Solar smart grid as a path to economic inclusion and adaptation to climate change in the Brazilian Semiarid Northeast

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Abstract

Purpose – This study aims to exploit the abundance of solar energy resources for socioeconomic development in the semi -arid Northeastern Brazil as a potent adaptation tool to global climate change. It points out a set of conjuncture factors that allow us to foresee a new paradigm of sustainable development for the region by transforming the sun's radiant energy into electricity through distributed photovoltaic generation. The new paradigm, as presented in this essay, has the transformative potential to free the region from past regional development dogma, which was dependent on the scarce water resource, and the marginal and predatory use of its Caatinga Biome.

Design/methodology/approach – The research uses a *pre ante* design, following the procedures of scenario building, as an adaptation mechanism to climate change in the sector of energy generation and socioeconomic inclusion.

Findings – The scenarios of socioeconomic resilience to climate change based on the abundance of solar radiation, rather than the scarcity of water, demonstrates its potential as a global adaptation paradigm to climate change.

Research limitations/implications – The developments proposed are dependent on federal legislation changes, allowing the small producer to be remunerated by the energy produced.

Erratum: It has come to the attention of the publisher that the article, Paulo Nobre, Enio Bueno Pereira, Francinete Francis Lacerda, Marcel Bursztyn, Eduardo Amaral Haddad and Debora Ley, "Solar smart grid as a path to economic inclusion and adaptation to climate change in the Brazilian Semiarid Northeast" published online in *International Journal of Climate Change Strategies and Management*, had some mislabeled and incorrectly cited figures. This error was introduced in the editorial process and has now been corrected in the online version. The publisher sincerely apologises for this error and for any inconvenience caused.

Practical implications – The proposed smart grid photovoltaic generation program increases the country's resiliency to the effect of droughts and climate change.

Social implications – As proposed, the program allows for the reversion of a pattern of long term poverty in semi-arid Northeast Brazil.

Originality/value – The exploitation of the characteristics of abundance of the semiarid climate, i.e. its very condition of semi-aridity with abundant solar radiation, is itself an advantage factor toward adaption to unforeseen drought events. Extensive previous research has focused on weighting and monitoring drought i.e. the paradigm of scarcity. The interplay between exploiting Northeast Brazil's abundant factors and climate change adaptation, especially at the small farmer levels constitutes a discovery never before contemplated.

Keywords Socioeconomic development, Climate change adaptation, Distributed photovoltaic generation, Semiarid Northeast Brazil

Paper type Conceptual paper

1. Introduction

Historically, the development of agricultural economies is ubiquitously associated with fertile soils, abundant water resources and high solar radiation. In such economies, semi-arid regions are commonly plagued with endemic poverty unless large amounts of capital are invested in technology and irrigation systems, such as in California and Israel. In Northeastern Brazil (hereinafter, referred to as NEB; see Figure 1), its poverty-stricken semi-arid region presents typical characteristics of abundant solar radiation and water scarcity, accompanied by recurrent droughts (Hastenrath and Heller, 1977; Serra, 1946), increasing temperature and reducing rainfall trends (Lacerda *et al.*, 2015).

Throughout the twentieth century, governmental programs "combating the effects of drought" contributed very little to securing agro-pastoral subsistence systems small farmers in the NEB (Bursztyn, 1984). With the relatively recent exponential growth of photovoltaic (PV) conversion worldwide and the price of the solar kilowatt hour (kWh) falling rapidly behind that of thermal and hydroelectric generation in several countries, including Brazil, solar PV transformation rises as a very attractive alternative for solar-rich areas in the world in general, and in the NEB in particular, to promote a new developmental paradigm based on its most abundant resource: the sun. Additionally, the fast growing changes on local hydrological cycles associated with global climate change have placed otherwise productive agricultural regions under stress. Orsato *et al.* (2017) shows that in terms of organizations, the required learning to adapt to climate change differs from traditional learning methods.

This article details the concept of exploiting the potential for distributed PV generation in the NEB, associated with local production of food in its drought resilient Caatinga Biome as a developmental and socioeconomic inclusion mechanism. It constitutes an unprecedented alternative to time-proven failed policies rooted on water availability for small-scale farming.

Section 2 covers the background and a brief literature review. Section 3 presents methodology and data. Results and discussion are presented in Section 4. Policy implications and conclusions are summarized in Section 5.

2. Background and literature review

The drought, as a scourge, has been a strong reference of the identity of the NEB, perpetuated in literature, culture and politics (Ribeiro, 1999). Droughts in the NEB became the object of the systematic action of the government after the great drought that hit the region between 1877 and 1879. Since then, regional policies undertaken by the Federal Government have focused to a great extent on seeking the provision of water, its most scarce resource.

Figure 1.
Map of the semi-arid
portion of the *NEB* (in
yellow) and the São
Francisco River (in
dark blue)

Conversely, the NEB abundant solar radiation and its drought-resistant biome, the Caatinga, were not perceived for their great comparative advantage, relative to its sibling regions in the country in which rainfall is plenty and forests are abundant.

The NEB is characterized with a high evapotranspiration potential due to the abundant incidence of solar radiation and high temperatures. In addition, the high inter-annual rainfall variability and the prediction of future rainfall reduction due to both global climate change and local changes in vegetation cover, make water increasingly scarce over this entire semi-arid region (Lacerda *et al.*, 2015). Most of the global climate models used in the preparation of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) and the Special Report on 1.5 C increase (IPCC SR1.5C) predict the increase in water deficit and the expansion of drier areas in the NEB until the second half of the twenty-first century (IPCC, 2013, 2018). This means potential reductions of 15-20 per cent in the São Francisco river[1] (Figure 1) flow rates, the largest river flowing into the NEB, the reduced rainfall by up to 20 per cent by 2040, and a temperature increase of up to 1°C (Marengo *et al.*, 2011).

Persistent water crises over the NEB have exacerbated conflicts between different water use stakeholders in the region. Recent developments have shown that, in the case of the Sobradinho hydroelectric power plant on the São Francisco River, the demand for irrigation is intense, but power generation prevails as a priority, causing losses to farmers and river-siders and hampering food supply to urban agglomerations. One way of minimizing conflicts over multiple uses of

water in hydroelectricity generation, without impacting the increase of greenhouse gases, lies in the establishment of a hybrid generation matrix from renewable sources.

Solar energy has been used by civilization for millennia, initially for its thermal effect for food drying and residential heating. The first applications of solar energy for electricity production date to the beginning of the twentieth century, using a solar concentrator systems for the production of steam and electric energy (Shuman, 1916). PV transformation, i.e. the ability to convert photons into electric current, first announced in the early nineteenth century by Edmond Becquerel (1839) and opening the doors to a new form of energy generation, only became more widely used from the end of the twentieth century and the first decade of the twenty-first century on. Since then, PV conversion processes became more efficient and economically attractive.

As recently as 2017, Brazil's energy matrix consisted primarily of hydroelectric generation with 65.2 per cent generation, fossil thermoelectric with 17.1 per cent, wind with 6.8 per cent, biomass 8.2 per cent, nuclear with 2.5 per cent and solar with 0.1 per cent (EPE, 2018). Electricity is distributed nationally through the national interconnected distribution network shown in Figure 2, which, as is detailed below, constitutes a definitive differential factor in the development of the PV potential in the NEB into both an important component for the energy security of the nation and a solid element contributing to eradicate endemic poverty in the region.

One important institutional milestone encouraging distributed PV generation in Brazil was the ANEEL Normative Resolution 482/2012, which establishes the general conditions
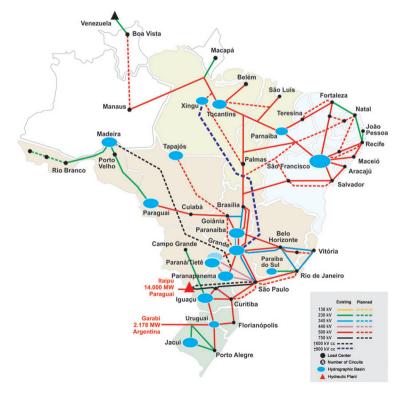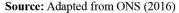

Figure 2.
Distribution of transmission lines of the National Electric System according to the legend to the right of the figure

Source: Adapted from ONS (2016)

for the access of micro generation and distributed mini-generation to electricity distribution systems. The adopted compensation model of produced/consumed electricity, net metering, allows consumers to reduce part or all of the energy they consume from the grid. While this may represent an advantage to large electricity consumers, it still has a small impact on single family household savings, with room for improvement.

There is considerable international experience from which to draw on, including that of the feed-in-tariff (Devine *et al.*, 2017) in the province of Ontario, Canada (Stokes, 2013), and other mechanisms that allow energy transactions through cooperatives and partnerships of private companies with local communities or indigenous groups. The Mexico Renewable Energy Program (MREP), co-sponsored by the US Agency for International Development and the US Department of Energy, was created with the objectives of enhancing economic and social development, creating new business opportunities and offsetting greenhouse gas emissions through the introduction of renewable energy technologies in Mexico (Hanley *et al.*, 2001).

Outside the Americas, solar photovoltaic projects, both stand-alone and grid-connected, have been successfully installed in arid and semi-arid regions. Kenya's PV market is considered one of the most successful worldwide with case studies from 1996 pointing toward the potential ahead and the numerous actors involved (Acker and Kammen, 1996; Byrne and Mbeva, 2017). In 2015, the World Bank invested in solar energy water pumping systems throughout Tanzania, providing much needed water in drought stricken areas with high solar radiation[2]. Although Middle East countries are known for their oil reserves, some countries, such as Iran and Iraq, are researching solar energy potential or in the process of completing solar and wind energy projects (Edalati *et al.*, 2017). In 2010, Saudi Arabia installed its first solar energy system of 2 MW, which has been followed by other solar energy projects (Edalati *et al.*, 2017).

In the United Kingdom in 2014, subsidies for solar farms were cut under the excuse that these were harming food production[3]. British farmers, meanwhile, claimed that the installation of PV panels increased livestock production due to the shelter offered to the animals by the solar panels. In the rotation system between agricultural and grazing purposes, the use of PV increased the income of the farm by up to three times and the revenues from the solar panels provided a continuous and sustainable income for the farmers.

These examples highlight the need to promote the capacity of legislators to incorporate changes in the current policy for the use of solar energy produced by individuals, increasing environmental sustainability. In addition, the interconnected grid system allows reducing the impact of PV production variability through the average production of the various generation sites scattered throughout the NEB region. This is owing to the fact that the multiplicity of generating centers distributed over a large area would minimize the net effect of shading.

3. Methodology and data

The methodology adopted in this work consisted of calculating the amount of PV energy that can be generated by three arbitrarily sized PV plants in the NEB:

(1) 200 m^2, equivalent to the "second water" Federal program for rainwater storage;

(2) 1,000 m^2; and

(3) 10,000 m^2 or 1 ha.

Using equation (1), we then calculate the amount of energy that can be generated by each of the idealized PV plants and use the estimates to evaluate three dimensions:

(1) the net market value of such projected annual PV energy generated (i.e. excluding transmission and taxes costs) is used to estimate possible income levels for distributed micro energy-producers in the region;

(2) the projected gross economic values (i.e. including transmission and taxes costs) of the PV energy are contrasted to traditional agricultural crop production;

(3) the potential impacts of the idealized PV plants on water security are evaluated, considering both the direct amount of rainwater that could potentially be collected by the PV panel surface, and the water management aspects of Brazil's interconnected hydroelectric generation system.

The following parameters are considered to estimate the PV generation potential in the NEB:

• annual average daily irradiance in the inclined plane (iMed) equals to 6.0 kWh/m^2/day (Pereira *et al.*, 2017);

• energy efficiency factor in the conversion (eConv) of 20 per cent with current commercially available polycrystalline silicon (p-Si) plates; and

• 70 per cent operational efficiency factor (eOper; Jahn and Nasse, 2004).

Thus, the mean electricity that can be generated per square meter of solar panels during a day in the NEB follows from equation (1):

$$PV_{pot} = iMed * eConv * eOper = 0.840\,kWh/m^2/day \qquad (1)$$

The data used for computing the temporal evolution of cumulative rainfall balance (the sequential summation of monthly rainfall anomalies relative to the 1961-1990 climatology) in the NEB presented in Section 4 are from INPE/CPTEC[4]. The model outputs used to computing future scenario of rainfall totals over the NEB, also shown in Section 4, are from the Brazilian Earth System Model – BESM (Veiga *et al.*, 2019; Nobre *et al.*, 2013) according to the radiative forcing scenario – RCP4.5[5] (Taylor *et al.*, 2012). The simulated rainfall anomalies used to compute time series for the model results are the monthly rainfall departures of BESM RCP 4.5 scenario for the period 2005-2100 from the climatological precipitation for BESM historical simulation, which used observed historical concentrations of atmospheric CO_2.
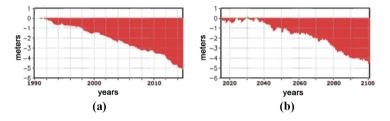
4. Results and discussion
This section explores the potentials and challenges for the implementation of the new paradigm of regional development based on the distributed generation of PV electricity, resulting in social inclusion.

4.1 Water and distributed photovoltaic generation in face of climate change
4.1.1 Growing water scarcity in the Brazilian semi-arid. To understand the social–economical structuring elements for the NEB, it is necessary to evaluate the water availability in the region and its long-term time variation. Figure 3 shows the time series of the sum of monthly rainfall anomalies (relative to the 1961-1990 climatology), averaged over the area of NEB. Of notice is the cumulative rainfall deficit for both periods: the already recorded for the past (Figure 3[a]) and the future scenario under IPCC RCP 4.5 scenario (Figure 3[b]) climate. The total cumulative deficit of 5 m^3 of water per square meter over the entire region, accumulated during the last 25 years (Figure 3[a]), and the climate change perspective of a continued process of reducing annual rainfall totals for the future

(Figure 3[b]) is noteworthy. The picture of water deficit in the region presented here is consistent with the results of Lacerda *et al.* (2015) for the semi-arid region of the state of Pernambuco, setting a resounding question-mark on development policies for the region based on this ever-scarcer element, *water*.

4.1.2 Harvesting water from PV panels: resiliency to drought. Another issue of consideration is water availability for human consumption and economic activities. We evaluate two water metrics associated with the installation of PV generation systems: rainwater collection directly from the PV panels' surface, and the volume of water that would be utilized in a single hydroelectric power plant to generate the equivalent electricity generated by the PV power plant.

For the first metric, considering total annual precipitation values ranging between 200 mm (in a very dry year, i.e. half of the expected annual rainfall of the driest portion of the semi-arid NEB) and 1,200 mm (in a very rainy year), the water harvested by the surface area of the PV panels considered in this study shall be between approximately 40-240 m^3 (for the 200 m^2 panels area, in a dry/rainy year) to 2,000-12,000 m^3 (for the 1 ha panels area, in a dry/rainy year) of rainwater per year (see Table I). Such volumes are comparable to the consumption of a family of 5 in the semi-arid (i.e. 120 m^3/year) (Andrade and Nunes, 2014), and can be used for drip irrigation of cash crop production and animal feeding. In addition to the direct capture of rainwater, the abundance of PV energy generated can be used to

Notes: (a) Observations for the period January 1991 to December 2015; (b) simulated by the BESM model for future atmospheric CO2 concentration for the RCP 4.5 scenario between 2005 and 2100. Unit: 1000 liters/m^2
Source: P. Nobre, for this study

Figure 3.
Summation of monthly anomalies of mean precipitation for the *NEB* from January 1991

Table I.
Estimate of water collected and equivalent of water used in hydropower for energy generation, by each PV installation area in the NEB, of 200 m^2, 1000 m^2 and 10,000 m^2, as in Table II

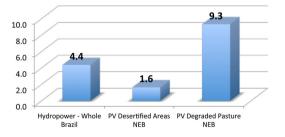|			
Area of PV panels (ha)	0.02	0.10	1.00
Rainfall water stored (m^3/year)	40-240	400-1,200	4,000-12,000
Equivalent water volume used in a hydroelectric power plant (10^9 m^3/year)	2.4	12.0	120.0

desalinate water from salinized wells (Fernandes, 2013). This is the case of the *Água Doce* Program[6] of the Ministry of the Environment (MMA), which in 2015 implemented the first desalination system powered by PV energy in the state of Rio Grande do Norte.

For the second metric, we calculate the volume of water used in hydroelectric generation to produce the equivalent amount of energy from PV production per unit area. Considering the average volume of 1.8 m^3/s/MW of water consumed in large hydroelectric plants[7] in Brazil (ANEEL, 2008), the volume of water used for the generation of the electricity generated by one hectare of PV panels during a year is approximately 120×10^9 m^3 (see Table I).

Thus, the generation of energy using PV technology presents itself as an excellent option as a way of complementing hydroelectric generation in Brazil. Such hybrid PV–hydroelectric production favors the management of reservoirs, especially during periods of lower rainfall, allowing the use of this water for other purposes, such as agriculture or water supply to households. They can also contribute towards the management of the electric power concessionaires, for example, through the postponement of investments in new power plants for energy generation.

To frame the potential of PV as a structuring energy source in Brazil's electric grid, it is useful to compare the potentials of electric energy generated by PV (considering the present day commercially available PV panels) and hydroelectricity, in the extreme cases in which degraded areas in the NEB were utilized for PV generation, and all hydroelectric potential in Brazil were explored. Such comparison is shown in Figure 4, which depicts energy generation potentials normalized by the amount of electricity actually consumed in Brazil during 2017 (i.e. 0.526 PWh/year; EPE, 2018). The PV potential of degraded pasture areas alone (i.e. 1,600,000 ha; source: IBGE, 2006) amounts to 4.90 PWh/year, which corresponds to approximately 9.3 times the national consumption of electricity during 2017. The PV equivalent for degraded areas sums another 1.6 times the national consumption. However, the national hydroelectric potential of 2.3 PWh/year (EPE, 2018), i.e. if all current and future hydroelectric potential in the main river basins in the country were realized, represents 4.4 times 2017's national annual consumption of electricity.

In addition to the estimates shown in Figure 4, it is important to notice that approximately half of the country's hydroelectric potential has already been exploited over the Tietê-Parana river basin, with the remaining hydroelectric generation potential lying

Figure 4.
Comparative histogram of national consumption of electric energy

Notes: PV generation potentials on desertified areas and degraded planted pastures in the semi-arid portion of the *NEB* and Brazil's hydropower potential. All above normalized by the national consumption of electricity in 2017 – 526 TWh
Source: EPE (2018)

over river basins in Amazonia. Such hypothetical exploitation of Amazon Rivers for hydroelectricity, however, would implicate tremendous deleterious consequences in loss of biodiversity and methane generation, with additional severe climatic implications (Fearnside, 2016).
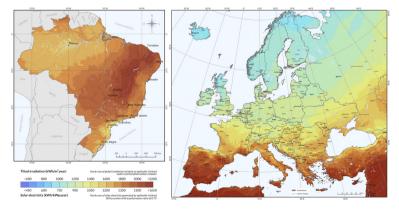
4.2 Opportunities and challenges for the distributed PV generation in the NEB
Despite being a country with continental dimensions and different climatic characteristics throughout its territory, Brazil presents ideal conditions for the use of solar energy. The annual average levels of global solar irradiation shown in Figure 5(a) range between 1,500 and 2,500 kWh/m^2 (Pereira *et al.*, 2017). Such values are around twice as those found in European countries that already make great use of solar resources, such as Germany, whose global annual solar irradiance values range from 900 to 1,250 kWh/m^2 (Figure 5[b]).

In addition, solar irradiance in the NEB has the advantage of being relatively uniform. The combined energy produced by only a few dozen stations, randomly distributed across the territory, reaches the definition of firm energy, i.e. energy that notwithstanding being intermittent can be dispatched during the period of solar incidence (see Figure 6).

In addition to its high PV potential, the intrinsic discontinuous characteristic of the degraded areas constitutes an excellent opportunity for the implementation of distributed PV micro power plants, without any conflict with food production or the disruption of natural ecosystems. The land characteristics allow for the installation of PV panels on the terrain cutouts, unlike either hydroelectric dams or large concentrated solar plants (CSP), which require large contiguous areas. The distribution of hundreds and thousands of micro-generation plants also count with a distinct advantage to mega-plants, including the greater potential for local employment for operation and maintenance and distributed generation to areas hard to reach by the national grid.

4.2.1 PV cost and intermittency barriers. A historical barrier to the deployment of massive distributed PV systems in the world (with Germany constituting an exception) in general, and in Brazil in particular, has been its high cost. While in 1977 the cost of PV panels was about US\$76.00 per watt, by 2015 it had already dropped to mere \$0.30, as

Figure 5.
Yearly sum of global irradiation incident on optimally inclined PV modules (unit: kWh/m^2.year) in (a) Brazil (Source: Pereira *et al.* [2017]) and (b) Europe (Source: PVGIS [2012])

Note: Also shown the equivalent yearly sum of solar electricity generated by optimally inclined 1kWp system with a performance ratio of 0.75 (unit: kWh/kWp.year)
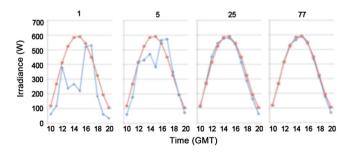
reported by Bloomberg New Energy Finance (Lemaire, 2015). The price of PV-generated electricity contracted by the National Electricity Authority (ANEEL) in Brazil in its April 2018 Generation Auction A-4/2018[8] was lower than those of both hydroelectricity and thermal biomass, with PV at Brazil's R$0.118 (US$0.0358)/kWh, while hydroelectricity and thermal biomass were priced above R$0.198 (US$0.0604)/kWh. The sharp reduction of PV generation costs in Brazil in recent years resulted from a number of factors, not only by the price drop for the PV panels in the international market, but also the systematic reductions in Brazil's Central Bank basic interest rate – SELIC (from 14 to 6.5 per cent during the last couple of years), lowering financing costs.

We use the information from Instituto Ideal (IDEAL, 2015) of US$2.67/Wp to calculate the costs of the PV system shown in Table II. Again at conceptual levels, using the residual between the average marketed energy value (i.e. US$0.071/kWh) and the value paid to the producer for the PV plant sizes in Table II, the payoff time for the initial investments, considering current interest rates of 4 per cent per year practiced by official Banks in Brazil for PV installations, would be of approximately 7 years. These represent only ballpark figures to conceptualize the real cost for adopting such measures for the generation of PV energy in the semi-arid NEB. A more rigorous project finance study would still be needed to get a sounder cost-benefit analysis.

As a measure of the economic feasibility of such PV facilities, the gross annual revenues of energy generation alone (without considering transmission costs and taxes) by the PV plants depicted in Table II correspond to 2.74 times the interest that would be earned in the financial market given the prevailing interest rate of 6.5 per cent per year.

4.2.2 The economic, social and environmental impacts. Although conservative, the numbers shown in this section should be taken with caution as they only represent a first-order approximation of the energy and economic potentials based on current technical and economic coefficients. Engineering and operational considerations for the deployment of such field possibilities require specific studies and projects not covered in this study.

We consider the area of degraded planted pasture and desertified land of the NEB, which encompass nearly 1.9 million ha (IBGE, 2006) to estimate the NEB's potential PV production. These degraded areas extend over 136,000 properties whose distribution by size is shown in Figure 7. Properties with areas ranging between 1 and 500 ha account for approximately 97 per cent of all properties considered, totaling about 130,000 properties and covering nearly 2/3 of the total degraded area (i.e. approximately 1,260,000 ha).
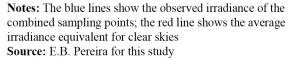

Figure 6.
Profiles of hourly mean solar irradiance for April 30, 2009 in the Northeast Region, for a set of 1, 5, 25 and 77 stations (respectively from left to right) taken at random
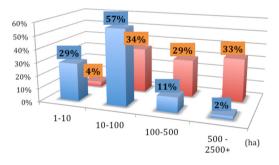
Notes: The blue lines show the observed irradiance of the combined sampling points; the red line shows the average irradiance equivalent for clear skies
Source: E.B. Pereira for this study

Based on the large availability of degraded land area suited for distributed PV generation in the NEB, we estimate the potential revenues from the PV plants under two sets of assumptions:

(1) the passive scenario, delivering the whole of the PV generated electricity to the grid in return of royalties; and

(2) the active scenario, using the PV electricity for further economic in-house activity, computing, in this case, both the avoided payment for the energy generated and the possible revenue emerging from self-sustained food production cells.

Area of PV panels (ha)	0.02	0.10	1.00
Annual PV energy production (MWh year)	61.32	306.60	3,066.00
Gross annual energy revenue [@US$0,0714/KWh] (US$/year)	4,380.00	21,900.00	219,000.00
Solar Royalties (US$/KWh)	0.01	0.005	0.0025
Annual solar income (US$/year)	613.20	1,533.00	7,655.00
Monthly solar income (US$/month)	51.10	127.75	638.75
PV system cost (US$)	24,571.00	122,857.00	1,228,571.00
Amortization rate (US$/KWh)	0.061	0.066	0.069
Payoff time (years)	7	6	6
SELIC [@6.5% per year] (US$)	1,597.14	7,985.71	79,857.14

Table II.
Scenarios of distributed PV energy in the NEB, for average solar irradiance values of $6.0\,kWh/m^2/day$, photovoltaic panels with nominal cell efficiency of 20 per cent and operational efficiency factor of 70 per cent, for three scenarios with total area of PV panels of $200\,m^2$, $1000\,m^2$ and $10,000\,m^2$

Notes: The number of properties (columns in blue) and the total area of degraded areas – i.e. degraded planted pastures and degraded lands: eroded, desertified, salinized, etc. (columns in red) according to the classes of area (ha) of properties (x axis), of a universe of 136,384 properties and 1,881,289 ha of degraded areas
Source: IBGE (2006)

Figure 7.
Land ownership structure in the semi-arid; in percentage (y-axis)

The annual average PV production for each area shown in Table II is computed by the product of the PV energy potential (equation [1]) by each of the PV areas. The annual energy is then multiplied by the current energy generation market value of US$0.0712 per kWh[9] to compute the gross annual revenue for each sized PV plant. The estimates of annual gross revenues are then used to create income scenarios, which consist of the sale of the generated energy to the grid, taking into consideration current market parameters. Assuming arbitrary fractions of the value of the electric energy generated, it would be possible to create reference revenues to the landowners, which range between US$51.00 and US$638.00 per month. The relevance of such values for the local society can be better understood when compared to the Federal Government conditional cash transfer program *Bolsa Família*, which ranges between US$11.00 and US$106.00 per month per family, depending on the family size and whose average monthly value is of the order of US$25.00 per family.

Even considering that not all families currently enrolled in the *Bolsa Família* program, in the order of 130 million families nationwide, would benefit from a distributed PV generation program, it still has the merit of creating a network of sustained income to thousands of small farmer families that are at the highest risk of extreme poverty, particularly during drought years in the NEB: when their subsistence corn and beans cultures are severely reduced, if not completely depleted.

However impressive the numbers presented in Table II are, one must consider other monetary flows associated with the commercialization of electricity, such as taxes and services that have ripple effects through the direct and indirect activation of other sectors of the economy.

Therefore, alternatively to selling the PV electricity to the grid, as discussed in the previous section, we consider the opportunities of using the PV energy generated for productive processes in the farm. We start by defining the PV's energy–density value, which is the amount of electricity that one square meter of currently available PV panels can produce in a year, multiplied by the average value of the electricity paid by a residential consumer (i.e. US$0.180 per kWh). Using equation (1), the annual amount of PV energy is computed as 0.84 kWh/m^2/day, equivalent to 306 kWh/m2/year. Thus, the PV's energy–density value is the product of 306 kWh/m^2/year times \$0.18 per kWh, which equals \$55.00 per square meter per year. Therefore, if all the energy generated by the PV plants sizes were utilized in house, it would represent savings of US$11,000, \$55,000 and \$550,000 per year, respectively. Such values are further scrutinized in Table III for the 1 ha PV plant.

Components of cost	Revenue (US$/KWh)	Annual revenue US$ (ref. 3,066,000 KWh)
Energy	0.07148	219,000.00
Taxes	0.04571	140,160.00
Distribution and transmission costs	0.06281	192,720.00
Total revenues	0.18000	551,880.00

Table III.
Values charged for domestic electric energy

Notes: Average values over the Nation for "green flag," i.e. the lowest tariff base [ABRADEE 2016] in US \$per kWh [central column]; itemized in: energy, taxes and distribution and transmission costs (left column); and respective annual revenues (right column) in US$, relative to the annual PV photovoltaic production in an area of 1 hectare in the NEB (shown in Table II)

The gross economic values emerging from the PV generation, shown in Table III, become even more impressive when they are compared with the gross economic value resulting from the production of rain fed maize, a traditional subsistence culture in the region (see Table IV). For the calculation of the values in Table IV, we use the average values of maize productivity for rainy years in the *NEB* (IBGE, 2006). Taxes and other services were used at the same rates of electric energy tariffs and services of Table III for comparison. The caveat is that this assumption may lead to the underestimation of the amount of capital movement by the production and sales of maize (e.g. transporting the crop by diesel trucks to the markets increases the cost of the product substantially). Yet, comparing the accounting for the output values of PV energy generation and maize production shown in Tables III and IV, one can immediately see that the former is approximately 500 times the latter, per unit area. This is a consequence of several factors, the first of them being the once-a-year, rainfall/season-dependent, maize harvest, against daily PV transformation all year long.

The previous estimates related to electric power generation shed light into features that are not immediately apparent. For instance, PV potential can be implemented gradually and modularly, with larger spatial granularity over degraded or salinized pasture areas. It can employ a large number of skilled workers distributed across the whole region, in cities and towns, generating local, direct employment. The photovoltaic sector has been the largest employer among renewables worldwide (IRENA, 2017). Meanwhile, hydroelectric plants are normally implemented in large, capital-intensive units, entailing the loss of all submerged terrestrial ecosystems, with strong impacts on the production of greenhouse gases (Fearnside, 2016), loss of cultural and archaeological sites and the disruptions caused by the construction of roads and housing for the workers. Furthermore, the investments necessary for the construction of hydroelectric dams are concentrated among a small number of large companies or investors, generating a number of temporary employments during construction phase leading to very low permanent social capillarity.

Yet, for PV projects, the environmental costs of panel production processes, nowadays heavily concentrated in countries that supply such technology, should be considered, as well as the need to conduct environmental zoning studies that delimit the most appropriate areas for its installation. In terms of the PV panels and the life-cycle of the overall systems, it is important to take into account the quality of the products and not just the costs. Proper certifications dully confirming the compliance to internationally recognized codes and standards would more effectively ensure the sustainability of the systems themselves, the overall integrity of the grid and the safety of the users.

The PV systems can bring an array of benefits through their multiple applications, which have been proven in other regions of the world, including in Latin America. The use

Components of cost	Revenue (US$/Kg)	Annual revenue US$ (ref. 2,681 Kg)
Maize wholesale cost	0.14	365.00
Taxes	0.09	228.00
Others (transport and other costs)	0.12	320.00
Total revenues	0.34	913.00

Table IV.
As in Table III, but for annual maize production per hectare in the *NEB* (i.e. 2,681 kg)

of PV systems for distance education in rural areas (Ley *et al.*, 2006) has helped children receive primary education without having to walk several hours to other communities. In the same way, PV systems have been used in health centers, widening the access to medication and health services, which have also proved useful during extreme weather events. Productive and communal applications have enabled the improvement of livelihoods by creating new economic opportunities, such as opening businesses including stores, carpentry workshops (Corsair and Ley, 2008; Foster *et al.*, 2006) and creating new social settings in which neighbors gather and strengthen trust bonds that then help increase their resilience to extreme weather events (Ley, 2006) by being better organized and unified in case of natural disasters and emergencies. This also brings out the important point that human and institutional actors are key to the success of any renewable energy project, as the motivation of human actors in implementing a project is an important project success driver (Ley and Corsair, 2008).

In addition to the relevant monetary value and the potential socioeconomic capillarity of PV power generation in degraded areas shown in the previous sections, there are also case studies of the use of PV panels in consortium with agricultural production (Agrivoltaic, or AV systems) in temperate regions with notable benefits for food production.

Current experimentations at the SERTA school in Ibimirim, in the interior of Pernambuco have indicated a potential for fishery, poultry and vegetables production that can reach, for instance, an output of up to 160 kg of fish per year per m^3 of water. At a current market price for the organic tilapia fish at approximately \$7.00 per kg, and considering a 4 m^3 water reservoir, one production unit alone can generate on the order of \$6,000 annual income from the sales of fresh fish catch alone (Alves, 2018).

5. Conclusions and policy implications
Challenging the dogma of the drought as a causal link to poverty in the semi-arid portion of Northeast Brazil (NEB), this article presents a conceptual proposal for the rational use of the abundant solar irradiation resources of the semi-arid climates of the world for their sustained socioeconomic development. The figures presented in this study reveal a relevant opportunity for income earnings through the distributed generation of PV energy, unprecedented in the history of Brazil.

The initial set of factors presented suggest the potential feasibility of such an endeavor and may justify the establishment of coordinated public policies led by the federal and local governments, with a significant participation of the private initiative, non-governmental entities and thousands of small land owners, in the establishment of a PV structuring program with economic, environmental and educational repercussions in the NEB. When locally demonstrated over the NEB, the program can constitute a valuable example for other semi-arid regions of developing countries in Africa and the Middle East.

In addition, considering the recurrent and increasing costs of assistance programs for drought-affected populations worldwide, it is worth considering the positive effect of a possible PV energy generation program linked to meeting the sustainable development goals (SDG), especially SDG7 and the "Sustainable Energy for All" initiative. Beyond helping the country meeting its climate change commitments, a distributed PV program can have multiple advantages in terms of vulnerability reduction to extreme climate events, disaster risk reduction (if used in conjunction with Early Warning Systems) and of climate change adaptation in general.

Compared to cultivating maize, which is usually planted by small family-based farmers who are highly vulnerable to recurrent droughts, the economic yield of PV energy production is of the order of 500 times higher per unit area, yet considering a year of regular rainfall.

In addition, these two activities are not competing with each other, as PV panels can be installed over degraded and unproductive terrains. The available degraded land, which is not suitable for agriculture, is more than sufficient to support the production of PV energy without competing with agriculture. On the contrary, there is considerable evidence to support the findings that the consortium use of PV panels and agriculture may in fact help regenerate degraded lands.

However, for the vast PV potential of the NEB to become a perennial source of income for a wide range of the historically excluded population, it is necessary to change the current legislation in Brazil, by regulating the energy transactions between the concessionaires and the local producers. A possible example to be adopted for PV micro-generation in Brazil could be similar to the one used of royalties from the exploitation of oil paid to land owners.

The geopolitical power of energy distribution constitutes an institutional barrier as its production is centralized but its consumption is distributed. This holds true especially in large-scale power plants independently of the energy source used. The establishment of a distributed PV micro-generation policy would need to contemplate the governance of such a system, which will certainly be orders of magnitude more complex than the current centralized model.

The use of PV panels for the collection of rainwater stored in cisterns and underground dams, as well as the shading for agro pastoral activities, represent additional factors of resilience to the semi-arid climate and ongoing climate changes.

Assuming a good performance of such a strategy, the degree of dependence upon compensatory cash-transfers by governments to low-income populations would tend to disappear over time. This, in itself, could justify, for instance, the study of subsidies or financing through reduced interest rates.

In spite of the potential macroeconomic advantages and possibilities discussed here, which remain to be properly assessed beyond this conceptual roadmap, the difference of this proposal is the change of paradigm, valorizing the abundance of climatic factors in the NEB. The development of public policies that focus on the native characteristics of the semi-arid climate may represent a definite difference for the promotion of regional economic development and social inclusion. However, the realization of the potential for economic emancipation suggested in this study requires a change in legislation and in social policies, from the current compensatory scheme to a scheme in which the producer is rewarded for the surplus of electricity generated in its property, and not just because of a situation of poverty.

These actions must occur in parallel with the Caatinga[10] biome recovery program, in view of local climate control and an extensive educational program focused on a highly interconnected global society in the digital age. Both fields of environmental and educational services mentioned here are complementary to the proposal, without having been further detailed in this conceptual note. Nonetheless, they are fundamental so that the potential income does not generate a situation of accommodation and conformism of the local population.

It is also important to adequately recognize property rights in the region and the role of women, so that the income generated can address distributional aspects fundamental to raising the level of wellbeing of the local population as well as include equity and justice elements.

Finally, it is worth mentioning that scientific knowledge and technological development, as well as the inflow of financial resources are important inputs, albeit insufficient *per se* to generate welfare and progress. To this end, other social processes compete for valuing the relationships between people and the environment in a society founded on respect for the truth.

Notes

1. Largest river flowing into NEB, with basin area of 641,000 Km^2, 2,830 Km long and a discharge of 2,943 m^3/s into the Atlantic Ocean.

2. www.worldbank.org/en/news/feature/2015/12/07/using-solar-energy-to-power-water-supply-in-tanzania

3. www.theguardian.com/environment/2014/oct/21/are-solar-farms-really-hitting-british-food-production

4. Unpublished dataset compilation from data sets collected by Federal and State agencies in Brazil.

5. Representative Concentration Pathway – RCP4.5 represents the value of 4.5 W/m^2 radiative forcing of the global atmosphere in the year 2100 relative to pre-industrial values.

6. www.mma.gov.br/agua/agua-doce

7. e.g. Tucurui, Itaipú, Ilha Solteira, Xingó and Paulo Afonso.

8. See page 5 of: www.epe.gov.br/sites-pt/sala-de-imprensa/noticias/Documents/Informe%20Leil%C3%A3o%20A-4%202018.pdf

9. The wholesale value of $0.0712 per kWh refers to the value paid by the end residential user for the energy generation fraction of the total electricity cost, dispatched to the grid. The additional costs of transmission and taxes are considered in the next section.

10. Caatinga is a semi-arid scrub vegetation characteristic of the Northeast region of Brazil.

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