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Modelling distributed photovoltaic system with and without battery storage: A case study in Belem, northern Brazil

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This paper focuses on simulating photovoltaic PV electricity output and the economics analysis of distributed grid-connected systems with and without battery in the city of Belem, northern Brazil. The work used the System Advisor Model to perform all simulations including the financial evaluation which was calculated using the levelised cost of electricity (LCOE), payback period, and net present value (NPV). The electricity output performance was very similar between both systems, though the system without battery storage achieved better results in all technological parameters. Concerning the net metering system, the system without energy storage returned 144.70 kWh to the grid during the first year whereas system with energy storage returned only 6.6 kWh to the grid. The economic analysis demonstrated that the feasibility of the project is influenced by the discount rate and inflation adopted, but mostly by the discount rate. The results point out better real LCOE and net present value on the system without storage. Although real LCOE estimated for the system with storage resulted in higher values than electricity tariff from the concessionaire and negative NPV, the payback and cash flow analysis reveals that the investment on any project is paid in less than 17 years.

1. Introduction

Solar energy is a renewable resource that has been increasingly studied in recent years because its operation does not contribute with CO_2 emission to the environment [1]. The installed capacity of this resource grew 43% from year 2010 to 2011 totalling 100 GW globally [2]. Brazil is one the countries with great potential to exploit solar energy either through photovoltaic (PV) or thermal uses. Its location near the tropical zone and high irradiance levels that reach the entire territory are parameters that point out the potential to use solar energy [3–5]. The Northeast region of Brazil demonstrated great potential to harvest energy from the sun due to its weather conditions, though the Amazon region in the north also presents high potential because of the relatively constant irradiation levels throughout the year [5]. For instance, the State of Para's (north of Brazil) potential for PV residential project installation of 339% is reported in the literature [6], however, the State has only 66 micro or mini-generator installed and registered [7]. Some studies support this idea by claiming good electricity performance output either through simulation models or in-situ studies [5,8]. Belem, capital of the State of Para, is the biggest city in the region, approximate population of 1,450,000 million people and gross domestic product (GDP) per capita of 6,504.70 US dollars, and it has the 5th highest electricity tariff in the country. It is noteworthy that the electricity tariff in Belem is also the highest among the northern states (value was taken in July 2017, tariff might vary over time). The combination of both parameters makes this city a good place to install photovoltaic projects. For a comparison perspective among different cities of Brazil, Belem is the eleventh largest city in the country. Rio de Janeiro (most known city of Brazil) and Brasilia (capital of Brazil) are the second and fourth place in population. The Fig. 1 shows the map of Brazil pointing out Belem, Rio de Janeiro, and Brasilia. Global horizontal irradiance (data from SWERA) is also indicated in the figure. Pereira et al. [9] describe the Brazilian potential for solar photovoltaic installation in the page 59 of their paper. Table 1 express population, GDP, mean irradiation levels per region, and electricity tariff without taxes of the three cities mentioned.

Most studies highlight distributed PV grid-connected installation for cities due to less complexity for equipment planning and lower costs compared to off-grid PV systems, which require

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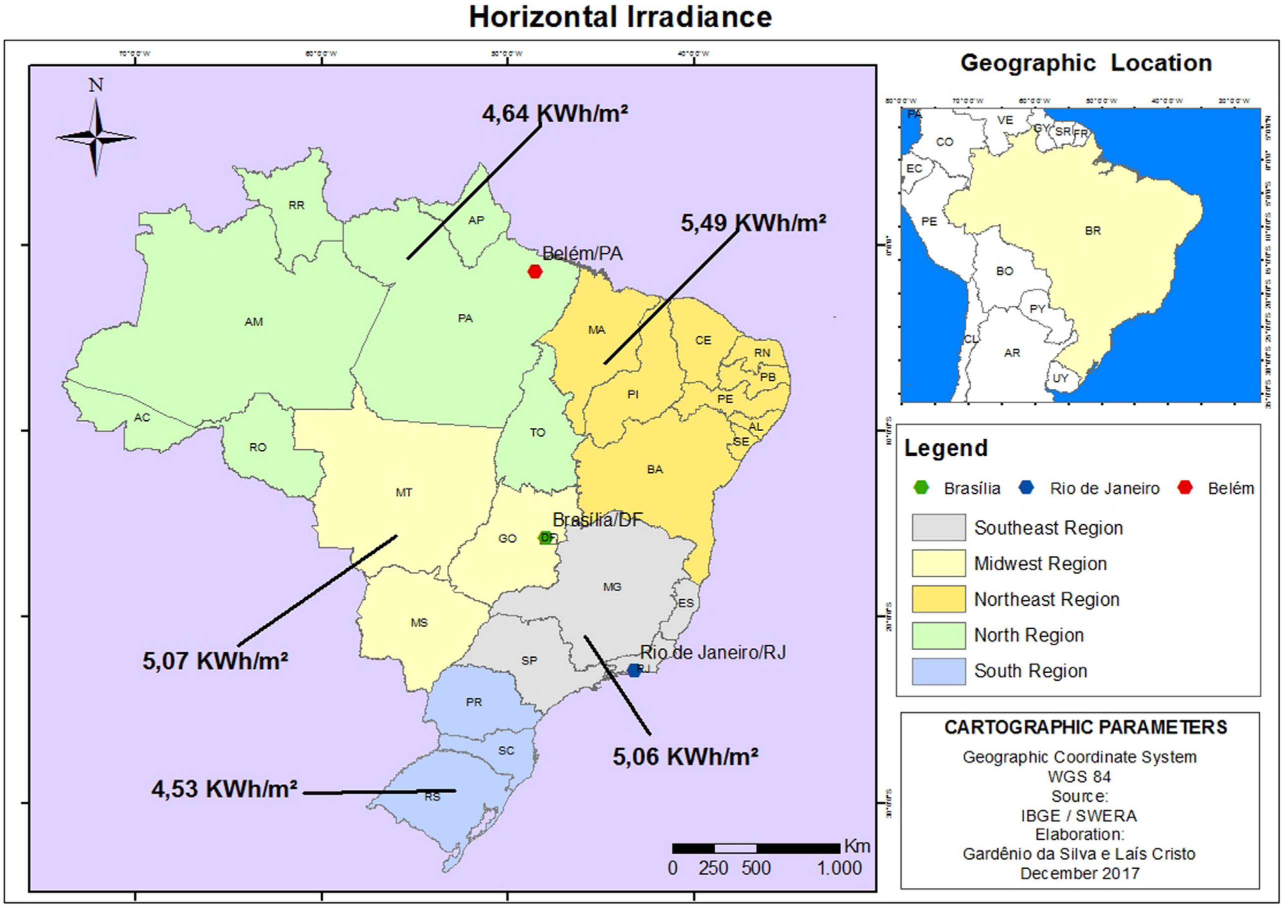

Fig. 1. Location and annual global horizontal irradiance for international context.

Table 1
Social-economic comparison in different cities.

City	Population	GDP/per capita	Tariff* ($/kWh)	Mean GHI	Location
Belém	1,452,275	6,504.70 $	0.1915	4.82 kWh/m^2	North
Brasilia	3,039.444	23,655.60 $	0.1541	5.08 kWh/m^2	Centre
Rio de Janeiro	6,520,266	15,838.81 $	0.1685	4.95 kWh/m^2	Southeast

[1]GHI: Global horizontal irradiance for the region. *without internalised taxes

battery storage bank, for remote areas not connected to the grid. Nonetheless, a new modality of PV systems connected to the grid and with battery storage is emerging [10,11]. The battery storage might even improve the production in conventional PV plants [12] and some technologies such as sodium-sulphur batteries can also be economically viable for PV systems [10]. Another benefit of this system with battery is the certain independence when the concessionary stops delivering electricity to the residence due to some malfunction. Due to weather conditions PV systems may experience intermittence in power generation. There will thus be variations in frequency and voltage in the PV system. Partial shading of modules in series or strings will lead to reduction in energy generation (mismatching conditions). The system (the array in series or string) might stop producing energy if a small portion of a module in array or a string suffers from shadowing. The mismatching condition will also cause voltage, current, peak-shave fluctuations in the PV system. This mismatching condition is related in the literature as a well-known problem in grid connected PV systems. The insertion of a battery bank is therefore being studied as a solution to integrate PV systems to the grid. The battery system is used to control fluctuations of voltage and current (overvoltage or overcurrent for instance), peak-load shaving, modelling the load curve, and minimise the intermittency in PV systems (stability and reliability for the PV system). Grid-connection PV systems with battery storage can be used to solve problems related to mismatching (intermittency) conditions [10–13].

Before implementation of a distributed grid-connected PV system with energy storage, electricity output simulations and economic analysis must be taken into account to estimate the real energy production and economic viability of the project. The System Advisor Model (SAM) developed by the United States National Laboratory of Renewable Energy (NREL) is a model used to run simulations and help with decision making for implementation of renewable systems [14]. Previous versions were only able to simulate grid-connected PV systems without battery storage [15] which helped to simulate electricity output through PV systems for the city of Belem and point out implications for a floating system [5]. New versions are able include the battery storage system in the simulation [16]. SAM also has the option to perform financial analysis according to parameters such as discount rate, inflation, incentives, net metering policy, and others. This paper thus aims to