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Grid parity analysis of distributed PV generation using Monte Carlo approach: The Brazilian case

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ABSTRACT

We have conducted a grid parity analysis of distributed PV generation in Brazil through the use of a probabilistic Monte Carlo approach. Essentially, we have derived the probability distribution of the levelized cost of electricity (LCOE) for both PV and grid electricity. We have thus assessed how likely grid parity will occur with respect to system's nominal power and financing scheme in a *net metering* framework, by computing the cumulative probability for which the LCOE difference is nonnegative: $P(\Delta LCOE \geq 0)$. Regarding southern Brazil, it appears that economic viability of many residential grid-connected PV systems in operation is far from guaranteed, due to the need for substantial own capital and nominal capacity. 4-kW systems might be viable ($P(\Delta LCOE \geq 0) = 0.82$) but only by relying on equity financing, while small systems around 2 kW will not ($P(\Delta LCOE \geq 0) \leq 0.3$). When debt financing is considered however, merely systems with nominal capacity above 7 kW present significant confidence levels ($P(\Delta LCOE \geq 0) > 0.95$). Eventually, it is outlined that electric company, state tax policy and consumption class are the effective leverages when assessing whether cost of distributed PV generation shall reach parity in the country.

1. Introduction

The significant contribution of renewable energies to the Brazil's economic growth between 1980 and 2010 [1] is likely to be the main reason for why the country is today one of the leaders of the market, especially because of ethanol and hydroelectricity resources [2,3]. However, penetration of modern renewable resources like wind or solar power in the country's energy scheme is still really low, despite the significant availability of the solar resource throughout the territory [2–4]. Regarding solar photovoltaics (PV), the market indeed still remains in its infancy, around a few tens of megawatts [2,3]. Nevertheless, within the overall context of fossil resource exhaustion and global warming, the technology has recently begun to be further investigated, so that the number of systems in use in the field has risen sharply [5,6]. It has supported the young Brazilian framework for distributed generation of electricity [3,7], such that grid-connected PV (GCPV) systems are now standing for more than 90% of the decentralized facilities [6].

In Brazil, decentralized generation of electricity is based on the *net metering* mechanism, whereby one can use self-generated energy as a credit on its own consumption [3,7,8]. Assessing viability of distributed GCPV systems therefore requires to estimate their corresponding lifecycle economic cost and to compare it against that of electricity from the distribution network. The first is commonly performed by computing the levelized cost of electricity (LCOE), which is the unit cost of the energy generated by a system over its lifetime [9–13]: it allows fair and straightforward comparison between different electricity generation technologies. Then, the grid utility retail price is mostly used as a proxy when considering *grid parity*, i.e. whether cost of PV electricity equals that of grid electricity [7–9,14]. However, this approach is also strongly biased as the grid cost of electricity is an instantaneous value while the LCOE is time-dependent: the right comparison must instead involve the LCOE of the electricity being supplied by the utility grid over the same period [14].

Monte Carlo method has been used for a while in computing lifetime economic cost of energy systems [15], but only recently it has been introduced for PV systems [11]. Unlike single-point estimates, this probabilistic approach allows uncertainty around expected LCOE to be assessed, by relying on input probability distributions [11,16–18]. This method appears especially relevant

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Nomenclature

B	borrowed amount of money ($)
COE_t	cost of energy for year t ($/kWh)
E	rated output energy per year (kWh/year)
e_{COE}	escalation rate of cost of electricity (%/month)
E_t	amount of electricity generated for year t (kWh)
i	discount rate (%)
I_t	initial investment ($)
L	constant loan yearly repayment ($)
l	loan term (years)
L_t	loan repayment for year t ($)
LCOE	levelized cost of electricity ($/kWh)
M_t	maintenance costs for year t ($)
N	system lifetime (years)
NPV	net present value ($)
O_t	operation costs for year t ($)
$P(\Delta LCOE \geq 0)$	cumulative probability for which LCOE difference is nonnegative
r	lending interest rate (%)
R_t	system's residual value ($)
t	time (years)
ΔLCOE	difference between grid and PV LCOE ($/kWh)
τ_d	yearly degradation rate of the PV array (%/year)

when instability characterizes the economic situation of a country such as Brazil, where lending rates, inflation or opportunity costs have been suffering steep changes from one year to another [19–21]: a wide probability distribution can give the realistic insight that one unique value cannot.

Essentially, we propose in this paper to combine the two methods, that is comparing within a Monte Carlo framework the LCOE of a PV system against the LCOE of grid electricity, so that one can estimate how likely grid parity will occur according to nominal capacity and funding model. In both cases, the literature remains very scarce: as noted by Swift [14], assessment of grid parity has been mainly determined by considering the electricity tariff, and so it is in the latest Brazilian study on PV distributed generation [8], while according to Heck et al. [16] Monte Carlo modeling for LCOE estimation has been very seldom used until now. To the best of our knowledge, this is therefore the first time this comparison is carried out using probability distributions. Indeed, the probabilistic approach appears well suited to an “all or nothing” issue such as grid parity, especially for renewable distributed generation: while buyers surely want to know whether their system shall be viable or not before investing, the ecological dimension of such an installation may result in PV prosumers first interested in making sure their system will be profitable regardless of the rate at which it might be.

We give here an in-depth description of our methodology for the Brazilian case, by using data from the southernmost state of Rio Grande do Sul. In practice, as a federal country based on a liberalized electricity market, Brazil would indeed require as many analyses as the 27 states it is made of [2,22]. The core idea is instead to rely on a local example in order to give the main keys to understanding the country's distributed PV generation framework, as well as those to easily downscaling and reapplying the same approach to other regions. Main steps of the whole procedure are outlined in the flowchart of Fig. 1: from exogenous parameters, we use the System Advisor Model (SAM) to model the output rated energy from a typical GCPV system in the region; it is then combined with economic criteria through a Monte Carlo simulation to compute the LCOE probability distribution of both PV system and corresponding grid electricity; finally, the distribution of the resulting difference is derived in order to infer the cumulative probability of grid parity. Ultimately, as the LCOE also depends on the type of system and funding scheme [11,17], we further examine how the corresponding distribution is likely to behave according to nominal capacity and debt financing. In regard to the latter, in order to apprehend how debt financing might affect grid parity at a glance, we also propose a Pareto-like approach where confidence level of the event occurring is depicted according to debt financing share and loan term.

Accordingly, this article is organized as follows: the first part deals with the actual solar PV framework in Brazil; the second introduces the LCOE concept; the third details the lifecycle analysis of distributed GCPV systems in Rio Grande do Sul; the fourth depicts the Monte Carlo and sensitivity approaches for generating and investigating LCOE probability distributions as well as their corresponding behaviors; the ultimate part attempts to extend the previous findings to the national level.

2. The Brazilian solar PV framework

From the country's energy framework to the specific aspects of the southernmost state of Rio Grande do Sul, we depict here how the grid-connected solar PV technology is currently being apprehended and implemented in Brazil.

2.1. The Brazilian electricity matrix

The Brazilian power system is peculiar in the world as electricity supply is mainly achieved through renewable resources, though essentially hydroelectricity, modern renewable power sources such as wind or solar having been far unexploited until now. As a matter of fact, in 2014, renewable resources accounted for 74.6% of the whole electricity generation in Brazil, among which 87.5% was from hydroelectric power plants (second largest hydropower capacity in the world), about 7% from bagasse and less than 3% from wind and solar energies [23]. The other 25.4% was from fossil fuels, among which natural gas (51.1%), oil (20%), coal (11.6%), uranium (9.6%) and industrial gases (7.6%) [23].

2.2. Grid-connected PV systems

Although solar energy appears substantial throughout the Brazilian territory [2,4], the PV installed capacity has remained especially low until recently, around 20 MW [2,24]. As the technology has started being investigated as a mean for meeting the country's energy policy strategy in mitigating GHG emissions [5], the installed power has dramatically increased over the past few years according to the Brazilian Electricity Regulatory Agency (*Agência Nacional de Energia Elétrica*, ANEEL) [6]. At the present time, GCPV systems for distributed generation stand for about 150 MW, with most of the facilities located in the states of Minas Gerais, São Paolo and Rio Grande do Sul [6].

2.3. Decentralized generation of electricity in Brazil

A specific framework for decentralized generation of electricity has been recently established in Brazil, including the differentiation between micro (until 75 kW) and mini (between 75 kW and 5 MW) generation and a scheme for balancing the generated electricity