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The impact of Net Metering policy design on the adoption rate of solar photovoltaic systems: a simulation using calibrated data from Brazil.

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1. Introduction: A comparative assessment of net metering and feed in tariff schemes for residential PV systems[1]

Net Metering (NM) policies have been widely used as a mechanism to allow the inclusion of distributed generation (DG) resources in the energy system by small consumers like households and small business. The core design of NM is to permit consumers connected to the utility grid to offset consumption by inputting self-generation surplus into the network. The regulatory and policy framework is key to determining the economics of DG (investment costs and benefits), and, consequently, to determining the adoption potential.

The preferred distributed generation technology used by households under a Net Metering scheme is Solar Photovoltaic (PV) Panels. Even though other sources of distributed energy resources are not excluded from most Net Metering policies, PV presents many advantages that encourage its use. It uses sunlight as its main energy source. It can be installed on rooftops, without compromising the area of the house. It is modularizable, allowing increased installation capacity over time (if there is space available). However, it also presents some limitations. The size of the roof presents a physical limit in terms of installation. Apartments buildings (such as condos) cannot have PV installed for units without a roof. In addition, the generation is intermittent, and it can only produce as much as 12 hours in a typical day.

Nonetheless, PV equipment prices and maintenance cost are decreasing, and generation efficiency is increasing worldwide (Candelise, Winskel, & Gross, 2013). Even in this improved scenario, other factors can still present challenges the adoption of PV, especially in non-developed and in-development countries. These limitations may have different sources, such as households budget constraints, complicated or unappealing financing mechanisms, lack of knowledge about distributed generation and Net Metering, the lack of local technical capacity to assist in installation, or a regulatory prohibition.

In Brazil, the National Electric Energy Agency (ANEEL) put in force a Net Metering Policy in 2012 (Normative Resolution 517/2012), which has rapidly increased the number of PV installations in the country.

The goal of this paper is to study Brazilian Net Metering Policy and its incentives for the adoption of Solar Photovoltaic Systems. First, we provide a deep analysis of policy design in Brazil. Then,

[1] We'd like to thank the comments and contributions made by Tomas Serebrisky, Arturo Alarcón, Edwin Malagon, Jordi Abadal, Jesus Enrique Chueca and Yi Ji.

we elaborate a simulation study to evaluate the impact of the current Net Metering policy in Brazil on the potential adoption rate of Solar Photovoltaic Systems. We combine a traditional cost-benefit approach, the NPV model, with an innovation adoption econometric model, the Bass Diffusion Model. Our results show that under the current policy, with technology and financing set up, the market for adoption of PV in Brazil can reach 50% of technically-viable consumers by 2030.

2. Net Metering Design Elements

Net Metering[2] is an intertemporal offset of distributed generated energy, converted into credits by a certain rate and unit of measurement, which can be later used for future electricity consumption. In formal terms, household energy surplus in t can be converted into cumulative credits – measured in energy (kWh) or monetary units – which can be used anytime between $t+1$ and $t+n$, with n being the maximum accumulation period (that can be indefinite).

Figure 1 exemplifies a simplified Net Metering scheme in which the accumulated credit (energy or money) in period 1 is offset to the consumption in period 2. The period between 1 and 2 can be as granular as policymaker sets (like minutes or seconds). The surplus of electricity generated in period 1 is converted into credits and transposed to period 2. At the end of period 2, the net energy consumption to be billed is almost completely compensated for by self-generation and Net Metering credits. In this case, the compensation rate (the ratio between generated energy and energy-equivalent credits) is unitary, meaning that every unit of energy injected into the grid as a surplus can later be consumed.

[2] Two terms define a similar policy with different units of measurement: Net Metering, in which the offset occurs in energetic terms, and Net Billing, in which the compensation is monetary. However, in many Net Metering experiences, the term Net Metering is commonly used for both schemes (IRENA, IEA, & REN, 2018).

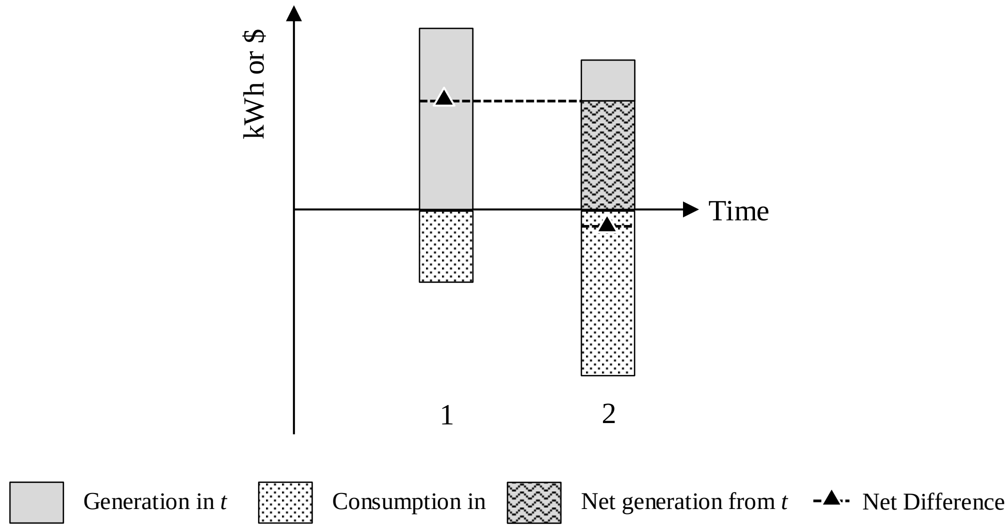

Figure 1. 2-periods net metering accumulation

Source: Own elaboration.

Note: Considering no hourly tariff and Compensation Rate equal to 1

In this example, the two compensations periods can be written with the following equation:

$$\begin{cases} NC_1 = C_1 - G_1, \qquad NC_1 < 0 \\ NC_2 = (C_2 - G_2) + NC_1 \cdot r \end{cases}$$

Where, NC_t is the net consumption at period *t*, G_t is the generation in *t*, C_t the consumption in *t* and r the Net Metering Rate, which accounts for the share of the surplus from previous periods that can be rolled over to the following periods. The bill in period 2 can be calculated by:

$$(NC_2 \cdot tariff + fixed) \cdot (1 + \%taxes)$$

Conversely, in a Net Billing Scheme, the system can be written as:

$$\begin{cases} NC_1 = (C_1 - G_1) \cdot tariff \cdot r, \qquad NC_1 < 0 \\ NC_2 = [(C_2 - G_2) \cdot tariff \ + fixed] \cdot (1 + \%taxes) + NC_1 \end{cases}$$

Where NC_2 is the bill in period 2.

Nonetheless, this simplified model represents the actual benefits of Net Metering policies for those who adopt distributed generation systems. On the one hand, consumers' benefits are restricted to recover the project investment and, if possible, a monetary surplus. In our model, we do not account for environmental concerns that may influence household behavior, which would make the decision process more complex and less predictable. The monetary surplus can point to higher (i) energy consumption, (ii) savings or (iii) non-electricity goods consumption. With metering policies, these benefits can be achieved by (a) reducing the bill, (b) receiving a monetary payment for energy input to the grid, or (c) levelling energy costs over time.

3. Modeling a Solar Photovoltaic Project under Net Metering

Many papers have advanced studies on the economic viability of PV projects. In the context of Latin American, (Gonzalez, 2018) develops a Net Present Value Model to assess the viability of Zero Energy Buildings in Colombia, while (Hancevic, Nuñez, & Rosellon, 2017) provide a similar study focused on distributed PV for the Mexican residential sector. Their contribution shows that the high capacity factor of PV generation in Mexico may increase households' welfare due to significant annual savings.

In the context of the United States, (Darghouth, Barbose, & Wiser, 2011) studied the impact of rate design and net metering on the net benefits of PV for residential consumers in California. A forecasting approach was adopted by (Dong, Sigrin, & Brinkman, 2017) for the California case. They compare the output of different models to predict the adoption rate of Solar PV. The results indicate that empirical models, like the Bass Diffusion Model, and case-specific models, like the dSolar, have similar results, and can be comparable.

(Poullikkas, 2013) adopted a similar approach to solar PV benefits in Cyprus. He compares two policies–Net Metering and Feed-in Tariff–for residential PV systems. His results show that "under certain conditions the net metering support scheme becomes profitable." And (Mohandes, Sanfilippo, & Fakhri, 2019) use an agent-based model to simulate the adoption of solar energy in the Arabian Gulf Region. Their simulation does not include Net Metering, and focuses on other policies, such as energy subsidies, carbon tax, and utility tariff differentiation. Their Business as Usual Scenario predicts a market penetration of 50% in around 10 years.

In our study, we assume that a household chooses the optimal size of the DG installation and consumption as a response to system variables, like tariff, interest rates, and other policy rules. Thus, the household is assumed to be a risk-averse investor that maximizes the net present value of the distributed generation system. Other studies also focused on other incentive policies for solar generation, both large and small scale, like (Eid, Reneses Guillén, Frías Marín, & Hakvoort, 2014), (Comello & Reichelstein, 2017), and (Vazquez & Hallack, 2018).

In Table 1, we summarize the variables that may affect the decision process of PV adopters. The variables are divided in four categories defined by the agent liable for setting them: (i) regulators, (ii) financial institutions, (iii) consumers, and (iv) variables defined exogenously.

All variables (with exception of income) are included in the project design of DG systems installation. In this section, we compare the benefits of generation with the costs of consumption over the whole project period. In this framework, households would invest in a DG system if, and only if, the NPV of the generation project is non-negative.

Table 1. Variables affecting the consumer's adoption behavior

Category	Variable	Unit
Regulators	Tariff Level	$/kWh and $/Period
	Net Metering Rate	% over the credit
	Cashback Scheme	Binary: Yes or No
	Accumulation Period	Months
	Accumulated Credit	Energetic or Monetary
Financial Institutions	Lending Interest Rate	% per year
	Payment Periods	Years
Consumers	Consumption Level	kWh
	Installed Capacity	kWp
Exogenous	Inflation Rate	% per year
	Taxes	% of Transactions
	Capital Cost of DG	$/KW
	Operational Cost of DG	$/KW/Year
	Depreciation Rate of DG	% per year
	Capacity Factor	% of potential output
	Income	$ / Period

Source: Own elaboration

3.1. Microeconomic Modeling

First, we assume the accumulation period as indefinite, which implies that, in present values, all surplus of self-generated energy can be converted in consumption credits.[3] Also, we assume that there are no arbitrage gains on tariffs,[4] which means that the difference in the consumption and generation prices at different periods can only be explained by the interest rate and inflation. The net present value of consumption over the period of t months can be written as:

$$\mathrm{NPV}_{Con} = \sum \frac{\left(C_t \cdot p_{kWh} + p_{fixed}\right)(1 + tax)}{(1 + \pi_t)(1 + i_t)^t} \qquad \text{Eq. 1}$$

[3] See annex 1. In a self-generation tax-free scheme, the indefinite accumulation of energy or tariff would be equivalent.

[4] This means that users do not receive monetary benefits from generating in t (with higher grid prices) to consume in t-1 (with lower grid prices). In practice, hourly-metering tariffs are possible, and would reduce the price distortion by creating a signal to the utility. However, it would also make the project viability calculation more complex to adopters, which could increase uncertainty.

Where C_t is the consumption in kWh in the period *t*, p_{kWh} and p_{fixed} are the variable and fixed tariffs, respectively, tax is the tax over the bill, π_t is the inflation rate in *t*, and i_t is the interest rate in *t*.

The net present value of self-generation over the period of *t* months can be written as:

$$\text{NPV}_{Gen} = I_0(S) + \sum \frac{(G_t(S) \cdot p_{kWh} \cdot N_{rate}) - M_t(S)}{(1+\pi_t)(1+\text{i}_t)^t} \qquad \text{Eq. 2.1}$$

Where, G_t is the self-generation in kWh in the period *t*, p_{kWh} is the variable tariff, N_t is the net metering rate, M_t(S) is the yearly operational and maintenance cost as a function of the installed capacity S, I_0 is the initial capital investment as a function of *S*, π_t is the inflation rate in *t*, and i_t is the interest rate in *t*. If we assume that the initial investment is financed over time:

$$F_t = \frac{I_0(S)/[(1+r)^t \cdot r]}{[(1+r)^t - 1]}$$

In this scenario, the NPV of self-generation over a period of *t* years can be rewritten as:

$$\text{NPV}_{Gen} = \sum \frac{(G_t(S) \cdot p_{kWh} \cdot N_{rate}) - M_t(S) - F_t(S)}{(1+\pi_t)(1+\text{i}_t)^t} \qquad \text{Eq. 2.2}$$

Plotting both curves NPV_{Con}[5] (Eq. 1) and NPV_{Gen} (Eq. 2.2), we get to the relationship showed in Figure 2. In this theoretical graph with a fixed generation capacity, there are three areas of interest. First, in area A, the generation value is higher than the consumption value. This means that the self-generator produces more energy than is consumed and has a surplus. In cases where policy design allows a cashback of energy surpluses, the hypothetical household would have incentives to move the generation function upwards by increasing the capacity and receiving the surplus. In area B, where the generation value is below the consumption value, the household would have positive net consumption. In this case, if the NPV_{Gen} is positive, the household's energy bill would decrease, creating a benefit. Point C represents an equilibrium between generation and consumption values. This would be the maximum optimal capacity for a household without a cashback scheme.

[5] The signal of the NPV_{Con} was inverted in Figure 2 to improve the visualization of the graph. This inversion does not affect the analysis since areas A and B would also be reversed with the original NPV. Precisely, the NPV_{Con} is an expenditure and should have a negative value.

Therefore, (a) if the accumulation period is indefinite and self-generators can withdraw the energy inputted into the grid and (b) if the NPV of the generation project is positive, and (c) keeping installed capacity as fixed, then all households with a consumption equivalent to point C or higher would benefit from Net Metering. In a cashback scheme, all households would also receive benefits.

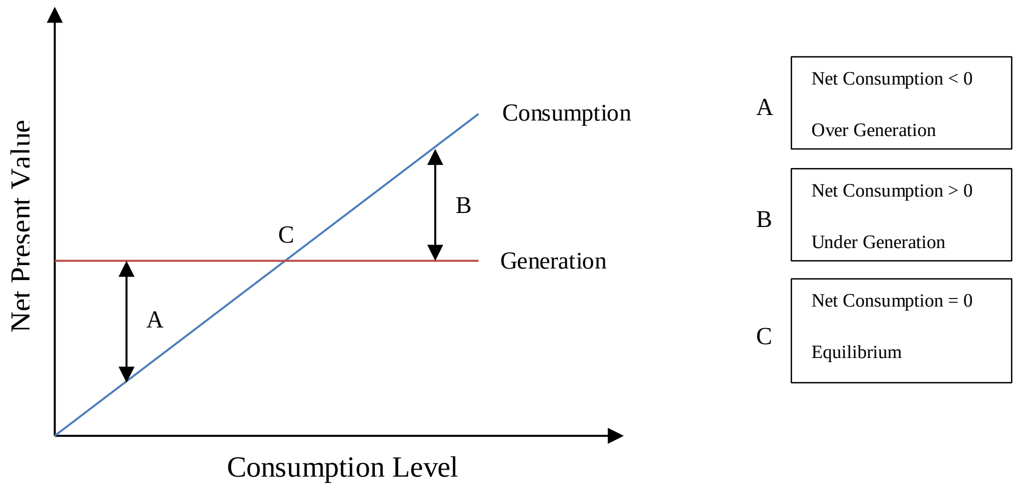

Figure 2. Intertemporal Net Consumption with self-generation
Source: Own elaboration.

The second scenario is the case in which the accumulation period is finite and defined by the regulator. This means that after period *n*, the amount of credits accumulated in *t* expires. When expired, credits may have three possible ends:

(a) Rollover to next period;

(b) Monetary compensation;

(c) Write-Off.

In the first case, credits are transferred to the next accumulation period to be used for compensation purposes. In the second case, the credits can be converted into monetary compensation, with or without the incidence of income taxes and other fees. In the third case, credits can be written-off and cannot be used or compensated to the self-generator. Each case provides different incentives to DG owners, which can affect how they measure the benefits of Net Metering policies. Rules *a* and *b* are not mutually exclusive, given that it is the regulator's decision to permit the use of each option.[6]

Figure 3 shows a hypothetical household with a 2 kW solar PV system, with 2.61 kWh yearly average daily consumption and 934 kWh total yearly generation.[7] Consumption level and capacity generation factor in the experience of seasonal variation.[8] Data was aggregated by month, which can be considered in this case as the minimum accumulation period. There are two easily identified metering periods during the year: from September to March and from April to August. In the first period, consumption is higher than generation, while in the second period, generation is higher than consumption.

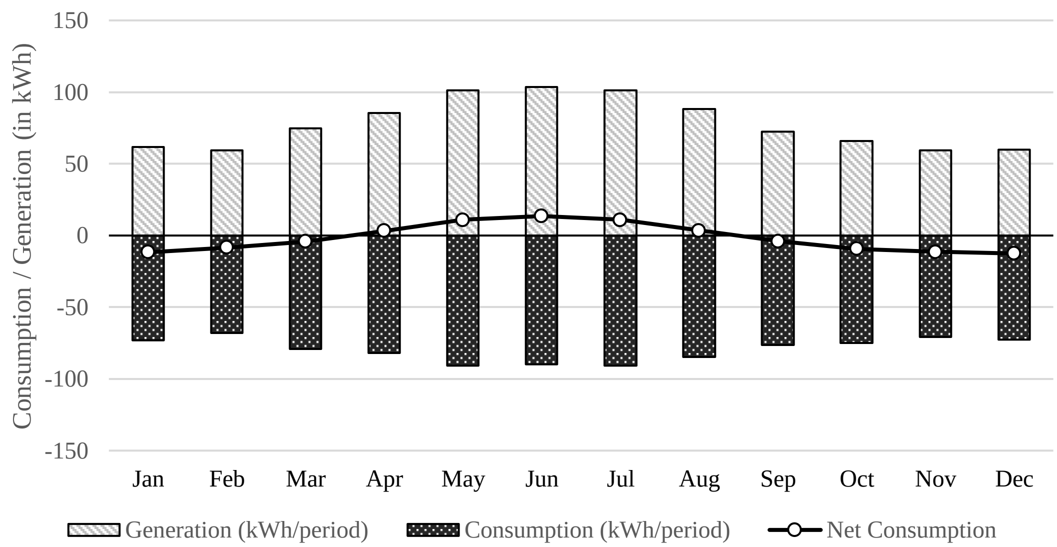

Figure 3. Hypothetical Yearly Curves of Generation and Consumption
Source: Own Elaboration

[6] For example, regulators may permit users to choose between having the credits rolled over and receiving monetary compensation. If users do not make any decision, the regulator may choose between an automatic mechanism (*i.e.* the rollover) and the write-off of credits.

[7] The hypothetical household uses a normal distribution of consumption over the year, with 90 kWh of maximum consumption in summer months and approximately 72 kWh in December. The generation pattern follows a similar distribution, calibrated with Mexico capacity factor. This calibration is approximately the consumption of a house with four members in Mexico. The 2 kW installation were chosen to roundly meet the total yearly consumption of the household (approximately 953 kW).

[8] The minimum generation level is 57% of the maximum and the minimum consumption level is 74% of the maximum.

If regulators change the accumulation period to a time granularity greater than one month, the balance of energy credit accumulated in the period changes. **Error! Reference source not found.** shows the balance of energy credits at the end of the billing period (monthly) for a household with three different rules of accumulation. The baseline case is the one with the coincident billing and accumulation periods (one month) without a rollover of credits. In this case, all positive surpluses are monetarily compensated or written-off. The second case is the one with a three-month accumulation period, in which the balance is liquidated every quarter and accumulation restarts. The third case is the one year accumulation period. All values greater-than zero are accumulations, and values less-than zero are billing debts (to be paid at the end of the billing period– in this case, one month).

Longer accumulation periods have more incentives to offset consumption over the year by alleviating billing costs on household during shorter periods. For instance, from the same starting point, the household only had real expenditures in the first four months with a one-year accumulation period, with the accumulation of positive surpluses from May to August, and the use of credits from September to December. However, if households give more value to a shorter period of monetary compensation (to increase budget liquidity, for example), then they would have a higher utility with shorter accumulation periods (or voluntary monetary compensation demand). It is important to notice that algebraically, the net present value of the DG project (as shown in the previous section) is not affected by short-term accumulation if monetary compensation (cashback) is possible at the end of each period.

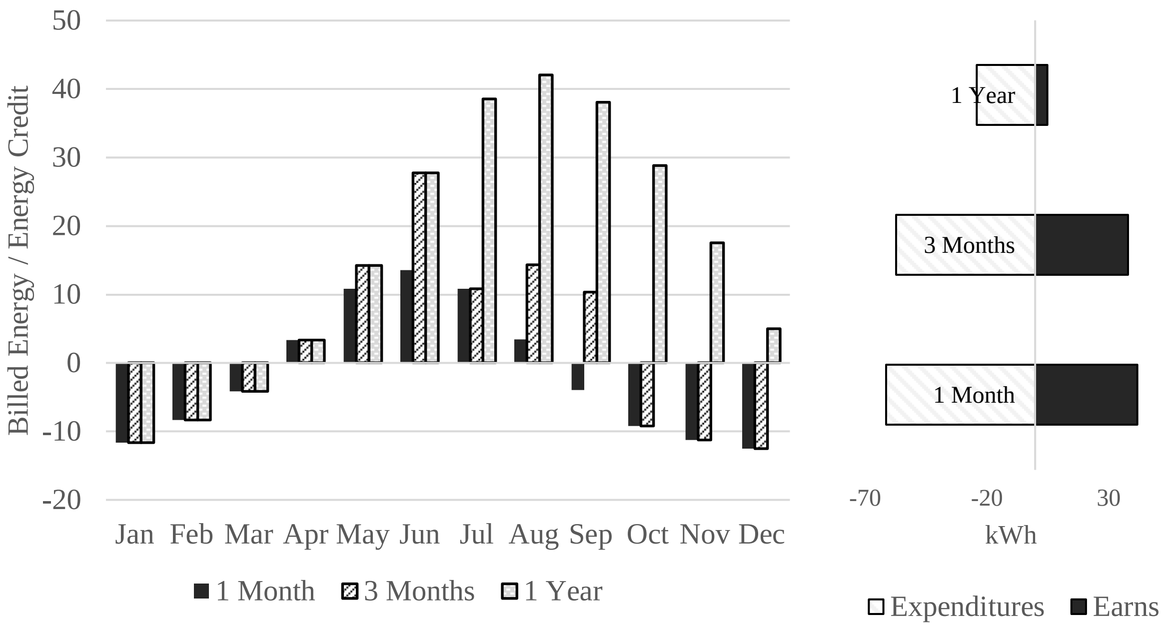

Figure 4. Different accumulation periods for the example of Figure 3
Source: Own elaboration

3.2. Simulating the adoption rate of Solar Photovoltaics

The Bass Model, as originally proposed by (Bass, 1969) is based on the empirical regularity of the diffusion of innovation as classified by (Rogers, 1962). In *Diffusion of Innovation*, Rogers splits the adoption of new technologies into five categories of adopters: (1) innovators, (2) early adopters, (3) early majority, (4) late majority and (5) laggards. According to the Bass (2004) reading, "adopters are influenced by the pressures of the social system, the increasing pressure for later adopters given the number of previous adopters." In the case of the adoption of distributed generation equipment in LAC, we are still in the first diffusion phase, where only very-early adopters (called "innovators" by Rogers) with exposure and a high capability to absorb new information. Many variables may influence the decision process of an agent when adopting a new technology, including, but not limited to, budget and financial constraints, uncertainty, the economic viability of the project, and the lock-in to the current state. However, the rationality of the original Bass Model (Bass, 1969) follows a simpler rule of adoption. Individuals adopt a new technology based on two tendencies: (1) innovation and (2) imitation. The first is the willingness of an agent to adopt a new technology autonomously, and the second is the willingness to adopt a new technology because those around are adopting it. Mathematically, the Bass Model can be written as:

$$\frac{f(t)}{1-F(t)} = p + \frac{q}{M}[A(t)]$$

Where, t is the period from $[0, \infty]$, p is the coefficient of innovation, q is the coefficient of imitation, M is the potential market (in number of adopters), $A(t)$ is the cumulative adopters at *t*, $f(t)$ is the share of adopters at time *t*, and $F(t)$ is the share of adopters by time *t*. The following equation can be used to estimate the fitting curve of the Bass Model (Bass, 2004).

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

The original version of Bass Model, however, does not include price as a variable in the adoption process. Considering the adoption of a new technology, price seems an important element when dealing with technologies with a fast decreasing price. (Kalish, 1985) proposed a new version of the Bass Model, where the market potential (*M* in the original version) is not exogenous but determined by the price-elasticity of the potential adopters and the uncertainty about product performance. A similar model was then proposed by Frank Bass himself (Bass, Krishnan, & Jain, 1994), where the effect of marketing variables plays an important role in the acceleration of the rate of diffusion, and this model is known as the Generalized Bass Model.

Here, we use a third procedure, adjusting price within the financial model of Part I and assuming price $P(t)$ follows a time-recursive function with a decreasing path of $(1-\alpha_p)$

$$P_t = P_{t-1}(1-\alpha_p)$$

Recursively, we have that

$$P_{t-1} = P_{t-2}(1-\alpha_p)$$

$$P_t = P_{t-2}\left(1-\alpha_p\right)^2$$

$$\therefore P_t = P_0\left(1-\alpha_p\right)^t$$

Thus, in our model (1) price is updated exogenously by α_p, and (2) the sensitivity of adoption to the price is determined by the economic viability of the new technology. Figure 5 describes the estimation procedure to integrate project viability and the Bass Model.

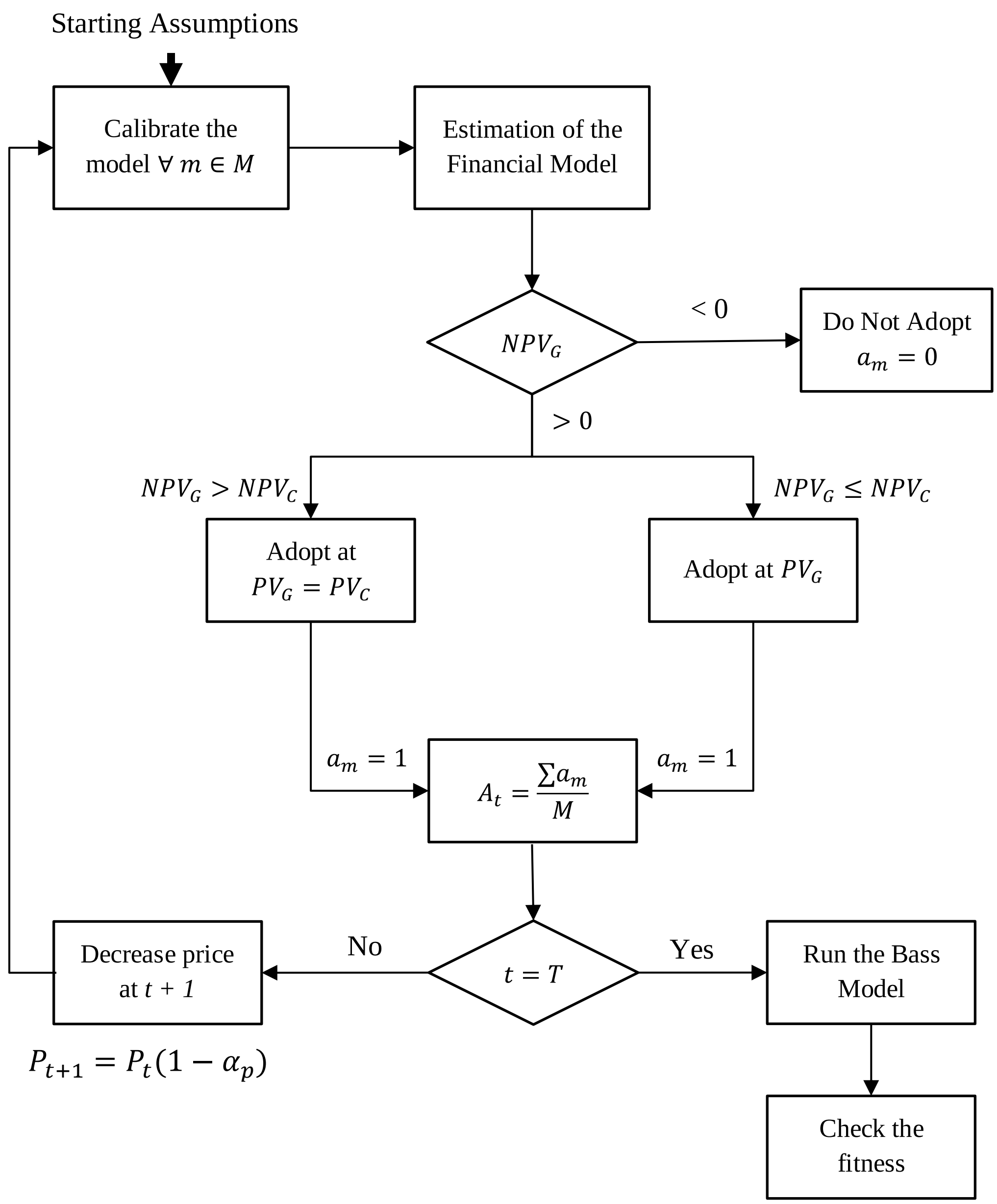

Figure 5. Estimation procedures of the Bass Model integrated with project viability

4. Calibrating Solar Photovoltaic Adoption Rate for Brazil

Net Metering Policy in Brazil is regulated by Normative Resolution 482/2012, issued by ANEEL, the electricity regulator. The resolution "*establishes the general conditions to access of microgeneration and minigeneration to electric energy distribution systems, (and) to the electric energy compensation system.*" Microgeneration is defined as an installation with installed capacity inferior to 75 kW, and minigeneration is an installation with installed capacity between 75kW and 5 MW. Both are eligible for Net Metering. About Net Metering (referred as the "electric energy compensation system"), the resolution defines it as the system by which "*the active energy injected by a consumer unit with distributed microgeneration or minigeneration is given as a free-of-charge loan to the local distributor, and later compensated with the consumption of active electric energy*." In other words, it means that Net Metering in Brazil uses an energetic accumulation scheme with a unitary metering rate. The accumulation period is up to 60 months including expired credits write-off. One special case is when the consumer adopts an hourly tariff. In this case, accumulation is done by tariff block using energetic units but can be converted from one to another block using monetary units.

In June 2018, the Brazilian National Bank for Social and Economic Development (BNDES) included households in the Climate Fund Program (sub-program "Efficient Machines and Equipment") to finance up to 80% of the costs to acquire water heaters and co-generation equipment, such as solar photovoltaic panels. The Climate Fund Program (CFP) was created in 2009[9] and implemented in 2010,[10] in order to use part of the reimbursable resources of the National Fund for Climate Change of the Ministry of Environment. Renewable Energy and Efficient Machines and Equipment are among the investments eligible to receive resources from the CFP.[11] Investments in "Efficient Machines and Equipment" aim to finance the acquisition and production of machines and equipment with improved energy efficiency indices or that contribute to the reduction of greenhouse effect gas emissions.[12]

The conditions of the financing scheme are:

- Finance 80% of the installation items
- Grace period of three – 24 months
- Payment period of 12 years (including the grace period)
- Interest Rate: 4% per year

[9] Law 12,114, approved in December 9, 2009.
[10] Decree 7,343, published in October 26, 2010.
[11] The other eligible investments are in: Urban Mobility, Sustainable Cities and Climate Change, Solid Wastes, Vegetable Coal, Native Forests, Carbon Management and Services, and Innovative Projects.
[12] https://www.bndes.gov.br/wps/portal/site/home/financiamento/produto/fundo-clima-maquinas-equipamentos-eficientes/, Accessed August 23, 2018.

We use these variables to calibrate the Net Present Value of a PV project using data from ANEEL's Brazil Consumer Satisfaction Index (IASC[13] in Portuguese), collected in 2017.

4.1. Data Description and Model Calibration

The IASC is a household yearly survey conducted by ANEEL for each distribution area concerning quality of service, price, perception, and consumption. We used the data collected between September and November of 2017. The original questionnaire asks each respondent about their electricity costs for the previous month. We used the average tariff of each distribution company from September to November to estimate consumption in kWh. One data limitation is that the survey is cross-sectional and does not capture seasonal consumption variation. Table 2 summarizes the electricity consumption variable statistics.

[13] ANEEL Index of Consumer Satisfaction.

Table 2. Summary statistics of electricity consumption in Brazil

Consumption Decil	Average Consumption (kWh)
Minimum	13.8
1	78.7
2	110.4
3	136.5
4	161.1
5	188.0
6	225.5
7	270.4
8	339.1
9	499.4
10	1869.6
Average	255.9
Standard Deviation	224.8

4.2. Model Calibration

To calibrate the model, we must define two sets of variables (1) the exogenous variables that affect the project viability and (2) the decrease in the capital cost to install new DG equipment. Here, we use Solar Photovoltaic Generation as the benchmark technology. The simulation variable assumes the following settings:

- **Financial Variables:**
  - Lending Interest Rate: 4.55% / year
  - Nominal Long-term Interest Rate: 11% / year
  - 80% of Capital Cost is financed
  - Payment over 12 years

- **Regulatory Variables**
  - Retail Tariff: From 0.1187 to 0.258 USD/kWh (using 3.32 BRL/USD[14])
  - There is no minimum module size
  - No Cashback Scheme[15]
  - 60 months of credit roll-over
- **Exogenous variables**
  - Yearly Average Capacity Factor: $0.15\ \mathrm{kWh/kWp\,.\,h^{-1}}$
  - Average Expected Generation Output:[16] $1494\ \mathrm{kWh/year}\,.\,kWp^{-1}$
  - Operational Costs: $30\ \mathrm{USD/year\ \ kWh^{-1}}$
  - Initial Capital Cost[17]: 2400 USD / kW
  - Invertor Replacement (Year 10): 700 USD/2kW
  - Depreciation rate: linear over 20 years, 5%/year
  - Housing: 90.5% of the Sample

To calculate the capital asset price trend, we used the recursive price update formula which assumes a linear deline in prices. We propose three scenarios. The first one is an optimistic scenario, with a 5% price decrease by year. The second scenario uses the National Renewable Energy Laboratory (NREL) capital cost forecast of an around 3.6% cost decrease per year.[18] The third scenario is less optimistic, assuming a 2% decrease in capital installation costs per year.

Data on household variables and the Financial Model calculated for each observation (household unit is taken from the IASC survey. A household is considered a potential adopter if the NPV of the project is greater or equal to zero. Other assumptions include: (a) tariff structure does not change, being updated only by the Nominal Long-Term Interest Rate, (b) the capacity factor does not change, (c) there is no financial constraint to use the financial scheme and to self-finance 20%

[14] Nominal Interest Rate in November 15th, 2017

[15] This implies that the maximum installed capacity is optimized by $Demand\ (kWh/year) = Capacity(kW) * Output(kWh/year/kWp)$

[16] Electricity Output is regionalized by city using data from the Global Solar Atlas (2018). The minimuim value is 1120.4 kWh/year, the maximum is 1748 kWh/year and the standard deviation is 115.6 kWh/year.

[17] Data from Portal Solar (2018), using the exchange rate of 3.42 BRL / USD.

[18] Based on the Annual Technology Baseline: https://atb.nrel.gov/electricity/2017/index.html?t=sr, accessed in August 27th, 2018.

of the capital cost, (d) consumption level does not change over the years, (e) the potential market does not imply adoption, which depends on more variables, such as the presence of an appropriate installation space, information, and the willingness to invest.

We control the presence of a roof by determining a cap for the market size. The cap was calculated by stratifying the housing type by (1) State and (2) Wealth, using data from the Continuous National Household Survey (PNAD) from the first quarter of 2017. The wealth variable was harmonized by minimum income groups (as defined in the IASC). Results were then calculated by State and Wealth (Table 3).

Table 3. Share of population living in houses, by State and Wealth (in minimal wages), 2017

Region	State	Household Income in Number of Minimal Wages							Total
		< 1	1 - 2	2 - 5	5 - 10	10 - 15	15 - 20	> 20	
North	Rondônia	97.2%	95.5%	96.2%	96.6%	97.2%	82.1%	93.3%	**96.4%**
	Acre	97.3%	95.5%	95.8%	91.4%	93.0%	88.2%	87.5%	**96.3%**
	Amazonas	96.7%	94.4%	92.0%	87.8%	78.1%	70.4%	61.3%	**94.7%**
	Roraima	96.7%	94.6%	94.8%	97.1%	97.8%	80.0%	100.0%	**95.8%**
	Pará	98.6%	97.7%	96.0%	92.3%	89.4%	61.2%	68.9%	**97.3%**
	Amapá	93.0%	92.1%	92.4%	81.8%	92.2%	91.7%	93.3%	**91.7%**
	Tocantins	99.2%	98.8%	98.4%	94.1%	91.9%	87.5%	100.0%	**98.5%**
Northeast	Maranhão	99.6%	99.4%	98.1%	94.8%	92.1%	100.0%	59.4%	**99.2%**
	Piauí	99.7%	99.6%	98.7%	95.8%	82.1%	65.6%	66.7%	**99.2%**
	Ceará	97.5%	92.6%	89.1%	80.5%	60.5%	78.4%	55.4%	**94.9%**
	Rio Grande do Norte	98.7%	98.4%	94.4%	83.5%	70.8%	90.9%	76.9%	**97.2%**
	Paraíba	97.8%	95.4%	90.5%	71.6%	61.0%	43.9%	51.0%	**94.9%**
	Pernambuco	97.9%	96.0%	90.0%	77.4%	74.6%	29.4%	61.5%	**95.5%**
	Alagoas	98.9%	98.4%	96.3%	91.0%	73.9%	83.3%	88.2%	**98.3%**
	Sergipe	98.4%	96.7%	93.1%	79.3%	73.1%	62.5%	85.7%	**96.7%**
	Bahia	97.8%	94.8%	90.5%	83.5%	74.2%	81.3%	60.0%	**95.8%**
Southeast	Minas Gerais	94.4%	93.1%	88.7%	79.0%	69.2%	61.6%	55.4%	**90.8%**
	Espírito Santo	93.8%	92.4%	86.8%	69.8%	53.8%	32.5%	40.5%	**88.5%**
	Rio de Janeiro	89.7%	91.6%	86.9%	71.5%	54.9%	44.0%	47.5%	**86.4%**
	São Paulo	92.7%	95.0%	92.8%	81.1%	72.3%	62.9%	55.5%	**90.7%**
South	Paraná	96.7%	96.9%	94.5%	87.2%	79.8%	73.7%	71.1%	**94.3%**
	Santa Catarina	92.2%	92.2%	90.0%	84.2%	73.6%	73.7%	68.0%	**89.3%**
	Rio Grande do Sul	93.3%	93.8%	88.9%	78.5%	65.7%	72.9%	59.8%	**89.4%**
Central West	Mato Grosso do Sul	97.9%	97.9%	98.1%	95.8%	98.0%	100.0%	82.9%	**97.7%**
	Mato Grosso	97.8%	97.9%	97.9%	94.8%	91.5%	89.0%	88.1%	**97.2%**
	Goiás	98.1%	96.9%	97.0%	89.6%	86.0%	78.3%	66.1%	**96.1%**
	Distrito Federal	76.6%	84.5%	77.3%	62.8%	51.3%	50.0%	52.9%	**72.9%**
	Brazil	**96.6%**	**95.1%**	**92.0%**	**83.3%**	**73.6%**	**68.0%**	**62.8%**	**93.6%**

Source: Own elaboration using data from the quarterly PNAD (2017)

4.3. Model Results

The Bass Model is estimated using its original specification (Bass, 1969) by a Non-Linear Least Square Regression. The goal is to analyze the coefficients of innovation *p* and imitation *q*, the confidence interval of estimated potential technology diffusion and to compare it with other experiences. We estimate it for the three scenarios (Figure 6). The estimation procedure uses a Non-Linear Least Square (NLS) to estimate the equation

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

Where $y(t)$ is the share of the market with $NPG_G > 0$ at t. Prices $P(\alpha, t)$ are endogenously incorporated into the NPV model as a function of the cost-reduction rate α and time t. The first and second scenarios (constant 3.6% and 5% of cost-reduction per year) show a trend that will reach the whole market in the long run. Otherwise, the 2% scenario shows a trend that will have a low ceiling in adoption. In the medium scenario (3.6%), this would indicate a potential market adoption of 36.95% by 2030.

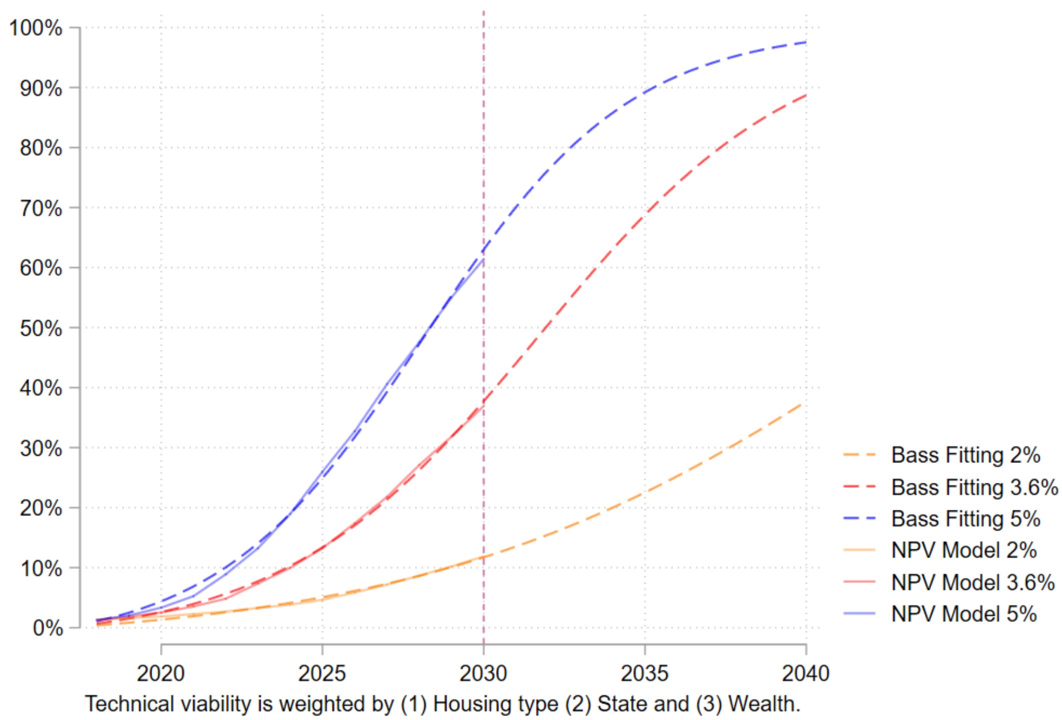

Figure 6. Economic viability of a Rooftop Solar PV project, 2018-2040, Brazil.

Source: Own elaboration using data from IASC/ANEEL (2017), PNAD/IBGE (2017), Global Solar Atlas (2018) and Portal Solar (2018).

The Bass Model estimation is shown in **Error! Reference source not found.**. Both coefficient – innovation and imitation–are positive and significant at 1%, as expected. This implies that estimated potential adoption using the NPV model follows a characteristic S-shaped curve. The R^2 is above 0.99, indicating the very good fitness of the Bass Model to the NPV simulation.

Table 4. Results of the Bass Diffusion Model Estimation, by Cost Scenario

Cost Scenarios	**2%**		**3.60%**		**5%**	
Coefficients	**Innov.**	**Immit.**	**Innov.**	**Immit.**	**Innov.**	**Immit.**
Value	0.00367***	0.134***	0.00596***	0.247***	0.00924***	0.304***
Standard Error	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
R-squared	0.995	0.995	0.999	0.999	0.999	0.999
Variable Index	p	q	p	q	p	q

*** p<0.01, ** p<0.05, * p<0.1

Note: Values were rounded to 3-decimal places.

The sensitivity of the Bass Model to the price is shown in Figure 7. The model is calculated assuming the price update function $P_t = P_0(1-\alpha)^t$ and $P_0 = \$2400$ as measured in 2017. Then, we substituted t in $y(t)$ equation by the function $t = \ln(P_t/P_0)/(\ln(1-\alpha))$ and estimated the new $y(P_t, P_0, \alpha)$ function. As P_t is described by a linear trend, the resulting shape is an inverted S-curve.[19] The graph below also shows that the confidence interval of the Bass Model fits with 99% of the confidence level.

[19] The rate or adoption is the first partial dA/dC (A is the adoption and C the cost of capital), which indicates a vector magnitude towards the A path.

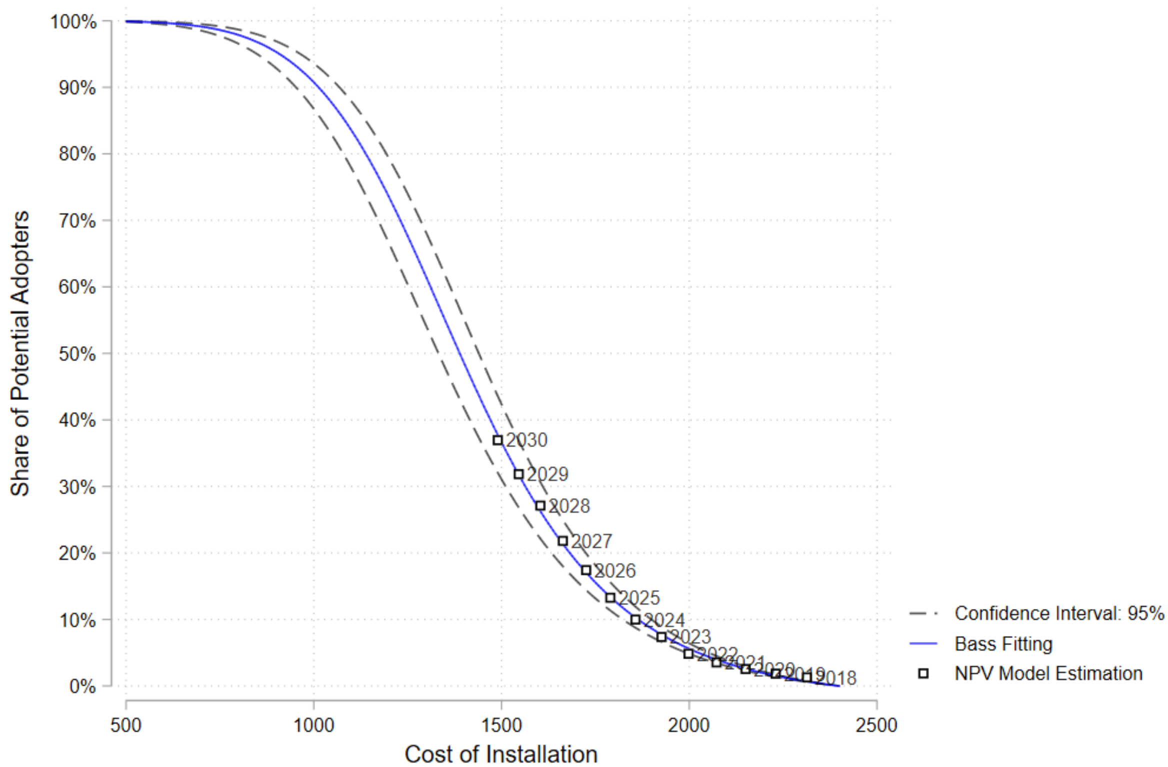

Figure 7. Results of the Bass Model Fitting Related to the cost level, 3.6% cost-reduction

In general, the Bass Model fits very well with the results of the NPV model, demonstrating that our model follows the pattern predicted by innovation literature. The model shows that, *ceteris paribus*,[20] the adoption rate depends primarily on path of variable α. For instance, according to the model used, to achieve a **50% share** of potential adoption, CAPEX should be:

- $1400.37 if cost-reduction is 2% per year. Equivalent to 26.6 years (from 2017);
- $1387.22 if cost-reduction is 3.6% per year. Equivalent to 15 years (from 2017);
- $1340.37 if cost-reduction is 5% per year. Equivalent to 11.4 years (from 2017).

Notice that the level of adoption of distributed generation that can disrupt the electricity infrastructure is not clearly defined. On the one hand, on-grid distributed generation may incorporate new flexibility services into the grid and reduce the need for new investments in

[20] Keeping financing schemes, the inflation rate, real electricity prices, technology efficiency, and consumption distribution unchanged.

infrastructure. On the other hand, these technologies may also distort the incentives created by tariffs to represent a signal regarding the economic viability of new network investments. In this study, we do not make assessments about the sustainability of the infrastructure in relationship to the high adoption rate. Conversely, we are concerned with the demand-side for new technologies, including adoption.

Model limitations

The integration of the NPV and the Bass Model has some limitations where it concerns forecasting the adoption rate of PV Panels – or any other technology. First, it can only calculate the potential adoption based on the entire market size. The market size is probably smaller than the ceiling of the adoption rate for some reasons, which include (i) technical constraints for the installation (like rooftop size), (ii) financial constraints of households and (iii) the willingness to adopt. Moreover, macro-level decisions may influence the model, including (iv) the sustainability of the fund to guarantee low interest rates and (v) the inflation rate. Regulatory decisions may also create barriers (or incentives) to the business model, affecting variables like (vi) the price of electricity and (vii) future changes in net metering rule. And, last, we suppose a linear cost-reduction in the price of capital. The path of the CAPEX may accelerate or deaccelerate the adoption rate of the technology. However, based on available data, both the NPV and the Bass Model show reasonable results compatible with the trajectory of disruptive technologies.

Conclusions

Our case study focuses on the Brazilian Net Metering Policy. The goal of the study was to evaluate how Net Metering policies can incentivize the adoption of distributed generation resources, in particular, Solar Photovoltaic Systems. We calibrated a project viability model using data obtained from the Consumer Satisfaction Index from ANEEL (2017) and data about potential generation, electricity prices, cost of investment and maintenance, and financial schemes.

Three scenarios were calibrated, an optimistic (with 5% of cost decreasing per year), a less-optimistic (2% of cost decreasing per year) and the scenario forecasted by NREL (3.6% of cost decreasing per year). For each scenario, we calculated the viability of PV for each consumer (an NPV model), and the share of the potential market with a positive net present difference (between a prosumer state and a grid-consumer state). Then we used the Bass Diffusion Model to estimate an S-shaped curve of technological adoption. The results found with the Bass Model fit the NPV Model with a confidence level of over 99%. For instance, following the NREL scenario, our results show that PV systems would be economically viable for 37% of residential consumers in 2030.

These results help to highlight the potential disruption that may come with the introduction of distributed solar generation. We do not intend to measure how significant the disruption will be or the aftermath of it. Our objective was to estimate the path and the potential adoption of Solar PV. As our results show, adoption rate may exponentially grow up to 2030, reaching almost 40% of households.

This mode has clear limits. We cannot predict or measure the effect of the willingness to adopt a new technology, the knowledge of the benefits of these technologies, or the beliefs of potential adopters that may be willing to pay even if the project is not economically viable. However, we are aware of these limitations, and the study is a valid analysis of the adoption cap using a microeconomic rational decision framework.

References

Bass, F. M. (1969). A New Product Growth for Model Consumer Durables. *Management Science*. https://doi.org/10.1287/mnsc.15.5.215

Bass, F. M. (2004). Comments on "A New Product Growth for Model Consumer Durables The Bass Model." *Management Science*. https://doi.org/10.1287/mnsc.1040.0300

Bass, F. M., Krishnan, T. V., & Jain, D. C. (1994). Why the Bass Model Fits without Decision Variables. *Marketing Science*. https://doi.org/10.1287/mksc.13.3.203

Candelise, C., Winskel, M., & Gross, R. J. K. (2013). The dynamics of solar PV costs and prices as a challenge for technology forecasting. *Renewable and Sustainable Energy Reviews*, *26*, 96–107. https://doi.org/10.1016/j.rser.2013.05.012

Comello, S., & Reichelstein, S. (2017). Cost competitiveness of residential solar PV: The impact of net metering restrictions. *Renewable and Sustainable Energy Reviews*, *75*(May 2016), 46–57. https://doi.org/10.1016/j.rser.2016.10.050

Darghouth, N. R., Barbose, G., & Wiser, R. (2011). The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California. *Energy Policy*, *39*(9), 5243–5253. https://doi.org/10.1016/j.enpol.2011.05.040

Dong, C., Sigrin, B., & Brinkman, G. (2017). Forecasting residential solar photovoltaic deployment in California. *Technological Forecasting and Social Change*, *117*, 251–265. https://doi.org/https://doi.org/10.1016/j.techfore.2016.11.021

Eid, C., Reneses Guillén, J., Frías Marín, P., & Hakvoort, R. (2014). The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives. *Energy Policy*, *75*, 244–254. https://doi.org/10.1016/j.enpol.2014.09.011

Gonzalez, R. E. (2018). *Designing Nearly Zero Energy Buildings: Energy Efficiency and On-Site Generation*. Universidade Federal do Rio de Janeiro.

Hancevic, P. I., Nuñez, H. M., & Rosellon, J. (2017). Distributed photovoltaic power generation: Possibilities, benefits, and challenges for a widespread application in the Mexican residential sector. *Energy Policy*, *110*, 478–489. https://doi.org/https://doi.org/10.1016/j.enpol.2017.08.046

IRENA, IEA, & REN. (2018). *Renewable Energy Policies in a Time of Transition*. Retrieved from http://www.iea.org/publications/freepublications/publication/IRENA_IEA_REN21_Policies_2018.pdf

Kalish, S. (1985). A New Product Adoption Model with Price, Advertising, and Uncertainty. *Management Science*. https://doi.org/10.1287/mnsc.31.12.1569

Mohandes, N., Sanfilippo, A., & Fakhri, M. Al. (2019). Modeling residential adoption of solar energy in the Arabian Gulf Region. *Renewable Energy*, *131*, 381–389. https://doi.org/https://doi.org/10.1016/j.renene.2018.07.048

Poullikkas, A. (2013). A comparative assessment of net metering and feed in tariff schemes for residential PV systems. *Sustainable Energy Technologies and Assessments*, *3*, 1–8. https://doi.org/https://doi.org/10.1016/j.seta.2013.04.001

Rogers, E. M. (1962). Diffusion of innovations. *The Free Press*.

Vazquez, M., & Hallack, M. (2018). The role of regulatory learning in energy transition: The case of solar PV in Brazil. *Energy Policy*, *114*(November 2017), 465–481. https://doi.org/10.1016/j.enpol.2017.11.066