2020a; Sidra, 2020.

Figure B7: Yearly Residential consumption in kWh 2018



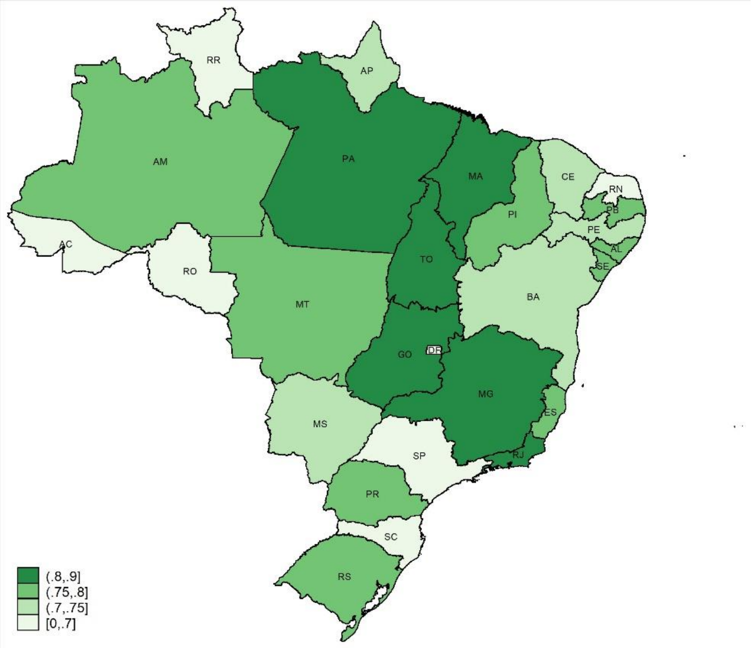
Source: EPE, 2020a.

Figure B8: Unemploment rate 2018



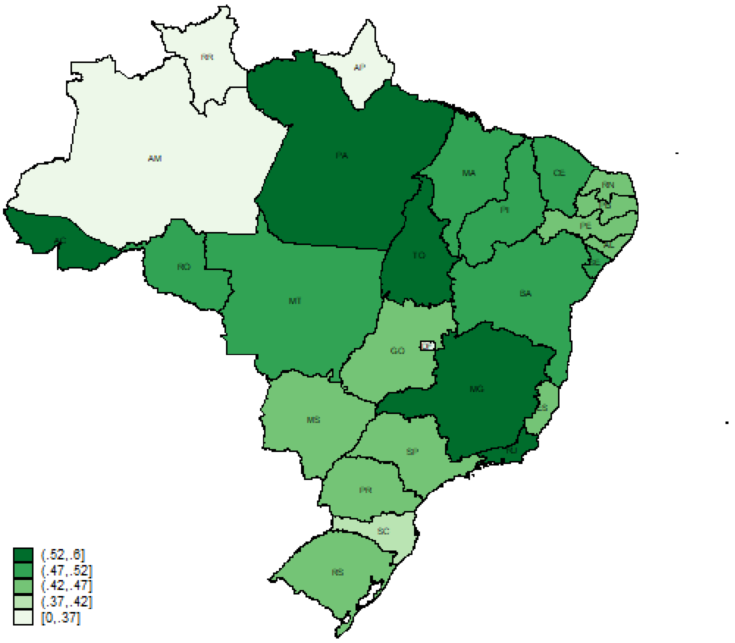
Source: IBGE, 2019.

Figure B9: Electric tariff in R$/kWh 2018



Source: ANEEL, 2019.

Figure B10: Electric tariff in R$/kWh 2014



Source: ANEEL, 2019.

Appendix C

Table C1: Early period – NICU

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing CU	0.173***	0.171***	0.171***	0.173***	0.170***
	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)
Electrification	-0.034***	-0.035***	-0.035***	-0.033***	-0.034***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Radiation	0.024***	0.020***	0.019***	0.021***	0.019***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
Electric tariff	0.045***	0.022***	0.039***	0.045***	0.040***
	(0.006)	(0.006)	(0.008)	(0.007)	(0.009)
Household income	0.011***	0.014***	0.014***	0.011***	0.013***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Unemployment	0.003	0.001	0.002	0.005*	0.005*
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
Population density	0.003***	0.003***	0.003***	0.004***	0.004***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Consumption	0.006***	-0.002	-0.001	0.006**	-0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
ICMS equipment		0.001			-0.001
		(0.001)			(0.001)
Tax exemptions		0.006***			0.006***
		(0.002)			(0.002)
Import duty		0.004***			0.003**
		(0.001)			(0.001)
Constant	-0.070**	-0.015	-0.033	-0.072**	-0.038
	(0.028)	(0.028)	(0.026)	(0.030)	(0.028)
Observations	211,660	211,660	211,660	211,660	211,660
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	Yes	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C2: Early period - NIP

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing potential	0.138***	0.134***	0.134***	0.138***	0.133***
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)
Electrification	-0.100***	-0.103***	-0.104***	-0.094***	-0.096***
	(0.013)	(0.013)	(0.013)	(0.012)	(0.012)
Radiation	0.075***	0.061***	0.056***	0.064***	0.055***
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)
Electric tariff	0.129***	0.057***	0.093***	0.133***	0.104***
	(0.014)	(0.013)	(0.018)	(0.015)	(0.020)
Household income	0.031***	0.039***	0.040***	0.034***	0.041***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Unemployment	0.007*	0.004	0.004	0.010*	0.012*
	(0.004)	(0.004)	(0.004)	(0.006)	(0.007)
Population density	0.011***	0.010***	0.010***	0.011***	0.011***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Consumption	0.025***	-0.005	-0.007	0.026***	-0.008
	(0.005)	(0.005)	(0.006)	(0.006)	(0.006)
ICMS equipment		-0.000			-0.004
		(0.003)			(0.003)
Tax exemptions		0.016***			0.014***
		(0.003)			(0.004)
Import duty		0.014***			0.009***
		(0.002)			(0.003)
Constant	-0.222***	-0.050	-0.061	-0.274***	-0.123*
	(0.067)	(0.067)	(0.063)	(0.072)	(0.069)
Observations	211,660	211,660	211,660	211,660	211,660
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	Yes	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C3: Later period – NICU

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing CU	0.322***	0.323***	0.305***	0.321***	0.304***
	(0.004)	(0.004)	(0.005)	(0.004)	(0.005)
Electrification	-0.477***	-0.464***	-0.485***	-0.336***	-0.374***
	(0.049)	(0.048)	(0.049)	(0.039)	(0.041)
Radiation	0.631***	0.548***	0.505***	0.246***	0.320***
	(0.047)	(0.048)	(0.050)	(0.048)	(0.048)
Electric tariff	0.524***	0.544***	-0.051	0.617***	-0.089
	(0.034)	(0.036)	(0.050)	(0.039)	(0.062)
Household income	0.100***	0.101***	0.175***	0.176***	0.196***
	(0.013)	(0.013)	(0.014)	(0.015)	(0.016)
Unemployment	-0.102***	-0.077***	-0.059***	-0.134***	-0.113***
	(0.009)	(0.018)	(0.018)	(0.010)	(0.024)
Population density	0.030***	0.029***	0.024***	0.024***	0.029***
	(0.003)	(0.004)	(0.004)	(0.004)	(0.004)
Consumption	0.063***	0.080***	-0.075***	0.092***	-0.129***
	(0.021)	(0.021)	(0.022)	(0.023)	(0.026)
ICMS equipment		0.042***			0.039***
		(0.010)			(0.011)
Import duty		0.016**			-0.123***
		(0.006)			(0.012)
Constant	-0.535**	-0.637**	0.070	-1.234***	0.328
	(0.247)	(0.257)	(0.258)	(0.249)	(0.291)
Observations	256,220	256,220	256,220	256,220	256,220
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	YES	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C4: Later period – NIP

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing potential	0.303***	0.302***	0.252***	0.301***	0.251***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Electrification	-1.080***	-1.121***	-1.217***	-0.884***	-1.014***
	(0.095)	(0.099)	(0.105)	(0.082)	(0.092)
Radiation	1.370***	1.407***	1.124***	0.552***	0.871***
	(0.092)	(0.095)	(0.101)	(0.095)	(0.101)
Electric tariff	2.019***	1.935***	-0.668***	2.321***	-0.885***
	(0.073)	(0.076)	(0.101)	(0.084)	(0.128)
Household income	0.374***	0.371***	0.664***	0.571***	0.668***
	(0.026)	(0.027)	(0.029)	(0.031)	(0.033)
Unemployment	-0.078***	-0.180***	-0.260***	-0.133***	-0.369***
	(0.017)	(0.034)	(0.035)	(0.020)	(0.048)
Population density	0.104***	0.107***	0.091***	0.084***	0.109***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)
Consumption	0.367***	0.327***	-0.336***	0.499***	-0.514***
	(0.042)	(0.043)	(0.045)	(0.046)	(0.054)
ICMS equipment		0.023			0.089***
		(0.020)			(0.023)
Import duty		-0.053***			-0.683***
		(0.012)			(0.024)
Constant	-4.898***	-4.167***	-0.446	-6.803***	1.232**
	(0.505)	(0.545)	(0.567)	(0.516)	(0.625)
Observations	256,220	256,220	256,220	256,220	256,220
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	YES	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C5: Regional division - NICU

VARIABLES	(1) North	(2) Northeast	(3) Southeast	(4) South	(5) Central-West
Existing potential	0.360***	0.282***	0.352***	0.314***	0.382***
	(0.027)	(0.013)	(0.008)	(0.009)	(0.022)
Electrification	-0.027	-0.105***	-0.522***	-1.057***	-0.284***
	(0.017)	(0.028)	(0.141)	(0.227)	(0.096)
Radiation	0.045	0.055	0.380***	0.359***	0.283
	(0.083)	(0.042)	(0.060)	(0.071)	(0.194)
Electric tariff	0.102	0.150*	0.359***	0.286***	-0.378**
	(0.074)	(0.090)	(0.123)	(0.054)	(0.163)
Household income	0.010	0.090***	0.104***	0.034**	0.094***
	(0.013)	(0.013)	(0.014)	(0.015)	(0.029)
Unemployment	0.001	-0.035	0.351**	-0.028	0.089
	(0.017)	(0.022)	(0.139)	(0.041)	(0.055)
Population density	-0.001	0.009***	0.011***	0.029***	0.020***
	(0.003)	(0.004)	(0.004)	(0.004)	(0.006)
Consumption	-0.004	-0.018	-0.074**	0.265***	0.292**
	(0.030)	(0.039)	(0.032)	(0.081)	(0.124)
ANEEL2015	-0.005	-0.009***	-0.043***	-0.020***	-0.021***
	(0.005)	(0.003)	(0.006)	(0.005)	(0.007)
ICMS equipment	-0.035***		0.016	0.021	
	(0.013)		(0.014)	(0.014)	
Tax exemptions	-0.001	0.002	0.001	0.002	0.000
	(0.003)	(0.002)	(0.004)	(0.004)	(0.006)
TUSD	0.043*	-0.003	0.208**	0.029	-0.065
	(0.025)	(0.024)	(0.084)	(0.029)	(0.052)
Import duty	0.000	-0.005**	-0.000	-0.001	0.002
	(0.004)	(0.002)	(0.003)	(0.003)	(0.004)
Constant	-0.112	-0.396	-0.179	2.636**	-1.865
	(0.319)	(0.266)	(0.795)	(1.259)	(1.280)
Observations	37,800	150,696	140,112	100,044	39,228
Number of municipalities	450	1,794	1,668	1,191	467
Policy?	Yes	Yes	Yes	Yes	Yes
Year FE?	Yes	Yes	Yes	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C6: Regional division - NIP

VARIABLES	(1) North	(2) Northeast	(3) Southeast	(4) South	(5) Central-West
Existing potential	0.300***	0.232***	0.333***	0.302***	0.365***
	(0.026)	(0.011)	(0.008)	(0.009)	(0.017)
Electrification	-0.151***	-0.282***	-1.244***	-1.931***	-0.761***
	(0.051)	(0.064)	(0.284)	(0.433)	(0.172)
Radiation	0.272	0.340***	0.862***	0.749***	0.651
	(0.207)	(0.093)	(0.115)	(0.140)	(0.397)
Electric tariff	0.119	0.191	0.619***	0.550***	-1.407***
	(0.180)	(0.191)	(0.224)	(0.119)	(0.330)
Household income	0.163***	0.355***	0.348***	0.186***	0.361***
	(0.038)	(0.032)	(0.027)	(0.033)	(0.045)
Unemployment	-0.002	-0.078*	0.661***	-0.006	0.233**
	(0.043)	(0.044)	(0.237)	(0.088)	(0.105)
Population density	0.031***	0.036***	0.050***	0.104***	0.058***
	(0.008)	(0.007)	(0.007)	(0.010)	(0.012)
Consumption	-0.023	-0.162**	-0.275***	0.404**	0.877***
	(0.076)	(0.083)	(0.062)	(0.170)	(0.214)
ANEEL2015	0.002	-0.011	-0.055***	-0.023**	-0.027*
	(0.006)	(0.007)	(0.012)	(0.011)	(0.014)
ICMS equipment	-0.092***		-0.028	0.033	
	(0.031)		(0.025)	(0.029)	
Tax exemptions	-0.003	0.009**	0.005	0.005	-0.002
	(0.006)	(0.004)	(0.009)	(0.009)	(0.012)
TUSD	-0.045	-0.208***	0.071	-0.362***	-0.502***
	(0.051)	(0.049)	(0.142)	(0.058)	(0.089)
Import duty	0.001	-0.008**	0.009	-0.000	0.008
	(0.008)	(0.004)	(0.006)	(0.007)	(0.009)
Constant	-1.393*	-1.831***	0.162	3.853	-5.924**
	(0.798)	(0.565)	(1.595)	(2.392)	(2.356)
Observations	37,800	150,696	140,112	100,044	39,228
Number of municipalities	450	1,794	1,668	1,191	467
Policy?	Yes	Yes	Yes	Yes	Yes
Year FE?	Yes	Yes	Yes	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C7: Fixed effects - NICU

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing CU	0.341***	0.338***	0.333***	0.341***	0.333***
	(0.004)	(0.005)	(0.005)	(0.004)	(0.005)
Electrification					
Radiation					
Electric tariff	0.143***	0.267***	0.059	0.143***	0.059
	(0.021)	(0.025)	(0.041)	(0.021)	(0.041)
Household income					
Unemployment	-0.149***	-0.109***	-0.042**	-0.149***	-0.042**
	(0.009)	(0.013)	(0.017)	(0.009)	(0.017)
Population density					
Consumption	0.109***	0.213***	0.218***	0.109***	0.218***
	(0.027)	(0.032)	(0.042)	(0.027)	(0.042)
ANEEL2015		-0.033***			-0.022***
		(0.003)			(0.003)
Tax exemptions		-0.025***			0.001
		(0.004)			(0.002)
TUSD		-0.017***			-0.023*
		(0.004)			(0.013)
Import duty		0.007**			-0.002
		(0.003)			(0.001)
Constant	-0.583***	-1.572***	-1.695***	-0.583***	-1.676***
	(0.219)	(0.274)	(0.357)	(0.219)	(0.365)
Observations	467,880	467,880	467,880	467,880	467,880
R-squared	0.439	0.440	0.441	0.439	0.441
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	Yes	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C8: Fixed effects - NIP

VARIABLES	(1) Controls	(2) Policy	(3) Year FE	(4) Region FE	(5) Complete
Existing potential	0.342***	0.328***	0.312***	0.342***	0.312***
	(0.004)	(0.004)	(0.005)	(0.004)	(0.005)
Electrification					
Radiation					
Electric tariff	0.593***	0.766***	-0.122	0.593***	-0.122
	(0.043)	(0.054)	(0.087)	(0.043)	(0.087)
Household income					
Unemployment	-0.185***	-0.204***	0.031	-0.185***	0.031
	(0.018)	(0.027)	(0.035)	(0.018)	(0.035)
Population density					
Consumption	0.026	0.159**	-0.153*	0.026	-0.153*
	(0.057)	(0.068)	(0.089)	(0.057)	(0.089)
ANEEL2015		-0.068***			-0.028***
		(0.006)			(0.005)
Tax exemptions		-0.036***			0.005
		(0.007)			(0.004)
TUSD		-0.146***			-0.319***
		(0.007)			(0.026)
Import duty		0.002			0.000
		(0.006)			(0.003)
Constant	-0.028	-0.989*	1.227	-0.028	1.543**
	(0.462)	(0.575)	(0.756)	(0.462)	(0.771)
Observations	467,880	467,880	467,880	467,880	467,880
R-squared	0.345	0.347	0.352	0.345	0.352
Number of municipalities	5,570	5,570	5,570	5,570	5,570
Policy?	No	Yes	No	No	Yes
Year FE?	No	No	YES	No	Yes
Region FE?	No	No	No	Yes	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1