The role of institutional learning in technology adoption: an agent-based model for the case of public financing of utility-level solar PV in Brazil (2014-2017)

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Abstract

We analyse the co-evolution of institutions and technology in the solar PV expansion in Brazil. Tenders and public financing are the Brazilian support framework for renewables. The maladaptation of wind's support framework by BNDES led to delays in solar PV projects due to unfeasible local content requirements. We developed an agent-based model. The expansion and the internalisation of solar PV in Brazil is hampered by a rigid behaviour of BNDES. However, a too-responsive BNDES leads to low local content requirements, preventing a significant internalisation of the industrial chain. The internalisation of the industrial chain happens only with more time.

Keywords: BNDES, Solar PV, Complexity, Agent-based modelling, Technology diffusion.

Área temática: Teoria Econômica e Economia Aplicada.

Introduction

Business institutions coordinate resources, including knowledge. This might be understood as a multi-layer decision-making process concerned with resource allocation. In that context, technological change develops along 'trajectories', which in turn appear after changes in the technological 'paradigm'. To perform those functions, business institutions develop a set of routines adapted to the technological trajectory, which constitutes their capabilities. Traditionally, other non-business institutions have been considered as a static element framing the decisions of business institutions, e.g. static laws that frame firms' decisions.

In this paper, on the contrary, we consider that both business and non-business institutions are involved in the resource allocation process, and hence their co-evolutionary dynamics cannot be disregarded (Nelson, 1994). Specifically, we use Ostrom's (2011) Institutional Analysis and Development (IAD) framework, in which the development of institutions is a multi-layer decision-making process. The IAD framework studies institutional change in a broader sense, by focusing on the design and evolution of rules that order actions. Therefore, the dynamics analysed in this work are driven by level-shifting strategies: after observing an outcome, all players (including firms) may engage in changes of rules.

We apply our framework to the Brazilian utility-level electricity industry, where power generation investment bases itself on long-term contracts awarded through public tenders. The financing of these projects relies on BNDES' funds (the Brazilian development bank). This combination allowed a widespread adoption of wind generation. However, we observe persistent delays in the construction of solar PV projects, even if the support framework (auctions plus BNDES' funds) for solar PV and wind are similar. The driver for those delays relies on the available financing mechanisms and their conditions. Although BNDES' funds are intended to promote renewable energy source projects with below-market interest rates, larger amortisation periods and other characteristics important for infrastructure projects, they have specific terms and conditions: local content requirements. Those are part of a local content policy towards green technologies. We show that the direct application of the wind's support framework led to unfeasible local content requirements that do not succeed in promoting PV solar technologies. Consequently, the rules may need to be re-adapted in order to promote solar PV adoption. The focus of our analysis is on the co-evolution of institutions and technology.

In order to understand the previous dynamics, we set up an agent-based model. We show that the expansion and the internalisation of solar PV in Brazil may be hampered by a rigid behaviour of BNDES. However, a too-responsive BNDES may lead to low local content requirements, thus preventing a significant internalisation of the industrial chain. In that sense, the internalisation of the industrial chain happens only when BNDES gives firms enough time to learn.

First we contextualize the Brazilian utility-level solar PV expansion while displaying the ABM equations and their rationales. Afterwards we discuss the main results of our model, including the policy implications. After this, we conclude and display the references. In an appendix we display the LSD equations and object structure.

1. Brazilian solar PV expansion and its internalisation of a novel industrial chain: contextualisation, methodology and model

The Brazilian electricity mix is mainly composed of renewables: hydro was responsible for 90% of the mix until mid-1990's[1]. Nevertheless, low dam levels due to years of underinvestment and low rainfall levels led to a supply crisis in the early 2000's. This in turn was followed by a move towards new renewables: biomass and wind at first. That move was due to sustainability issues of new hydro power plants with dams: the unused hydro potential in Brazil is located in the Amazons, as such, large dams would endanger indigenous people and wildlife (EPE, 2017a, 2017b; Hochstetler and Kostka, 2015; Pinto Junior, 2007). Thus, the first objective of the move towards new renewables is to keep the Brazilian electricity mix clean.

The federal Government supported programs PROEÓLICA and PROINFA were starting points for the move towards new renewable in the early 2000's. Although fairly unsuccessful, both programs aimed to support the internalisation of the industrial chain of biomass and wind power generation technologies. This directive, however was improved after the programs (Dutra and Szklo, 2008; Ferreira et al., 2014; Podcameni, 2014). Thus, a second objective of the move towards new renewables is the progressive internalisation of parts of those novel industrial chains.

Given those two objectives, we characterise the Brazilian support framework for renewables as the following: it is composed of two mechanisms, an auction mechanism that aims to contract utility-level capacity with long-term power purchase agreements (PPAs); and a public financing mechanism, which aims to enable the construction of the contracted power plants. The electricity regulator (ANEEL) and the Brazilian energy planning company (EPE) under supervision of the Ministry of Mines and Energy operate the auction mechanism, whereas the National Development Bank of Brazil (BNDES) operates the public mechanism (IEA, 2015). Utility-level solar PV, due to its large agents, larger scale and lower costs was supposed to be the flagship of solar PV in the country, introducing the source into the electricity mix (EPE, 2012).

In the recent solar photovoltaic (solar PV) expansion in Brazil, more than 50 companies were awarded power purchase agreements (PPAs) for over 100 projects comprising 3.75 GW of total capacity (ANEEL, 2016a). All PPAs were awarded through auctions and tenders between 2014 and 2015 (Table 1). Among those, there are leaders in solar PV worldwide, such as Enel Green Power, Canadian Solar Inc, Solairedirect and Electricité de France (EDF). Those companies have utility-level solar PV projects completed and in construction in Latin American countries (Vazquez et al., 2018).

[1] For a more complete contextualization of the Brazilian Solar PV expansion amidst the support policies for renewables we recommend Andreão (2018), Andreão, Vazquez and Hallack (2017) and Vazquez et al (2018).

Table 1 - Contracted capacity of solar PV at LER auctions – Brazil – 2015-2016

Companies	Plants		Potency		Investment in Dec. 2017 US$[(i)]	
	Units	%	MW	%	$1,000.00	
Enel	22	23.40%	619.98	23.64%	$	1,206,555
Canadian Solar Inc	11	11.70%	329.97	12.58%	$	466,006
Lintran do Brasil Participações S.A.	9	9.57%	269.97	10.29%	$	405,445
Solairedirect SAS	7	7.45%	199.98	7.62%	$	284,818
Sune Solar B.V.	5	5.30%	148.57	5.66%	$	194,660
Renova Energia S.A.	5	5.32%	129.59	4.94%	$	215,911
STEELCON	3	3.19%	90.00	3.43%	$	194,636
Rio Energy EOL IV Geração e Comercialização de Energia Ltda	3	3.19%	89.91	3.43%	$	147,915
European Energy A/S	2	2.55%	60.00	2.29%	$	114,835
Fotowatio do Brasil Projetos de Energia Renováveis III Ltda.	2	2.13%	60.00	2.29%	$	98,443
SPE CESP COREMAS	2	2.13%	60.00	2.29%	$	90,640
Grupo Gransolar S.L.	2	2.13%	60.00	2.29%	$	82,092
Kawa	2	2.13%	54.00	2.06%	$	78,777
Companies with less than 50 MW of contracted capacity (38)	19	19.82%	450.93	17.19%	$	811,099
Total	**94**	**100%**	**2622.89**	**100%**	**$**	**4,391,831**

(i): corrected by the IGP-M index of November 2017 according to BCB (2017) and the exchange rate of December 13th 2017 according to Bloomberg Markets (2017).

Source: Own elaboration based on ANEEL (2016a) as depicted in Andreão (2018). We multiplied the capacity and investment numbers of each project by the participation of companies within consortia, according to ANEEL (2016b, 2015a, 2015b).

Nevertheless, most of the Brazilian solar PV capacity was yet to begin construction until December 2017 (ANEEL, 2017a, 2017b). Solar PV capacity behind scheduled far surpassed the capacity on schedule between July and December 2017 (ANEEL, 2017c, 2017a). That happened even with the completion of the first solar PV projects in Brazil alongside a cancellation auction for troublesome solar PV projects (ANEEL, 2017b; Bloomberg new energy finance, 2017; Enel Green Power, 2017a). Although there were no new solar PV contracted between November 2015 and December 2017 (EPE, 2017c, 2016a, 2016b), the contracted capacity had PPA contracts and clear deadlines for starting commercial operation, with penalties if companies failed to do so (Dutra and Menezes, 2005; Ferraz, 2014; SITAWI and CEBDS, 2016).

Within the Brazilian electricity industry, there is a clear dependence of companies on BNDES' funds (Ferreira, 2017; Hochstetler and Kostka, 2015; Podcameni, 2014). BNDES stands as the sole option for most companies with infrastructure projects, especially in the energy sector (Vazquez et al., 2018, 2016), as BNDES' funds represent the only feasible option for infrastructure projects: with below-the-market interest rates, longer amortisation periods, among others (BNDES, 2017a, 2017b). As such, one could understand that as the common behaviour or *status quo*: companies used to rely on BNDES' funds. One could understand that using BNDES' funds is an exploitative choice or part of the standard algorithm of behaviour of a company[2].

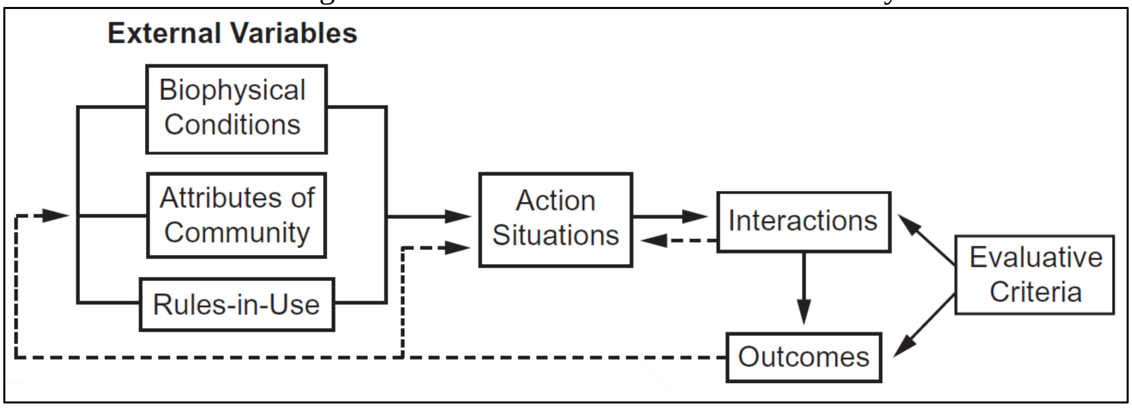
Nevertheless, there are three main companies with relative success in financing and thus building their solar PV projects in Brazil: Enel Green Power; and EDF in conjunction with Canadian Solar

[2] Drawing inspiration from both Frenken (2006) and March (1991).

Inc. Enel Green Power uses Chinese solar PV panels in their projects, going against BNDES' local content requirements, and as such, the company is not accessing BNDES' subsidised funds (Enel Green Power, 2017a, 2015). This decision by Enel was not the same for other projects, further supporting the hypothesis that companies exploit BNDES' funds (Enel Green Power, 2017b). In this sense, Enel *explored* other options to BNDES' funds in order to successfully finance its projects. Enel went further than the standard behaviour of companies in that context, *changing* its algorithm of behaviour.

To understand how a company may learn, Ostrom's (2011) IAD framework (Figure 1) is useful. Companies evaluate their outcomes, deciding which ability to enhance in the next period in order to access funds that are more competitive. Our interpretation of Ostrom's IAD framework as a multi-layer decision framework follows Vazquez and Hallack's (2018) understandings. Companies' criteria of efficiency are based on rather subjective characteristics: agents possess "mental models" coherent with incomplete information, possessing mechanisms to acquire and process information[3].

Figure 1 - A Framework for Institutional Analysis



Source: Ostrom (2011, p. 10).

However, the remaining companies with the exception of Enel were not fully unsuccessful. After EDF entered alongside Canadian Solar Inc. in some of its projects, the companies started the construction of a solar PV module manufacturing facility in Brazil (PV Tech, 2016; Reuters Brasil, 2016a, 2016b). That decision lead to the construction of a facility capable of producing solar PV modules in accordance with BNDES' local content requirements, thus allowing both companies to access BNDES' subsidised funds (Canadian Solar Inc, 2016). Therefore, companies are able to learn from their mistakes and to enhance their abilities to make contracts in order to access BNDES' funds by complying with BNDES' local content requirements. In terms of the experiment, we therefore model one company able to go beyond the status quo and is successful and several others that are not able to go beyond the status quo and are unsuccessful.

As such, companies may learn and adapt in order to access better resources, i.e., they may learn how to better comply with BNDES' local content requirements; or they may learn how to bypass them by accessing other non-public funds. The first option is the one followed by EDF and Canadian Solar Inc, whereas Enel Green Power followed the second option.

In the model, the abilities of firms to comply with BNDES' local content requirements is the *technological ability* (*teccap*), since BNDES' requirements are related to the internalisation of solar PV industrial chain in Brazil, which goes through contracts with panel manufacturers capable of producing the needed technology. The abilities to comply with non-public banks are called *commercial ability (comcap)*, since commercial banks make other requirements, related to collaterals, firm's profits, etc. Both abilities are contained in the group of real positive numbers[4] ($\mathbb{R}^+$). As BNDES keeps a local content policy, firms decide to enhance either ability by analysing the current minimum

[3] Following Arthur's (1994) inductive reasoning terms and given Simon's (1979, 1959) bounded rationality of agents within a fundamentally uncertain environment in Dequech's (2011) terms.
[4] We capped both capabilities to 500 in the simulation.

local content requirements. The higher the local content requirements, the harder it is for companies to access BNDES funds, and so they will focus on trying to access alternative funding (if they are capable) or waiting to see what happens (if they are not).

$$comcap_{i_{t+1}} = comcap_{i_t} * (1 + {local_{content}}_t^{concavity} * 0.05 \frac{portfolio\_condition_{i_t} - portfolio\_condition_{average_t}}{portfolio\_condition_{average_t}}) \quad (1)$$

$$teccap_{i_{t+1}} = teccap_{i_t} * \left(1 + (1 - {local_{content}}_t\right)^{concavity} * 0.05 \frac{portfolio\_condition_{i_t} - portfolio\_condition_{average_t}}{portfolio\_condition_{average_t}}) \quad (2)$$

Those dynamics are displayed on equations 1 and 2. In both equations, the capability of a firm *i* on the *t+1* period is a simple replicator, i.e., the better the firm in relation to the average, the more likely it is for that firm to experience a growth in its capabilities. That relation is measured not directly in relation to the capability, but in relation to an index devised as a combination of both capabilities and the local content requirements (displayed in the equation 3). That growth is adjusted by the local content requirements of BNDES, with the *concavity* parameter (a positive integer) adjusting it: if it is zero, the multiplier is one, for higher values the multiplier is smoothed.

Therefore, in the experiment we have essentially two successful companies: one that goes beyond the standard algorithm of behaviour, and one that used the standard algorithm of behaviour. Most companies however are unsuccessful. In order to analyse success in the model, we analyse the index of efficiency of companies[5]. Opportunities are open to companies within the industry, however they differ in terms of how much successful they are in exploiting opportunities. Companies with higher index of efficiency are in stronger positions to other firms.

A hypothesis of our model is that companies have similar portfolios of projects in terms of number and capacity. We made this simplification in order to focus the analysis of heterogeneity on firm behaviour rather than on firm size. Moreover, since companies involved in Latin American infrastructure projects normally use project financing rather than corporate financing (Vazquez et al., 2018, 2016), one could argue that "each project is a separate project".

In light of this, our portfolio condition index, measured in real positive numbers, reflects the likelihood of companies successfully financing their projects and thus avoiding penalties. The more successful a company is, the higher its index. In conclusion, the portfolio condition is an index for the relative number of projects which will not face penalties when the deadline arrives.

$$portfolio\_condition_{i_t} = comcap_{i_t}^{local\_content} * teccap_{i_t}^{1-local\_content} \quad (3)$$

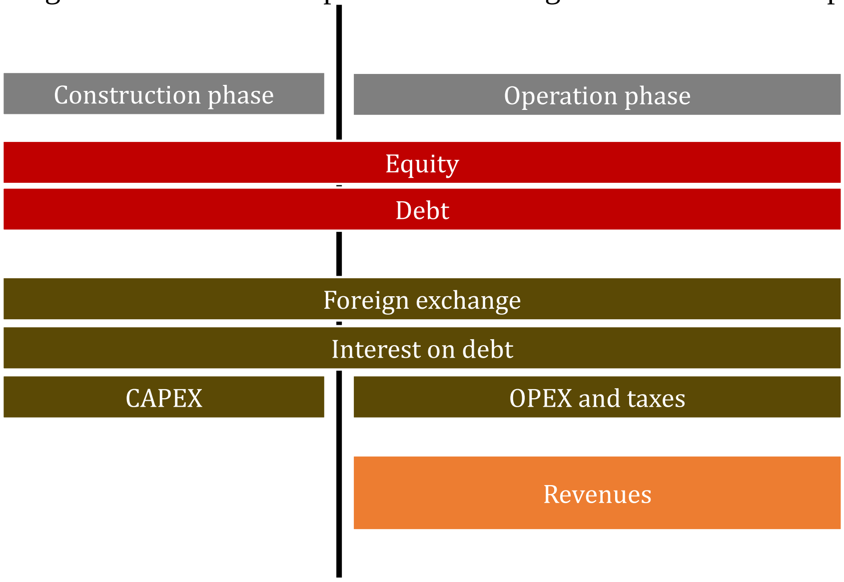
Equation 3 displays how the portfolio condition index is measured, being a simple cobb-Douglas equation based on the company's capabilities, with the local content requirements acting as α of the equation. The likelihood of a company being able to finance its portfolio of power plants is a function of its capabilities and also of the BNDES' local content requirements: if BNDES raises the local content requirements, a company with a higher capability to interact with BNDES than with other banks (i.e. a bank focused on accessing BNDES' funds) would be impaired by BNDES' decision. On that case, a company focused on the alternatives to BNDES would improve its likelihood of being able to finance its power plants. On the case of lowering local content requirements, that decision by BNDES' would impact positively the first company and negatively the second company.

In relation to BNDES, since early 2000's, it was clear that BNDES had to finance the expansion of renewable sources in Brazil. The failure of PROEÓLICA (Olz, 2003; Wachsmann and Tolmasquim, 2003), the relative success of PROINFA (Dutra and Szklo, 2008) and the success of the auctions made clear that BNDES played a pivotal role in the expansion of the Brazilian electricity mix (Dutra and Menezes, 2005; Ferreira, 2017; Podcameni, 2014; SITAWI and CEBDS, 2016). Through the tender and auction mechanism, companies have a secured remuneration of their investments, i.e., companies secure their cash-flows. In the operation phase, the infrastructure is completed and, with PPAs it is able to produce sufficient cash-flow to justify its implementation. Nevertheless, before that,

[5] Similar to Ericson and Pakes' (1995) concept of index of efficiency.

in the construction phase, little to no cash-flow is generated and the PPA support is absent. In that phase, the use of financial instruments to support the construction is mandatory (2013). That division of phases is depicted in Figure 2. Hence the importance of BNDES in financing the expansion of Brazilian electricity industry (Ferreira, 2017; Podcameni, 2014; Vazquez et al., 2016).

Figure 2 – Schematic representation of a generic infrastructure project.



Source: Adapted from Vazquez et al. (2018, p. 12).

Therefore, the experiments need to incorporate the policy dimension of BNDES. In that sense, given Ostrom's (2011) IAD framework, BNDES stands as a policy maker, evaluating outcomes and affecting rules that, consequently affect the next outcomes. As such, BNDES affects the dynamics and feedbacks of the system. Its evaluation criteria, in terms of the IAD framework, is its requirements of local content: BNDES requires compliance with its local content policy in order to allow companies to access its subsidised funds (BNDES, 2017c, 2014a).

We understand that BNDES possess an evaluative criteria based on efficiency, however, in Arthur's (1994) inductive reasoning terms and given Simon's (1979, 1959) bounded rationality of agents within a fundamentally uncertain environment in Dequech's (2011) terms, BNDES' criteria of efficiency is based on rather subjective characteristics than on objective characteristics. As such, BNDES analyses companies by using a "mental model" coherent with incomplete information, possessing mechanisms to acquire and process information.

The solar PV expansion was planned in 2013 and implemented in 2014, following the initial success of the wind expansion. As such, it faced a severely different context: the Brazilian economy was facing recession unlike Europe or the United States (Podcameni, 2014; SITAWI and CEBDS, 2016). Nevertheless, the failure of the expansion is not exclusively due to external or macroeconomic factors: there was a clear misalignment of policy goals and sector conditions. While EPE (2012) and BNDES (2014b) were confident of the success of solar PV expansion, companies reported insufficient abilities to comply with local content requirements, thus blocking firms from accessing BNDES' funds (Reuters Brasil, 2017; SITAWI and CEBDS, 2016; Solarplaza, 2017). The high initial local content requirements were directly related to the adaptation of a mechanism designed for wind into a mechanism for supporting solar PV (Andreão, 2018; Andreão et al., 2017). In turn, BNDES waited almost three years to revise its methodology for financing solar PV panels, which companies claimed that was incoherent with their deadlines (Reuters, 2016). We understand that the status quo behaviour for BNDES is to avoid significant and frequent changes to its methodology. One could understand that this is intended to inform agents that the current rules are supposed to remain intact for a significant period of time. Therefore, in the experiments, BNDES first introduces a medium to high local content requirement (measured in percentage), unrelated to the sector (randomly distributed) and do not change it throughout the simulation.

$$local\_content_{t+1} = local\_content_t * (1 - (portfolio\_condition_{observed_t} - portfolio\_condition_{target}))^{2*responsivity - 1} \quad (4)$$

Given the fact that BNDES took over 2 years to change a faulty methodology, can we imply that BNDES and firms interact? As a matter of fact, yes, since the revision in methodology of June 2017 was motivated by the lack of disbursements towards solar PV projects and by the fact that BNDES expected three manufacturing facilities in the country in 2016 only to have one completed by December 2016 (BNDES, 2017d; Canadian Solar Inc, 2016; Reuters Brasil, 2017, 2016b).

In the model, this interaction occurs through the analysis of the aggregate portfolio conditions of companies. We hypothesise that BNDES cannot *directly* analyse companies' abilities in exploiting or exploring, and that it is too cumbersome to produce a complex mental model to relate exploiting and exploring to local content requirements. Therefore, BNDES simply analyses the success or failure of companies in financing their portfolio of projects. Nevertheless, BNDES is not *directly* concerned about the expansion but rather about the internalisation of the solar PV industrial chain. As such, BNDES accepts some degree of unsuccessful companies: it is better to maintain somewhat high levels of local content requirements in order to support the internalisation, than to lower the requirements in order to fully support the expansion.

That rationale is depicted in the equation 4. In that equation, the *target portfolio_condition* is a parameter that depicts the targeted average interpretation of the average portfolio condition that BNDES desires. That target portfolio condition is compared to an *observed portfolio condition* at that the time[6], and the higher the difference, the more likely BNDES will be to review its local content requirements for the next period. BNDES does not observe *directly* the portfolio condition of firms: BNDES wants companies to be above a certain threshold, as such it analyses how many companies are above that parameter. The index of the equation is comprised of the *responsivity* parameter, responsible for measuring the responsiveness of BNDES: the lower that parameter, the more responsive BNDES is. As such, a more responsive BNDES is more likely to revise its local content requirements each period, and also to revise its policy due to smaller differences between the targeted and the actual aggregate portfolio condition. The index is always an odd number, as such, BNDES can either lower, maintain or rise its local content requirements depending on its responsiveness and on the difference between the targeted and the actual average portfolio condition. BNDES decide between raising, lowering or maintaining its local content requirements.

In relation to BNDES' behaviour, we have to model a variable for determining how big the difference between the actual and acceptable aggregate portfolio conditions needs to be in order for it to be a significant difference. We also have to model how much BNDES is willing to change its local content requirements in relation to the significance of that difference. We simplify the model by using the parameter for both processes: the *responsivity* parameter. The more responsive BNDES is, the smaller the difference needs to be in order to be considered significant, and the more willing BNDES is to make significant changes to its local content requirements. Therefore, the experiment models an unresponsive BNDES that makes little to no revisions in its local content requirements, and when there is a revision, it is minimum, i.e. we model a BNDES with a low tolerable aggregate portfolio condition which faces a low actual aggregate portfolio condition.

2. Results and discussion

In order to calibrate the model, the control experiment needs to show that BNDES sets high initial local content requirements unrelated to the sector and is not willing to revise its policy. Companies are unable to exploit BNDES' funds, leading to major unsuccessfulness of both the expansion and the internalisation. In those terms, a single company must be able to overturn that context by exploring other funds, however, most companies must be limited to exploiting BNDES, being unable to access

[6] In relation to that, BNDES compares the percentage of companies above that portfolio condition threshold to the target of percentage of companies above that threshold. That interpretation of BNDES is in line with Arthur (1994).

BNDES' funds due to the incoherently high local content requirements or to access other funds due to path dependence.

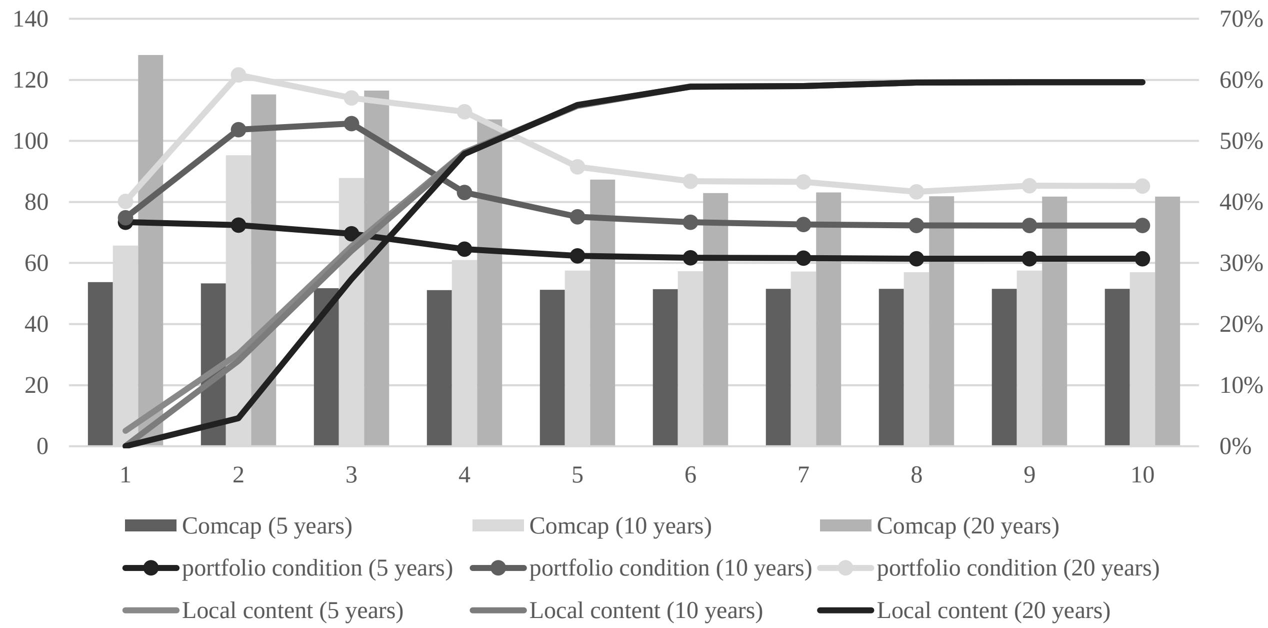
Table 2 – Last period capabilities, portfolio condition and local content for different BNDES' responsivities in 60, 120 and 240 months.

Cases	Comcap (5 years)	Comcap (10 years)	Comcap (20 years)	Teccap (5 years)	Teccap (10 years)	Teccap (20 years)	Local content (5 years)	Local content (10 years)	Local content (20 years)	portfolio condition (5 years)	portfolio condition (10 years)	portfolio condition (20 years)
1	53.72	65.73	128.1	74.11	75.42	80.14	2.526%	0.028%	0.008%	73.41	74.88	80.15
2	53.33	95.32	115.2	76.81	106.4	123	15.140%	13.950%	4.577%	72.4	103.7	121.6
3	51.76	87.81	116.5	81.69	121.5	114.6	32.700%	31.970%	27.360%	69.63	105.7	114.1
4	51.09	60.95	107	82.41	136	139.1	48.130%	48.040%	47.840%	64.55	83.14	109.6
5	51.27	57.53	87.34	81.76	133.4	151.7	55.800%	55.710%	55.900%	62.31	75.2	91.49
6	51.47	57.29	82.88	81.47	129.5	153.3	58.940%	58.880%	58.870%	61.74	73.32	86.82
7	51.58	57.19	83.14	81.53	128.7	152.8	58.990%	58.970%	58.970%	61.66	72.66	86.64
8	51.52	57.05	81.85	81.4	128.6	153.6	59.560%	59.560%	59.560%	61.43	72.31	83.35
9	51.53	57.5	81.79	81.4	128.6	153.2	59.600%	59.600%	59.600%	61.42	72.28	85.28
10	51.53	57.05	81.78	81.4	128.6	153.6	59.610%	59.610%	59.610%	61.42	72.28	85.27

Source: own elaboration

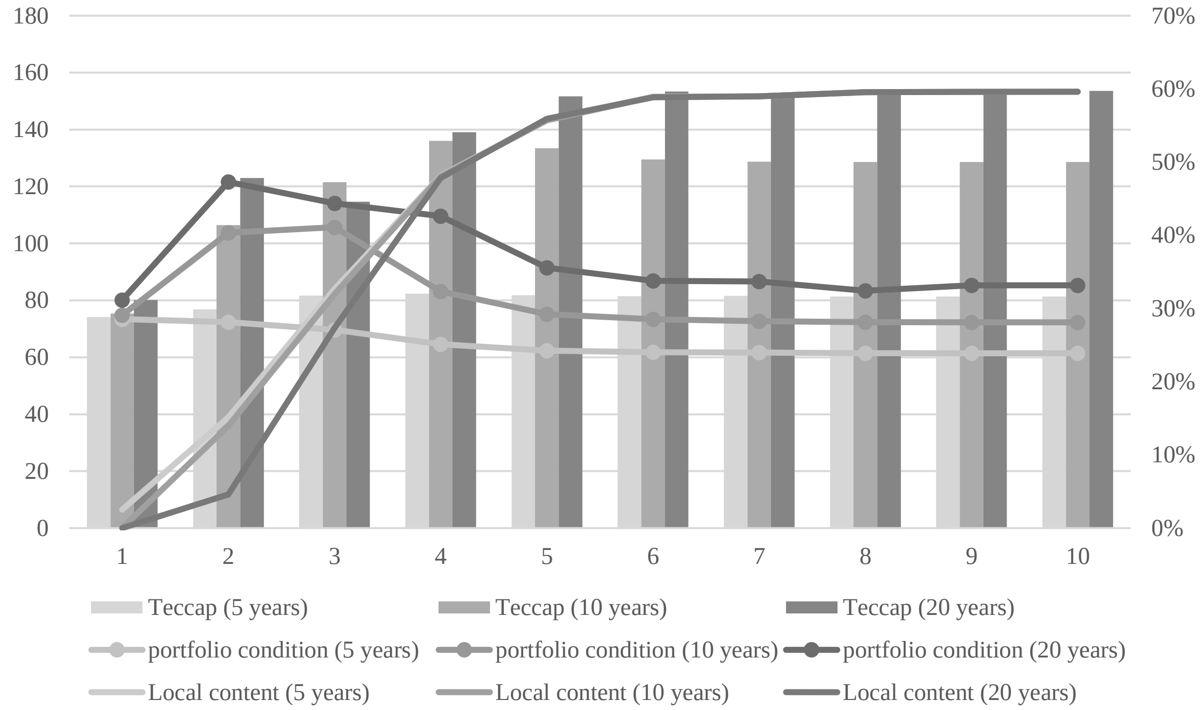
The expansion is characterised by favourable portfolio conditions, i.e., high likelihood of having plants financed in time. The internalisation is characterised by two factors: not too low local content requirements by BNDES; expansion of companies' technological capability; and favourable portfolio conditions. Companies with favourable portfolio conditions that are able to enhance their technological capabilities while BNDES maintains at least medium local content requirements indicate that companies are successfully interacting with panel manufacturers in order to internalise portions of the solar PV industrial chain.

Chart 1 - Last period commercial capability, portfolio condition (left axis) and local content (right axis) for different BNDES' responsivities in 60, 120 and 240 months.



Source: Own elaboration

Chart 2 - Last period technological capability, portfolio condition (left axis) and local content (right axis) for different BNDES' responsivities in 60, 120 and 240 months.



Source: Own elaboration

As such, we set up 49 companies that started with its ability to meet BNDES' requirements (technological capability) 25% higher than its ability to meet the commercial banks' requirements (commercial capability), and one company that has the opposite abilities (commercial capability 25% higher than the technological capability). Then, with BNDES setting up initial local content requirements between 40% and 80% and not changing them, that last company thrives (in relation to its portfolio condition) whereas the remaining 49 companies struggle to finance their projects in the 5 years span of the first set of auctions, thus replicating reality. The threshold is significantly close to the portfolio condition of most companies.

Table 3 – Variation (in percentage) of capabilities, portfolio condition and local content in relation to each period's average for different BNDES' responsivities in 60, 120 and 240 months.

Cases	Comcap			Teccap			Local content			Portfolio condition		
	5 years	10 years	20 years	5 years	10 years	20 years	5 years	10 years	20 years	5 years	10 years	20 years
1	3.55%	0.59%	32.67%	-7.82%	-38.01%	-41.72%	-94.40%	-99.94%	-99.98%	12.94%	-7.04%	-15.12%
2	2.79%	45.88%	19.31%	-4.46%	-12.55%	-10.55%	-66.43%	-68.74%	-89.41%	11.39%	28.74%	28.77%
3	-0.23%	34.39%	20.65%	1.61%	-0.14%	-16.66%	-27.49%	-28.37%	-36.71%	7.13%	31.23%	20.83%
4	-1.52%	-6.72%	10.81%	2.50%	11.78%	1.16%	6.72%	7.64%	10.67%	-0.69%	3.22%	16.06%
5	-1.18%	-11.96%	-9.55%	1.69%	9.64%	10.32%	23.73%	24.82%	29.31%	-4.13%	-6.64%	-3.11%
6	-0.79%	-12.32%	-14.17%	1.33%	6.43%	11.49%	30.69%	31.92%	36.18%	-5.01%	-8.97%	-8.06%
7	-0.58%	-12.48%	-13.90%	1.41%	5.78%	11.12%	30.80%	32.13%	36.41%	-5.13%	-9.79%	-8.25%
8	-0.69%	-12.69%	-15.23%	1.25%	5.69%	11.71%	32.06%	33.45%	37.78%	-5.49%	-10.23%	-11.73%
9	-0.67%	-12.00%	-15.29%	1.25%	5.69%	11.41%	32.15%	33.54%	37.87%	-5.50%	-10.26%	-9.69%
10	-0.67%	-12.69%	-15.30%	1.25%	5.69%	11.71%	32.17%	33.56%	37.89%	-5.50%	-10.26%	-9.70%
average	51.88	65.342	96.558	80.398	121.672	137.504	45.10%	44.63%	43.23%	64.997	80.547	94.43

Source: own elaboration.

Table 2 depicts the results for type 2 companies (the 49 companies with higher technological capabilities) in relation to the abilities and their portfolio condition as well as for the local content requirements by BNDES. From that table we can understand that changes to BNDES' responsivity affects the enhancement of capabilities by affecting BNDES' willingness to change its local content requirements, thus affecting companies' likelihood of having their projects financed (portfolio condition). In the short term, a more responsive BNDES lowers significantly its local content requirements, leading companies to focus on their commercial capabilities as their low technological capabilities are enough to meet BNDES' requirements. A more responsive BNDES also affects positively on companies' portfolio conditions, leading them into more favourable positions.

Chart 1 and **Erro! Fonte de referência não encontrada.** depict the short-term trade-off between BNDES' local content requirements and companies' likelihood of being financed (portfolio condition). As such, with 5 years to finance their projects and an unresponsive BNDES, companies are unable to finance their projects (low portfolio conditions) and to internalise the industrial chain (low enhancement of the technological capability).

From both charts and the table, we acknowledge that the short-term 5 year span is not enough for companies to enhance their capabilities, as such we also simulated 10 years and 20 years of interactions between companies' and BNDES. From the experiments with more time, we can see that lower local content requirements lead companies into enhancing more its commercial capabilities, whereas higher local content requirements lead them into enhancing more its technological capabilities in order to comply with those requirements.

Table 4 – Variation (in percentage) of capabilities, portfolio condition and local content in relation to all period's average for different BNDES' responsivities in 60, 120 and 240 months.

Cases	Comcap			Teccap			Local content			Portfolio condition		
	5 years	10 years	20 years	5 years	10 years	20 years	5 years	10 years	20 years	5 years	10 years	20 years
1	-24.61%	-7.76%	79.76%	-34.53%	-33.37%	-29.20%	-94.30%	-99.94%	-99.98%	-8.23%	-6.39%	0.20%
2	-25.16%	33.76%	61.66%	-32.14%	-6.00%	8.67%	-65.84%	-68.52%	-89.67%	-9.49%	29.64%	52.02%
3	-27.36%	23.22%	63.49%	-27.83%	7.34%	1.24%	-26.22%	-27.87%	-38.27%	-12.95%	32.14%	42.64%
4	-28.30%	-14.47%	50.15%	-27.19%	20.15%	22.89%	8.60%	8.39%	7.94%	-19.30%	3.94%	37.01%
5	-28.05%	-19.27%	22.57%	-27.77%	17.85%	34.02%	25.90%	25.70%	26.13%	-22.10%	-5.99%	14.37%
6	-27.77%	-19.60%	16.31%	-28.02%	14.41%	35.43%	32.99%	32.85%	32.83%	-22.82%	-8.34%	8.54%
7	-27.62%	-19.74%	16.67%	-27.97%	13.70%	34.99%	33.10%	33.05%	33.05%	-22.92%	-9.17%	8.31%
8	-27.70%	-19.94%	14.86%	-28.09%	13.61%	35.70%	34.39%	34.39%	34.39%	-23.20%	-9.60%	4.20%
9	-27.69%	-19.31%	14.78%	-28.09%	13.61%	35.35%	34.48%	34.48%	34.48%	-23.22%	-9.64%	6.61%
10	-27.69%	-19.94%	14.76%	-28.09%	13.61%	35.70%	34.50%	34.50%	34.50%	-23.22%	-9.64%	6.60%
Average	71.260			113.191			44.320%			79.991		

Source: own elaboration.

From Table 3 and In that regard, the **Erro! Fonte de referência não encontrada.** depicts the penalisation of time in relation to the internalisation of the industrial chain, as better results occur with more time, *independently* of BNDES' responsivity, although BNDES' responsivity affects the distribution of capabilities as well as the overall likelihood of companies having their projects financed and built in time.

we can observe that the relation between BNDES' local content requirements and firms' portfolio conditions indicate a non-linear relation: a very responsive BNDES has a similar negative impact on companies as a very unresponsive BNDES, and in the 20 years case, a very responsive BNDES is *worse* than a very unresponsive BNDES. From those tables we can observe that BNDES must than have a medium responsivity (between 2 and 4) in order to conjugate high enough local content requirements with a satisficing portfolio condition for firms, and that must be done in more than 5 years in order to give companies enough time to build their capabilities in order to internalise the solar PV industrial chain into Brazil.

We infer that responsivity is relevant for BNDES to promote the expansion, nevertheless it is not enough to promote the internalisation of the solar PV industrial chain into Brazil[7]. For that, companies

[7] The type 1 company reaches maximum portfolio condition around the 60^{th} month, as such indicating that they have a 100% likelihood of having its power plants financed and built in time, thus replicating reality. We refrain from analysing more in depth the type 1 company as that result always holds true and it does not comprise the majority of companies

and BNDES need more time to interact, in order for companies to build better capabilities to interact with panel manufacturers, inducing the internalisation of the industrial chain.

In that regard, the **Erro! Fonte de referência não encontrada.** depicts the penalisation of time in relation to the internalisation of the industrial chain, as better results occur with more time, *independently* of BNDES' responsivity, although BNDES' responsivity affects the distribution of capabilities as well as the overall likelihood of companies having their projects financed and built in time.

Conclusion

Solar PV was a source locked-out from the Brazilian power sector, possessing almost no capacity until 2014. As such, solar PV required adequate support mechanisms for it to be promoted. The adaption of wind's support framework lead to unfeasible local content requirements which did not succeeded in promoting the technology as expected.

We produced a simulation model to analyse the co-evolution between BNDES' and firms' decisions. The ABM models the capability enhancement process of companies, in constant feedback with the evaluation of BNDES and its decisions of revising or not the local content requirements. We used the LSD program for the model, performing over 1000 simulations.

From the results of the ABM we identify that time is a key factor for the enhancement of capabilities, as well as a more responsive BNDES. We understand that, in the case study, BNDES was not as responsive as needed, thus failing to act as a facilitator of the solar PV expansion and of the internalisation of the solar PV industrial chain. By responsive we mean that BNDES should be willing to readapt its methodology if it is apparent that BNDES' financing mechanism is not working properly.

Nevertheless, responsiveness should be executed with moderation. From the simulations, it is clear that there should be a balance in this operation: a too rigid BNDES with unrealistically high local content requirements is as unfit as a BNDES that is too willing to adapt to companies' needs. The result from both situations, in relation to the emerging phenomenon, i.e., the development of firms' capabilities as a response to local content policies, is the same in practical terms: firms do not develop the required capabilities. We identify that BNDES should be willing to adapt and to revise its policy to the sector's needs, but giving it time to enhance its capabilities. Moreover, it is clear from the simulation that a single round of auctions is not enough to promote the internalisation of the solar PV industrial chain in Brazil, indicated by the low levels of enhancement of capabilities when simulating for only 5 years in contrast to their evolution when companies are allowed more time to build their power plants.

The fact that the model simulates *one* round of auctions and its aftermath represents the more direct line to expand the research in regard to the simulation. The simulation will also benefit from a better analysis of the financial sector, introducing different interest rates, amortisation periods, exchange rates for external financing, etc. Including the effects of the macroeconomic environment will be useful as well. Furthermore, we only simulate one technology, thin film solar panels and varieties of silicon solar panels are not analysed.

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Appendix: LSD Initial Values

In the model we set up the initial parameters and initialised variables as depicted in Table 5. Each step in the simulation is a month.

Table 5 – Initial values for parameters and lagged values according to objects, in order according to LSD

Object	Variable/Parameter	Initial Value
Market (1)	Avg_portfolio_condition (V_1)	1
	Obs_portfolio_condition (V_1)	1
BNDES (1)	Local_content (V_1)	0
	Tgt_portfolio_condition (P)	0.5
	responsivity (P)	*
	threshold (P)	75
	variance_of_capabilities (P)	10
	initial_comcap_type_1 (P)	75
	initial_teccap_type_1 (P)	50
	initial_comcap_type_2 (P)	50
	initial_teccap_type_2 (P)	75
Firm (50)	portfolio_condition (V_1)	0
	type_of_company (P)	**
	concavity (P)	2
	teccap (V_1)	0
	comcap (V_1)	0
Capabilities (1)	h1 (V)	***
	h2 (V)	***

*: parameter changes from case to case
**: 0 for type 1 companies (first company of each case) and 1 for type 2 companies (the other 49 companies)
- : variable without lag
*** : variable without lag
V_1: variable with lag 1
P: Parameter
(Number): number of repetitions of that object

Source: own elaboration.