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Deployment of photovoltaics in Brazil: Scenarios, perspectives and policies for low-income housing

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Abstract

Solar irradiation in Brazil is favorable for electricity generation, yet this energy source represents less than 0.1% of the Brazilian energy matrix. This article presents photovoltaic solar panels as an important alternative in the context of the Brazilian energy crisis. Solar irradiations levels were considered to calculate the number of solar panels necessary to supply the average electricity demand of social housing programs. A scenario approach and an OFAT sensitivity analysis were used to evaluate feasibility (IRR, NPV, cash flow and payback) based on existing electricity charging policies and usual long-term financing plans for social housing programs. The results for all the proposed scenarios indicate that photovoltaics are an environmentally and economically feasible alternative. Deploying between four to seven 217 W photovoltaic panels onto each house would meet the needs of all solar irradiation zones considered, making dwellers significantly less dependent on the grid and capable of up to 47% grid feedback for up to 30 years. Finally, feed-in tariff policies and a trust fund for maintenance and reinvestment costs are suggested in order to stimulate the use of photovoltaics as a sustainable alternative.

Keywords: Energy policy; BIPV; Photovoltaics; Feed-in tariff

1. Introduction

The increasing demand for energy, resulting from increasing socio-economic activities around the world, must be considered in terms of efficiency, reliability and environmental aspects. In this context, renewable energy alternatives have become the focus of many studies addressing environmental and economic issues. Some countries are on the cutting edge of technological and regulatory investments in cleaner energy generation, enabling countries that have just recently begun to take alternative energy sources into consideration to learn from their experiences (Razykov et al., 2011; Saidur et al., 2011; Moosavian et al., 2013; Enteria et al., 2014).

Solar power has great potential to contribute to many of the social and environmental aspects of growing electricity demands (Razykov et al., 2011; Mahesh and Jasmin, 2013;

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Cicea et al., 2014; Enteria et al., 2014). In addition to low carbon emissions, solar energy requires no fossil fuel input and can present favorable payback time if deployed under adequate irradiation conditions and considering the relevant and applicable economic parameters. When analyzing international solar energy policies and projects, several opportunities are notable for adaptation and deployment to stimulate the use of this technology in Brazil (Leite, 2007; Ordenes et al., 2007; Rüther et al., 2008a; Razykov et al., 2011; Pao and Fu, 2013a; Aman et al., 2015).

Brazil is a developing country located in tropical and subtropical climatic regions, in which the intensity of sunlight radiation and several economic variables favor the use of solar technologies (Ordenes et al., 2007; MME, 2011; Rüther and Naspolini, 2011; ANEEL, 2014; Pao and Fu, 2013a; Reuters, 2014; Mohammed et al., 2014; EPE, 2014).

The Brazilian energy matrix consists mostly of hydraulic and natural gas sources, both of which require large investments and, often, more than five years to be fully operational. (Aldabó, 2002; Martins et al., 2008a,b, 2012; Rüther et al., 2011; ANEEL, 2014; MME, 2015). However, throughout the last 20 years, this heavy reliance on hydraulic energy – hindered by low precipitation during usually rain-intensive seasons – and on natural gas – with supplies directly affected by political and diplomatic instability – has not been seriously questioned (Knox-Hayes et al., 2013; Pereira et al., 2011, 2013; Pereira et al., 2012; Pao and Fu, 2013a,b; Sthel et al., 2013; Guerra et al., 2015; Camioto et al., 2014).

Considering the estimated annual growth in Brazilian electricity consumption of up to 4.2% until 2023 (MME, 2012; ANEEL, 2014; EPE, 2013), and despite the recent US$ 1.1 billion invested by the government, the country faces an energy crisis that could have been averted if earlier investments and policies had been made towards fostering renewable energy sources (Palz, 1995; Hinrichs and Kleinbach, 2004; Jochem et al., 2005; Leite, 2007; Martins et al., 2008b; MME, 2010; Rüther et al., 2008a, 2010, 2011; Pereira et al., 2012).

As shown in Fig. 1, solar irradiations considered good for electricity generation (above 4 kW h/m^2 per day) cover over 90% of Brazilian territory, however, installed capacity today is just 15 MW h (Patel, 1999; Sen, 2004; Martins et al., 2007; Mubiru and Banda, 2008; Janjai et al., 2009; Behrang et al., 2010; Janjai, 2010; MME, 2012, 2015; ANEEL, 2014; EPE, 2014). Further arguing in favor of the deployment of solar power based alternatives are the Brazilian Energetic Research Company (EPE) and the Brazilian National Institute for Space Research (INPE), which demonstrated that (a) Brazilian solar power potential exceeds approximately 230% of its current electricity consumption, and that (b) the deployment costs of photovoltaic solutions tends to annually decrease in the range of 3.3–6.5% until 2030 (EPE, 2013, 2014).

In comparison to Germany – a country in which solar irradiation is considerably less favorable yet electricity generation from solar power is almost five times higher (AGEB, 2015; BGR, 2015; EPE, 2013, 2014), and when analyzing Brazil's difficulties in making use of this technology, the main issue becomes clear: lack of policies and programs that stimulate photovoltaic deployment and that contribute to the creation of a more competitive market for both manufacturers and retailers (Bodach and Hamhaber, 2010; Silva et al., 2010; Ruiz-Arias et al., 2015; Saidur et al., 2011; Rüther and Zilles, 2011; Echegaray, 2014; Moosavian et al., 2013).

In the last ten years, few new energy policies or programs have been created in Brazil; most of those implemented are focused on biodiesel (e.g., National Alternative Energy Stimuli Program (PROINFA) and the National Biodiesel Production Program (PNPB)) and ethanol (e.g., National Ethanol Agricultural Zoning Program (ZAECANA)). Alongside the aforementioned examples, the State and Municipal Energy Development Program (PRODEEM), which encompasses solar and wind sources and compensates/rewards companies that deploy clean energy in their production systems, is seen by the market as bureaucratic, superficial and unwelcoming to the deployment of new technologies (Aldabó, 2002; Leite, 2007; MME, 2011; Rovere et al., 2011; ANEEL, 2014; Padula et al., 2012; Castanheira et al., 2014).

From a regulatory perspective, the Brazilian National Electric Energy Agency (ANEEL) has brought into force legislation that encompasses solar energy, such as Resolution N°77/2004 – that reduces transmission and distribution fees up to 80% until 2017 and to 50% after 2017 for renewable electricity generation enterprises – and Resolution N°482/2012 – that defines the kW h ranges for micro- and mini-generation systems as well as establishes the compensation system for individuals or companies to abate their electricity bill based on energy fed back to the grid. The latter also sets the criteria and parameters for the measurement, calculation and operation of the compensation system, however limiting the use of grid feedback credits to 36 months without cross-discount possibilities (ANEEL, 2004, 2012a,b,c).

These regulatory initiatives from ANEEL, however, do not configure policies or programs such as those seen in the United States, the Netherlands, the United Kingdom, Canada, Germany, Spain, Australia, China, India, Malaysia and France, for example. These nations have robust and comprehensive policies that tackle solar energy from all angles, including the regulatory (e.g. tax exemptions, subsidies, feed-in tariffs (FIT), cross-discounts), without ignoring the need for investment incentives, technological research and development stimuli, renewable energy education and operational standards for building-integrated photovoltaics (BIPV).

Since these countries have begun making solar energy available to more residential consumers while establishing a holistic solar energy market support structure, significant results have been achieved: by 2016, the overall average growth of this energy source is expected to be 30% higher than in 2008 (Patel, 1999; Sen, 2004; Costa et al., 2008;

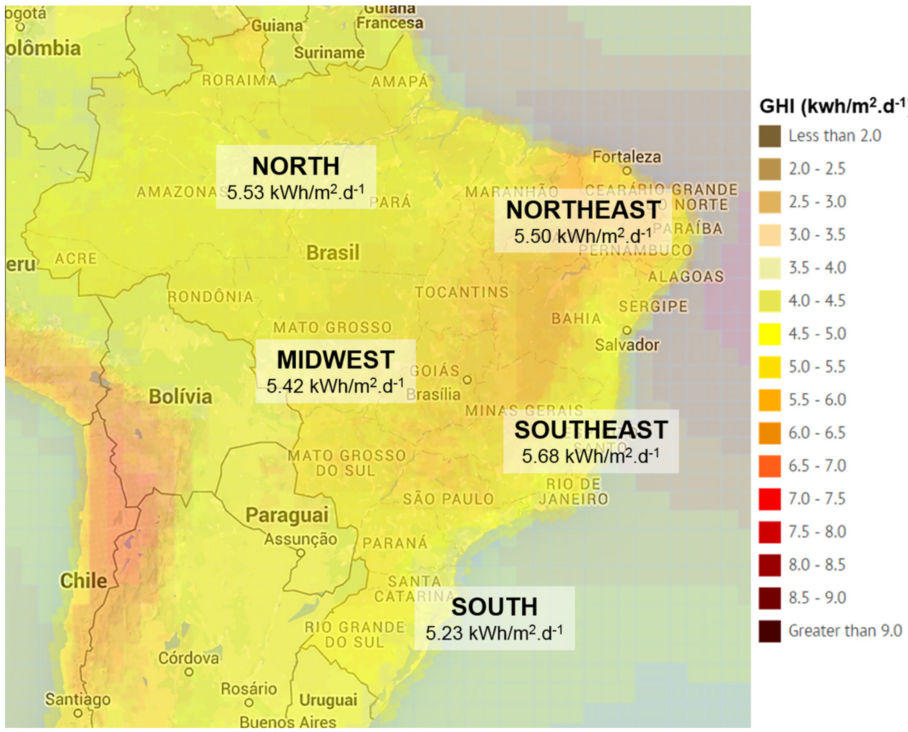

Fig. 1. Global Horizontal Irradiance in Brazil, regional averages highlighted (adapted from SWERA, 2016; SIGEL, 2016).

Liu et al., 2010; Razykov et al., 2011; Saidur et al., 2011; Echegaray, 2014; Moosavian et al., 2013). Additionally, through these policies, previous barriers such as (a) unskilled workforce; (b) low availability or high costs of secondary electrical materials; (c) import and export bureaucracy; and (d) intense political lobbying from consolidated energy sources have become less impeditive as competitive markets begin to adapt to solar technology (Sen, 2004; Pasqualetti and Haag, 2011; Saidur et al., 2011; Timilsina et al., 2012; Devabhaktuni et al., 2013; Moosavian et al., 2013; Echegaray, 2014).

Thus, the authors of this paper perceived the possibility of associating photovoltaic panel deployment with government housing projects as an alternative to supply electricity to underprivileged residential dwellers who are currently not extensively included in electricity generation and distribution projects in Brazil. To this end, the following examples of international BIPV projects that create affordable and feasible sustainable housing projects through the use of solar panels on rooftops were considered: Sharma et al. (1994, 2012), Ahmad (2002), Rylatt et al. (2003), Rüther et al. (2008b), Liping Wang et al. (2009), Na Wang et al. (2009), Ordóñez et al. (2010), Filho et al. (2010), Muhammad-Sukki et al. (2011), Norton et al. (2011), Pasqualetti and Haag (2011), Zmeureanu and Leckner (2011), Mekhilef et al. (2012), Enteria et al. (2014), Mulcué-Nieto and Mora-Lopez (2014), Telaretti et al. (2014).

In order to verify the photovoltaic alternative in regions with different solar irradiations in Brazil, energy savings and electricity generation were calculated for fifteen different scenarios. The results were associated with quantity and model of photovoltaic panels, energy balance and calculations for a series of proposed Feed-In Tariff (FIT) principles.

2. Methodology

This paper proposes a BIPV project specifically for social housing programs with 30-years-long financing plans. In Brazil, the most common social housing unit has 62 m^2 of roof surface, costs approximately US$ 19360.00 and consumes, on average, 150 kW h per month (COHAB, 2015; MME, 2014, 2015). Construction of social housing is managed by COHAB (Government Habitation Company), and performed by a contractor selected via public bidding. For the calculations, this paper considered the estimated 73,762 housing units to be completed and made available for new dwellers to move in by the end of 2016 (COHAB, 2015).

The calculations were made considering 217 W (nominal maximum) photovoltaic flat panel collectors operating at 96.8% module efficiency at up to 65 °C ambient temperature, each measuring 1 × 1.5 m (Energia Pura, 2014; Neosolar, 2014; Energy Team Brasil, 2014), for which each dweller would have a specific and proportional monthly increase in their financing plan's installment. If located below the Equator Line, these panels should be installed facing north at an angle that varies between 34.3° (southernmost latitude) and 0° (in the Equator Line itself); if located above the Equator Line, these panels should be installed facing south at an angle that varies between 5.1° (northernmost latitude) and 0° (in the Equator Line itself), according to Siraki and Pillay (2012) and data from the Brazilian Institute for Geography and Statistics (IBGE, 2015).

The electric energy generation calculation was made using the equation below:

$$Q \times (\mathrm{NP} \times \mathrm{ME}) \times \mathrm{GHI} \times L \times T \quad (1)$$

Q quantity of panels.
NP panel's maximum nominal power (W).
ME panel's module efficiency.
GHI global horizontal irradiance (kW h/m^2 d^{-1}).
L losses (e.g. panel degradation rate).
T period of time (days).

An annual average degradation rate of 0.4% was considered to affect the panels, which require minimal maintenance during their first 15 years operating, from a total of 30 years of lifespan. To compensate for electricity generation rates below 90% after 15 years of operation, this study considered reinvestment and maintenance costs to take place at year 16, in order to bring panels back to full generation potential (Energia Pura, 2014; Neosolar, 2014; Energy Team Brasil, 2014). The calculation of these costs considered the economic inflation as well as the projected tendency for the costs of photovoltaic solutions to decrease. The origin of the resources to subside these costs during year 16 consisted a working capital trust fund of (a) the earnings from investing the cash inflows until the end of year 15 at an average 1% interest rate per month, discounting the economic inflation during the period, plus (b) supplementary withdrawals (proportional to each scenario's needs) from the accumulated cash inflows of the project until the year 15.

The electricity starting price (year 1) of US$ 0.16 per kW h was calculated based on the average national price for residential consumers, also considering the scaling cost after the 100 kW h range, and the 10% electricity bill discount ceded to low income users that consume between 100 and 220 kW h per month, also known as the Electric Energy Social Tariff (TSEE), from which 18.83% of residential users currently benefit (ANEEL, 2014; BRASIL, 2010; Rüther and Zilles, 2011; Rüther and Mitscher, 2012).

The electricity surplus generated by the proposed hardware could be fed back to the grid. To that end, it was assumed that the photovoltaic panels were connected to the house's electric system via an inverter, as well as to the grid via a net metering unit, which would also avoid the need to install batteries. In order to enable feedback, the project complies with the existing energy savings and electricity bill compensation legislation (ANEEL, 2004, 2012a,b,c).

The inverter and net metering units considered for the calculations were chosen based on their capacity to fully operate with eight of the chosen solar panel model. Both equipment are capable of working with inputs and outputs of 2 kW (nominal maximum for 127 and 220 V @ 60 Hz) within an efficiency curve that varies between 94.9% and 96.0% in ambient temperatures up to 48 °C (Neosolar, 2014; Energy Team Brasil, 2014; Energia Pura, 2014).

The FIT credit considered was 25% (average between existing FITs in European countries; EEP, 2014) for 30 years over the price of each exceeding kW h fed back to the grid, based on the current electricity bill's price of US$ 0.16 per kW h. However, current Brazilian legislation for systems capable of supplying energy back to the grid does not allow dwellers to collect any direct revenue, nor for the credit to be used as discount in an installment, tax or fee – a practice known as cross-discount (MME, 2014; ANEEL, 2004, 2012a,b,c).

Table 1 summarizes the fifteen scenarios that were created. The scenarios combine the five Brazilian geopolitical regions with three consumption patterns based on the mean 150.0 kW h/month consumption of a Brazilian residence. Monthly, seasonal and annual Global Horizontal Irradiance (GHI) levels – which encompass both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DIF) – were obtained from a total of 113 collection and measurement points from either the National Aeronautics and Space Administration (NASA), the National Renewable Energy Laboratory (NREL) or the Brazilian National Institute for Space Research (INPE), in an attempt to avoid interpolation whenever possible.

During the development of this study, two perspectives were considered: that of the dweller – so as to suit the social purpose of the proposed BIPV project – and that of the government – in order to ascertain its feasibility. The indicators used to evaluate this project's feasibility were chosen based on the most common project management practices

Table 1
Summary of scenarios. Sources: SWERA (2016) and SIGEL (2016).

		Consumption scenario groups		
		1	2	3
		150 kW h/month (no intended grid feedback)	150 kW h/month +25% potential grid feedback	150 kW h/month +50% potential grid feedback
Solar irradiation zones	SOUTH (S) 5.23 kW h/m^2 d^{-1}	S-1	S-2	S-3
	SOUTHEAST (SE) 5.68 kW h/m^2 d^{-1}	SE-1	SE-2	SE-3
	NORTHEAST (NE) 5.50 kW h/m^2 d^{-1}	NE-1	NE-2	NE-3
	MIDWEST (MW) 5.42 kW h/m^2 d^{-1}	MW-1	MW-2	MW-3
	NORTH (N) 5.53 kW h/m^2 d^{-1}	N-1	N-2	N-3

and on their representative applicability to the variables involved: Net Present Value (NPV), Internal Return Rate (IRR), Payback Period and Cash Flow (Brito, 2004; Rocha, 2009).

Considering that Brazilian economy tends to fluctuate, a sensitivity analysis methodology known as One-Factor-at-a-Time (OFAT) was used at all times in an attempt to safeguard the project's results against economic variability. The authors acknowledge that during the time it took for this study to be fully developed, Brazil may have gone through changes in its economic reality but, in any case, it is important to note that however capable of numerically altering the results, these economic changes would do so by affecting variables (e.g. U.S. Dollar exchange rates, Annual Economic Inflation, electricity prices per kW h for residential consumers) that interact proportionally to one another when calculating cash flows and overall project costs, thus keeping mostly unaltered the discussions presented later in the paper with regard to solar energy exploitation potential.

To analyze and compare the scenarios shown in Table 1, the data presented thus far was used to create pessimistic, realistic and optimistic cash flows for each scenario. As is most usual in feasibility analyses (Brito, 2004; Rocha, 2009), sourcing- and operation-related variables such as Residential Electricity Demand Growth, Photovoltaic Solutions' Cost Reduction and Annual Panel Degradation Rate were directly and cumulatively applied to the deployment/investment costs of each region's cash flow throughout the years.

The consequent cash flows and the Annual Economic Inflation, on the other hand, composed the economic comparison made by using the equations and the variables summarized in Table 2.

It is important to note that (a) all currencies were converted into U.S. dollars at an exchange rate of R$2.025, and that (b) the quantities of panels necessary for the houses on each geopolitical region were rounded to the closest unit numbers according to the surface area necessary for electricity generation as well as to encompass monthly and seasonal variations for each specific GHI. Table 3 summarizes the costs involved, based on the average prices for bulk acquisitions from three nationwide retailers.

3. Results and discussions

The results from the proposed BIPV project throughout 30 years of simulated operation are shown in Fig. 2, in which the green[1] curves represent the estimated consumption growth patterns and the blue layers the potential energy generation of each solar panel arrangement. Fig. 2 is a multi-variant pivot chart and its baseline derives from the results of the realistic approach of the sensitivity analysis, also encompassing:

- The sensitivity analysis' range between the optimistic results (bottom end) and the pessimistic results (top end) within each of the estimated consumption growth patterns (green curves); and
- The seasonal generation variations, from highest annual generation potential (top end) to lowest annual generation potential (bottom end), within each of the potential energy generation of each solar panel arrangement (blue layers).

Through the years, as consumption grows and solar panels' generation slightly decays, a wider gap is formed between electricity supply and demand. This is clearly depicted in Fig. 2, however, different solar panel arrangements and different consumption patterns create substantially different exploitation potentials.

Fig. 2 also depicts the tendency that scenario groups 2 and 3 have to directly affect the demand by generating additional electricity to supply the projected growth without encumbering the grid (less steep slope angles). This becomes even more noticeable in the long-term, when houses without grid feedback potential (scenario group 1) do not have their demand growth suppressed by readily available generation and soon overcome the generation capacity of their solar panel array (year 12), unlike houses in scenario group 2 (year 17) and scenario group 3 (year 24), which rely on solar energy for much longer.

In Fig. 2, it is also possible to notice overlaps among the energy generation results of each solar panel arrangement. The most prominent overlap occurs between 6 and 7 panels' arrangements, pointing to a more homogeneous operation through 30 years' seasonal variations in scenario group 3, in comparison to scenario groups 1 and 2.

When analyzing the results from the dweller's perspective (Table 4) alongside Fig. 2, the most efficient amount of panels to deploy should be that which provides the most kW h per dollar increased in the installments. In other words, it would be to associate the lowest installment increase with the highest electricity generation possible, especially if FIT credits can be of use. However, keeping in mind that the government has to compromise cash flow to enable this, a balance should be found between the dweller's perspective and the project's economic feasibility so as to ensure its long-term financial and operational sustainability.

As seen in Table 4, the minimum amount of panels that covers the average consumption of 150 kW h/month during an entire year is depicted in scenario group 1. In this group, electricity was only fed back to the grid when generation was above the 150 kW h consumption average, making potential additional feedback, however possible, merely proportional to the saving behavior of each dweller. Scenario groups 2 and 3 are those that targeted 25% and 50% grid feedback, respectively, beyond supplying the

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

Table 2
Summary of OFAT sensitivity analysis variables and equations.

Variable	Pessimistic (%)	Realistic (%)	Optimistic (%)	Sources
Residential electricity demand growth	5.2	4.2	3.2	MME (2012, 2015)
Photovoltaic solutions' cost reduction	3.3	4.9	6.5	ANEEL (2014)
Annual economic inflation	7.0	6.0	5.0	EPE (2013, 2014)
Annual panel degradation rate	0.5	0.4	0.3	Energia Pura (2014)
				Neosolar (2014)
				Energy Team Brasil (2014)

Equations	Components
$\mathrm{NPV} = \sum_{n=0}^{N} C_n : \ (1+r)^n = 0$	N = project duration (years)
$\mathrm{IRR} = r_a + [\mathrm{NPV}_a : (\mathrm{NPV}_a - \mathrm{NPV}_b)] \cdot (r_b - r_a)$	r = discount rate (inflation)
	n = year of the cash flow
	C = net cash flow
	a = at the lower discount rate
	b = at the higher discount rate

Table 3
Average costs for solar equipment acquisition and total house construction cost. Sources: Neosolar (2014), Energy Team Brasil (2014), Energia Pura (2014).

Item description	Cost (US$)	Amount of panels			
		4	5	6	7
217 W 1.5 × 1 m panel	383.68 (per panel)	1534.72	1918.40	2302.08	2685.76
2 kW inverter + net meter	1675.74 (per house)	1675.74	1675.74	1675.74	1675.74
Labor costs	46.83 (per panel)	187.32	234.15	280.98	327.81
Electric wiring costs	296.43 (per house)	296.43	296.43	296.43	296.43
Construction costs	19360.00 (per house)	19360.00	19360.00	19360.00	19360.00
Total		23054.21	23484.72	23915.23	24345.74
PV in total cost		16.02%	17.56%	19.05%	20.48%

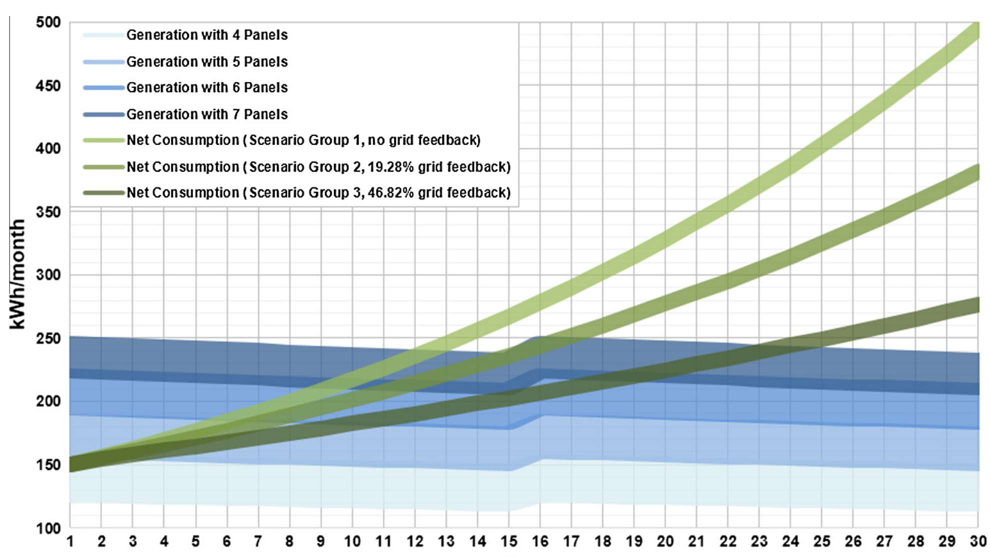

Fig. 2. Energy consumption patterns and electricity generation during 30 years.

average consumption. Both of these groups' feedbacks can also be enhanced if the dwellers reduce their monthly electricity consumption.

Even in the least favorable scenarios (scenario groups 1 and 2) and under the least favorable seasonal conditions (winter and autumn), at least 83.5% of the energy demand of the housing unit can be supplied by the solar panels. This means that, even after paying a proportionally increased monthly installment, the dwellers will still save money as their electricity bills decrease substantially.

In all scenarios, deploying more panels in regions with better irradiation would generate even more electricity that could be fed back to the grid, however, deployment costs and monthly installments would also increase accordingly, to the disadvantage of the dweller. This configures a break-even point: when the installment increase surpasses the value of the electricity bill, nullifying potential savings for the dweller. If FIT credits were to be made available for the dweller, this break-even point would be higher, enabling more panels to be deployed and more electricity to be generated, however, at the expense of the government's cash flow.

As stated in the methodology and considered for the calculations, the most common financing plans that the Brazilian government offers to underprivileged consumers who wish to acquire a house by means of a social program lasts 30 years. Therefore, the BIPV project represents a monthly increase per panel in the financing plan's installment that ranges from US$ 1.81 (optimistic) to US$ 4.44 (pessimistic), an average of US$ 3.04 per panel in scenario group 1, US$ 3.34 per panel in scenario group 2 and US$ 3.40 per panel in scenario group 3.

From the government's perspective (Table 5), nevertheless, more variables need to be taken into consideration: the best amount of panels to deploy would be that which least affects the cash flow while simultaneously ensuring (a) energy generation capable of meeting growth in demand, (b) reduced cost per kW h when compared to the current cost, and (c) the shortest possible payback time so as to avoid excessive reinvestment and maintenance withdrawals.

Despite an overall investment that varies between 270 and 345 million dollars for over 73 thousand housing units, all of the scenarios present results that could stimulate the Brazilian government to reconsider how to manage and stimulate changes in the country's energy matrix. This analysis derives from the fact that, in every scenario, (a) IRRs are higher than the projected economy inflation rate, (b) NPVs are positive and exceed the negative cash flows, (c) payback time is lower than half of the solar panels' lifespan, and (d) the cost per kW h can be reduced from US$ 0.16 to an average of US$ 0.04.

From the dweller's perspective, household cash flow regarding electricity would be positive for all scenario groups because, even when having to pay increased installments, the electricity bill is significantly cheaper. Even better household cash flow would be possible if FIT credits were made available. From the government's perspective, on the other hand, project cash flow for all scenario groups would be negative because the revenues from the increased installments would not configure a profit, but the capital to repay the necessary investments. Additionally, by deploying solar panels, the government no longer receives the amount formerly paid by dwellers as electricity bills and could also, if so it chooses, give FIT credit back to the dweller, which would configure another cash outflow.

As previously discussed, the dweller eventually faces a break-even point regarding the amount of panels to deploy, but the same statement is not true from the government's perspective. Considering that the results showed that it can be approximately 75% cheaper (from US$ 0.16 to US $ 0.04 on average) to produce electric energy using photovoltaics, the more panels deployed, the better for the government; even if at the expense of its cash flow, and especially if no FIT credits are given to the dweller. In other words, the increased installments would subside/repay the investments while grid feedback and FIT would compensate the dweller, creating a win–win situation as long as a balance between both perspectives is found.

By jointly analyzing Fig. 2 and Tables 4 and 5, the amount of panels per house that would create this win–win balance, regardless of seasonal variations, are those in scenario group 3, which also presents the highest grid feedback potential. Deploying panels in such a way is, in comparison to the other alternatives and regardless of FIT, the option which (a) generates the most grid feedback, (b) has the lowest payback times, (c) presents the highest IRRs, (d) has the best NPV to cash flow relation, and (e) lays in the frontier of the dweller's break-even point. Furthermore, in scenario group 3, the average annual cash withdrawal per house nearly matches that of scenario group 2, which supports the fact that despite higher investments (economic point of view) it is proportionally cheaper to maintain (financial point of view).

In this sense, the government would only be redirecting the costs of generation from its current grid (operating at US$ 0.16/kW h) to the deployed solar panels (operating at either US$ 0.0492/kW $h_{withFIT}$ or US$ 0.0453/kW $h_{withoutFIT}$). Simultaneously, dwellers would not pay an electricity bill and could still have FIT credits even under unfavorable seasons.

In scenario group 3, as seen in Fig. 2, grid feedback can be sustained for up to 24 years. As energy consumption grows beyond this point, feedback would gradually decrease. Nevertheless, this scenario group would still be able to provide year-long feedback to the grid until the 30th year, although unfavorable seasons such as winter would begin to hinder its ability to fully meet the potential 46.28%.

Scenario group 1, despite providing the dwellers with more substantial savings, would only be operationally applicable up to 12 years, since after this point the energy generated would not cover the projected growth in demand, especially for houses located in regions where solar radiation is below 4.5 kW h/m^2 d^{-1}. Scenario group 2, despite being able to fully supply the energy demands of a house up to 17 years while generating up to 19.28% grid feedback, is the most financially costly option, generating a proportionally worse cash flow than scenario group 3.

Mixing and matching the results and their analysis in an attempt to improve on the potentials further subsided the proposed solar panel arrangements, especially scenario

Table 4
Summary of inputs and results from the dweller's perspective for a single house in each scenario (realistic baseline).

Scenario	Average GHI (kW h/m^2 d^{-1})	Panels[a]	Panel cost (US$)	Average monthly generation year 1 (kW h)	Potential grid feedback		Monthly electricity bill (US$)	Monthly FIT credit[b] (US$)	Monthly installment increase (US$)	Net monthly savings[c] (US$)
					Target	Actual				
S-1	5.23	5	4124.72	164.71	0%	9.79%	0 (−100.00%)	0.59	11.68	12.32 (−51.32%)
SE-1	5.68	4	3694.21	142.96		−4.71%	1.12 (−95.34%)	0.00	12.88	11.12 (−46.34%)
NE-1	5.50	4	3694.21	138.63		−7.57%	1.82 (−92.40%)	0.00	12.88	11.12 (−46.34%)
MW-1	5.42	4	3694.21	136.61		−8.91%	2.15 (−91.06%)	0.00	12.88	11.12 (−46.34%)
N-1	5.53	4	3694.21	139.39		−7.07%	1.70 (−92.90%)	0.00	12.88	11.12 (−46.34%)
S-2	5.23	6	4555.23	197.65	25%	24.09%	0 (−100.00%)	1.91	16.27	7.73 (−32.20%)
SE-2	5.68	5	4124.72	178.71		16.05%	0 (−100.00%)	1.15	17.47	6.53 (−27.22%)
NE-2	5.50	5	4124.72	173.28		13.45%	0 (−100.00%)	0.93	17.47	6.53 (−27.22%)
MW-2	5.42	5	4124.72	170.77		12.17%	0 (−100.00%)	0.83	17.47	6.53 (−27.22%)
N-2	5.53	5	4124.72	174.23		13.92%	0 (−100.00%)	0.97	17.47	6.53 (−27.22%)
S-3	5.23	7	4985.75	230.60	50%	34.92%	0 (−100.00%)	3.23	20.86	3.14 (−13.08%)
SE-3	5.68	6	4555.23	214.47		30.02%	0 (−100.00%)	2.58	22.06	1.94 (−8.09%)
NE-3	5.50	6	4555.23	207.93		27.88%	0 (−100.00%)	2.32	22.06	1.94 (−8.09%)
MW-3	5.42	7	4985.75	239.05		37.27%	0 (−100.00%)	3.56	20.86	3.14 (−13.08%)
N-3	5.53	6	4555.23	209.07		28.27%	0 (−100.00%)	2.36	22.06	1.94 (−8.09%)

[a] The values in this column directly reflect the quantity of panels necessary to supply each scenario's electricity demand and grid feedback (when applicable). These values can change from one scenario to another as a consequence of different GHI per region, seasonal variations and the need to conciliate the dwellers' (most electricity generated per US$ in installment increase) and the government's (project's economic feasibility) perspective. The less panels deployed, the more homogeneous the operation.

[b] If FIT credits were to be used as cross-discount on another bill or tax, these values would add to the Net Monthly Savings (last column), representing an additional non-withdrawal from the dweller's perspective.

[c] Considers the Monthly Electricity Bill and the Monthly Installment Increase. Represents how much less money the dweller would spend every month if the photovoltaic panels were deployed onto his/her house's roof. Even with less favorable GHIs and less homogeneous operations, scenarios in which more panels were deployed can result in better savings: during spring and summer the additional panels overcompensate the lower generation from winter and autumn.

Table 5
Summary of results from the government's perspective for deploying solar panels onto the 73,762 housing units planned for 2016, respective to their locations and solar irradiations (realistic baseline ± optimistic/pessimistic range).

Scenario group	1		2		3	
	With FIT	Without FIT	With FIT	Without FIT	With FIT	Without FIT
Average cost per kW h[a] (US$)	0.0372 ± 0.0003	0.0371 ± 0.0003	0.0420 ± 0.0005	0.0413 ± 0.0004	0.0492 ± 0.0014	0.0453 ± 0.008
Average NPV[a] (10^6 US$)	61.66 ± 1.65	61.65 ± 1.65	84.47 ± 2.25	84.02 ± 2.13	108.44 ± 3.26	105.86 ± 2.60
Average annual cash flow[a] (10^6 US$)	−7.78 ± 2.83	−7.77 ± 2.83	−9.29 ± 3.63	−9.20 ± 3.65	−9.52 ± 3.23	−8.88 ± 3.41
Maintenance and reinvestment costs in cash flow[a,b]	15.47% ± 5.32%	15.48% ± 5.32%	21.76% ± 5.58%	22.25% ± 5.61%	31.38% ± 4.65%	36.07% ± 4.76%
Average annual cash withdrawal per house[a,c] (US$)	105.42 ± 38.40	105.40 ± 38.40	125.91 ± 49.19	124.68 ± 49.53	129.02 ± 43.81	120.42 ± 46.17
Average IRR[a]	12.27% ± 0.97%	12.27% ± 0.97%	13.52% ± 0.95%	13.44% ± 0.99%	14.51% ± 0.92%	14.16% ± 1.06%
Average payback[a] (years)	10.00 ± 0.12	10.01 ± 0.12	9.09 ± 0.09	9.18 ± 0.09	8.35 ± 0.8	8.67 ± 0.8
Average annual generation (GW h)[d]	122.47 ± 0.87		152.31 ± 1.07		184.98 ± 1.31	
Average available grid feedback[d]	0.00%		Up to 19.28%		Up to 46.82%	
Total initial investment (10^6 US$)	274.48		306.24		340.81	

[a] Results depict the realistic OFAT sensitivity analysis, including the difference (±) to the pessimistic and optimistic results. Calculations consider 30 years of operation and comply with criteria and parameters set by specific legislation (ANEEL, 2004, 2012a,b,c).
[b] Represents the amount of maintenance and reinvestment costs that configure a cash outflow after the working capital trust fund has been redeemed.
[c] Represents the overall amount of money spent by the government annually to enable 30 years of photovoltaic operation for each of the houses in the program.
[d] Considering monthly and seasonal variations.

group 3. Deploying fewer panels in an attempt to provide more savings for the dweller, however ideal, poses as just as a great a barrier from the government's perspective as deploying excessive panels would pose for the dweller.

When trying to optimize the results achieved in scenario group 3 by using what was learned from scenario groups 1 and 2, it was noticed that the electricity generation's standard deviation within the project would decrease – signaling a potentially more homogeneous operation. However, the resulting cash flows of these attempts were worse than the original cash flow in scenario group 3. Furthermore, those attempts were incapable of coping with future maintenance and reinvestment needs, as well as projected consumption growth.

To safeguard both dweller and the government from future reinvestment and maintenance costs during the project's operation, it was suggested investing the cash inflows until the end of year 15 in a working capital trust fund. From the results, by year 16, this fund would cover at least 60% of the necessary costs, depending on the chosen scenario. The remainder of the necessary amount, seen in Table 5, would then be amortized from cash inflows from years 16 to 30, improving financial sustainability of the project in comparison to its first half. This amortization could be done in ways to suit three different purposes, depending on the government's intention after reinvesting on year 16, namely (a) reduce the installments for the dwellers until the year 30, (b) recompose the project's cash flow, or (c) start a new working capital trust fund for a future project.

Associating social housing with a program for clean energy deployment is one way to improve the existing PRODEEM and TSEE policies or even create a new one, and, albeit costly, can provide significant social and environmental benefits to at least 300 thousand underprivileged Brazilian citizens for at least 30 years.

As seen in Table 5, NPVs, IRRs and payback times are even better when FIT credits are made available to the dwellers. This happens because the additional electricity is given a value to face its generation cost. Otherwise, it would be given back to the government for free and the respective amount in credit would no longer be redeemable after 36 months – which is what currently occurs according to ANEEL legislation in force.

Based on the improvements seen in the results depicted in Tables 4 and 5 when adopting FIT discounts, the creation of FIT principles for a nationwide policy based on a 30-year outlook is recommended. Keeping ANEEL's Resolutions N°77/2004 and 482/2012 in mind, objectivity, practicality and consumer-level cost-effectiveness were taken into account so as to avoid overly complex processes that could create entrepreneurial insecurity or excessive bureaucracy:

(a) *Discounts on electricity bill (partially in force today;* ANEEL, 2004, 2012a,b,c): Consumers capable of micro- or mini-generation that feed electricity back to the grid should receive a proportional and direct discount on the next electricity bill, based on the 150 kW h average, regardless of seasonal productivity variations.

(b) *FIT credits (not in force today):* Discounts that exceed 100% of the next electricity bill should configure FIT credits at a rate of 4:1 (25%, average between existing FIT in European countries; EEP, 2014), used to discount future electricity bills in which 100% compensation is not achieved, up to 36 months from its creation. FIT credits should at no time configure currency, bond or asset and are subject to ANEEL's regulatory jurisdiction.

(c) *Home Ownership Tax cross-discount (not in force today):* Every year, if an underprivileged residential customer has surplus FIT credits, he/she should be allowed to cross-discount that amount to the Home Ownership Tax (known as IPTU in Brazil, which nowadays costs US$ 66.93 annually for low-income home owners) up to 100% of its value.

(d) *Unused FIT credits (not in force today):* FIT credits that eventually exceed 100% of the IPTU can be cross-discounted in other fees or taxes to be determined by the government in the future or be kept as credit for the next 36 months from its creation, following the order of use in items (b) and (c).

An additional result of the proposed BIPV project would be the increase of participation of solar energy in the Brazilian energy matrix from 0.01% to 0.09% (scenario group 1), 0.11% (scenario group 2) or 0.13% (scenario group 3). By expanding the proposed BIPV project onto the rooftops of over 9 million houses built by similar programs in Brazil since 1964, solar participation in the Brazilian energy matrix would be able to reach the percentages that exist in countries such as Germany, for example.

Finally, in addition to presenting itself as a financially and environmentally friendly system, the proposed BIPV can also help municipal and state governments reduce the need for energy transmission infrastructure. In Brazil, most electricity transmission lines are made of copper and aluminum, both metals that lose significant amounts of energy due to cable heating (Leite, 2007), and which enables easy recycling when they are no longer needed. By deploying solar panels on low-income housing, energy transmission demands are substantially lowered by energy feedback to the local grid. The consequent decentralization can also reduce the need for overall long-range system management investments and maintenance costs. Furthermore, energy not consumed by these houses can be made available to regions where peak consumption hours are more demanding.

4. Conclusions and recommendations

Despite its continental area and solar incidence deemed good for photovoltaic electricity generation, the Brazilian energy matrix takes little to no advantage of its potential for solar alternatives. In order to take advantage of this energy source, this paper shows that the deployment of 217 W photovoltaic panels would vary between 4 and 7 per house, nationwide, in order to provide economic feasibility and energy generation results that could directly address the energy crisis.

Deploying solar panels onto the roofs of the 73,762 low-income housing units planned for 2016 would contribute to energetic autonomy, reduce grid electricity consumption and dependency, as well as help change the cultural perception towards renewable energy alternatives by affecting the lives of at least 300 thousand people at an average cost of US$ 0.04 per kW h.

Greater results could be achieved if governmental policies were created towards further deploying solar panels onto the roofs of the over 9 million houses built since 1964, as well as to boost investment incentives, technological research and development stimuli, renewable energy education and operational standards for building-integrated photovoltaics. To that end, the authors also suggested four principles on which to base the creation of a FIT credit system.

In order to broaden the scope and reach more customers and energy efficiency projects, BIPV deployment in industrial locations – which are major stakeholders in energy consumption – as well as on residential buildings – which predominate in Brazilian urban areas – is strongly recommended.

The lack of field data currently limits the scenario analyses to the 113 collection and measurement points available, but aims to create an incentive for future studies and projects that discuss and subsidize policy development in Brazil. For more precise calculations, a case-by-case approach for each social housing program's location would be preferable.

Furthermore, the creation of a national database that encompasses the relations between (a) seasonal consumption patterns, (b) seasonal radiation variations, (c) solar energy exploitation capabilities, and (d) energy transmission capacities could also help to further substantiate specific solar energy deployment projects and academic initiatives.

Finally, the implementation of pilot projects is recommended, preferably alongside government representatives, in order to identify further positive and negative aspects as well as ascertain the sustainability of deploying the suggested BIPV project and the recommended FIT principles.

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