Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil

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The proposition of Net Plus-energy Buildings (NPEB) leads to the need to carry out studies of load matching in contrast with the grid impacts of distributed generation (DG). This paper performs simulations with the EnergyPlus software tool concerning a NPEB operating in four Brazilian metropolitan areas. The analyses include photovoltaic (PV) performance parameters and Load Matching and Grid Interaction indicators (LMGI). New grid impact indicators are defined in order to study the impacts of DG in the power grid. In the second stage, the work investigates economic aspects under net metering supporting. Results show the annual amount of electrical demand covered by PV varies from 29 to 51% with more potential in situations with higher PV production and higher cooling load, and the annual PV electricity that supplies the loads varies from 24 to 36% according to the seasonal variations of PV-load correlation. The levels of exported electricity into the grid are high in Brazil with annual mean power peaks surrounding 0.7 but can surpass 0.8 in the sunniest periods. The economy demonstrates the building achieves grid parity from 6 to 18% discount rates and the payback time is given for different scenarios of investment costs, discount rates and electricity tariffs.

1. Introduction

In recent years, building designs are undergoing major changes with energy efficient use and strategic electricity supply though passive design studies and thermo-energetic simulations. These buildings must be sustainable, reasonably priced for construction and maintenance, and with high life cycle [1]. In this context, Photovoltaics (PV) is one of the most promising renewable energy in achieving sustainable building design [2] because it is the only electricity generation technology that can be widely integrated in the urban environment. The life-cycle greenhouse gas emissions per GWh is far lower than conventional fossil-fuel-based electricity generation technologies because PV does not require any fuel to operate [3], even as during operation, photovoltaics have zero emissions of CO_2 and pollution.

Net Plus-energy buildings are typically characterized by low energy consumption through passive energy design strategies. In general, in single-family residential buildings, electricity demand can be met on an annual basis, from a roof-mounted PV generator. As the amount of electricity produced by a PV system in a residential building is constrained by the size of the roof, it is also advisable to reduce electricity demand. This minimizes the requirement for power generation and the required area for PV modules [4]. The net-plus balance means that the annual electrical energy surplus fed-in to the grid is greater than the annual electrical energy imported from the grid [4]. The main advantage of the NPEB is that it produces more electricity than it consumes in annual terms, so that the PV electricity surplus is used to supply nearby buildings and infrastructure (public lighting, etc.), contributing to a sustainable distributed power generation in urban areas. Many interesting examples of PV integration in residential buildings can be found in the Solar Decathlon (SDE) international competition [5].

In general, the combination of high residential tariffs with high solar radiation availability suggests that PV electricity can reach economic feasibility for grid-connected roof top installations [6]. In this respect, a building with a PV system achieves grid parity when PV electricity costs are equal to retail electricity price (considering revenues, savings, cost, taxes and depreciation). However, the ways to reach grid parity are not straightforward due to the influence of many non-technical and uncontrollable factors (i.e. investment costs, loan discount rate), which means that, in practical terms, political support and financial incentives are still needed [7–9]. In countries where feed-in tariffs (FiT) are applicable, the PV

Table 1
Building characteristics (envelope).

Envelop Elements	Area (m^2)	Material description and thickness (From exterior to interior)	U-value (W/m^2 K)
Walls	100	Fiber cement board (10 mm), Aerogel (60 mm), OSB (18 mm), Glass wool (60 mm), OSB (18 mm), Air (42 mm), Fiber cement board (10 mm)	0.15
Glazing	34.05	Glass with metal oxide thin film (6 mm), Argon air chamber (12 mm), Glass (6 mm)	1.32
Ground floor	55.62	Wood flooring (20 mm), OSB (18 mm), Glass wool (60 mm), OSB (18 mm)	0.16
Roof and ceiling	55.62	PV modules (46 mm), Air space (240 mm), Aluminum tile (8 mm), OSB (18 mm), Glass wool (60 mm), OSB (18 mm)	0.10

Fig. 1. The Ekó house designed by the Brazilian Team for Solar Decathlon Europe 2012.

systems owners receive a fixed rate for each unit (kWh) fed in the power grid. However, FiTs are being phased out in most countries, and new supporting mechanisms are being implemented [10]. For example, recently in Brazil, the Brazilian National Electrical Energy Agency (ANEEL) approved Normative Resolution n° 687/2015 [11], which established an energy compensation system (net metering), whereby the active power injected into the grid by a consumer unit with distributed micro or mini generation offsets the active power consumption, admitting the consumer unit to have credits in amount of active energy. This resolution also assigns the installed PV capacity must be limited to the grid connection capacity and in the case that the prosumer[1] requests to install a superior PV capacity it must increase equally the connection capacity.

Nevertheless, self-consumption support mechanisms are being increasingly promoted in many countries (Germany, Italy, Denmark, Belgium, USA, Chile, etc) [13,14]. These mechanisms focus in a better use of on-site generation to partly meet the local consumption and can help on the evolution of smart grids by controlling more efficiently the electricity flows between PV system, loads and power grid. In this context, the LMGI indicators proposed in this study, are useful for a range of applications involving operation perspective of a NPEB [15]. However, studies and applications of these indicators are poorly explored in Brazil and hence this study attends for LMGI responses for the Brazilian residential sector through simulation mechanisms. Load matching indicators refers to the ability of a PV system to match the building load. They are functional for building designers and owners to analyze the PV array capacity required for a given load demand profile and grid connection capacity and they can provide a variety of approaches to designing self-sufficient solar buildings. Grid indicators refers to the energy exchange between the building and the power grid. They are suitable for grid designers and operators in order to analyze grid operation effected with grid-connected PV systems and to evaluate DG network expansion in urban areas.

The main purpose of this article is to evaluate the energy performance of a NPE house provided with rooftop PV system. During the course of this study, it was investigated the technical-economic viability of the PV installation operating in four Brazilian State capitals, with different climatic conditions. In this aspect, firstly, daily and annual electricity flows in the house were analyzed emphasizing on LMGI indicators results. Then, an electrical energy performance analysis is presented, including the solar resource (Y_R), photovoltaic yield (Y_F) and Performance Ratio (PR) complemented with an economic analysis under currently applicable Brazilian DG regulation.

2. Methodology

2.1. Ekó house: SDE 2012 prototype

The NPEB study case is the residential building built by the Brazilian Universities team for the Solar Decathlon competition of 2012, which took place in the city of Madrid, named Ekó House (Fig. 1) [16]. The house was designed to Brazilian climatology adapted to the competition with some changes in technical issues (i.e. PV modules inclination and orientation). The Ekó house used several energy efficiency strategies in order to reduce the overall energy consumption and improve indoor thermal comfort, such as thermal insulation with glass wool and aerogel, glasses with solar control, natural cross-ventilation and efficient air conditioning system. It was employed structural independent modules as an architectural concept, using solid lumber wood components, processed wood and lattice structure. The team project considered the use of sustainable materials such as 5.4 m^3 of Cumaru hardwood applied internally, Oriented Strand Board (OSB), and fiber cement board. The house with 55.62 m^2 of net area and with a conditioned volume of 183 m^3 was designed for two people consisting of living room, dining room, kitchen, bedroom, bathroom, verandas and service area. The thermal insulation was designed for both cold and warm climates. The use of building materials with higher thermal capacity, as in the case of glass wool and aerogel, reduces the amplitude of the indoor temperature in relation to the outdoor temperature and the temperature peak verified externally is not perceived internally. The house adopted low-e double glazed

Table 2
Thermophysical properties of building materials.

Material	Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat (J/kg K)
Fiber cement	1400	0.65	0.84
Aerogel	3–150	0.014	0.99
OSB	650	0.13	0.13
Air	1000	0.026	0.10
Glass wool	20	0.38	0.67
PV module	2700	0.78	0.84
Aluminum tile	7800	45	0.46

windows with visible transmittance of 0.47 and aluminum frame. Table 1 presents the main building envelope characteristics and materials thicknesses. The U-values demonstrate the house acts as a passive house with high degree of thermal insulation. For example, recent reports on EU countries governmental strategy indicate the objective U-values of walls are 0.18 W/m^2 K in Sweden and Norway and 0.25 W/m^2 K in UK [17] that is of special interest to reduce energy consumption levels of buildings and to decrease CO_2 emissions. Although, the intended U-values depend greatly on the climatic conditions of each country and the main interest of using high insulation materials in Brazil is clearly to reduce cooling load. Table 2 presents the thermophysical properties of building materials used to model the building.

2.2. Climate and weather data

Both hot/dry and hot/humid climates from Brazilian state capitals were considered in the study. Brazil is a low-latitude country characterized by a high availability and uniformity of solar radiation [18]. The analyses were performed for four cities with different solar resource, located at approximately every 5° of latitude and representative of the country climatic diversity: Brasília (Lat. 15.7°S), Belo Horizonte (Lat. 19.9°S), São Paulo (Lat. 23.5°S) and Florianópolis (Lat. 27°S). Fig. 2 introduces monthly statistics corresponding to the daily average values of Global Horizontal solar Irradiation (GHI) (left) and dry bulb temperature and relative humidity (right) for the four cities in study. Brasília is characterized by tropical climate with dry season in the winter and hot summer with annual mean temperature of 21 °C. Belo Horizonte has humid temperate climate with dry winter and hot summer, with mean temperatures above 18 °C in the coldest month, and above 22 °C in the hottest month. São Paulo has a humid subtropical climate, with four well-defined seasons, characterized by hot and usually humid summers, but with temperatures increasing by the effect of pollution and concentration of buildings, and mild to cool winters with annual mean temperature of 19.5 °C. Florianópolis has typical humid subtropical climate of the southern Brazilian coast, presents four well-defined seasons, hot summers, tendency of rainfall concentration, and with daily mean relative humidity above 80% in the summer months. For state capitals the weather data used for the simulations studies were taken from SWERA database [19]. The daily average of GHI in Brazil is higher in Brasília and Belo Horizonte and Florianópolis, city located in the south, has the lowest values in the country. The daily annual average of solar resource of the considered state capitals ranges from 4.52 kWh/m^2 to 5.38 kWh/m^2.

2.3. Building simulations

Energy modeling of the house, including appliances, lights, space cooling, electric boiler for DHW, and PV system was done in EnergyPlus environment (version 8.1). The three-dimensional model was generated in the 3D modeling program SketchUp and the legacy OpenStudio Plugin for SketchUp has been used to create an EnergyPlus input file based on defined construction material properties, boundary conditions and other parameters. To perform the simulations in the Brazilian state capitals the PV modules were oriented to the north and the tilt angles were approached to the latitude of each location to maximize annual PV output. Similar results based on simulations for different tilt angles for 78 Brazilian cities were also proposed by [18].

The simulations assumed the use of the house by two occupants with a 30% radiant fraction. Occupancy activity level was assumed to have internal heat production rate of 132 W per person and the occupancy schedule was determined with one person staying at home all the time while the second goes out during office hours, but lunches and dines at home. Other internal heat gains were set for appliances (30% radiant fraction) and lighting system (20% radiant fraction and 20% visible fraction). The maximum flow rate expected from outdoor environment into the thermal zone was set to 4 m^3/s and the infiltration air change was assumed 0.15 ACH.

2.4. Space air conditioning and DHW

The cooling & heating system considered on the simulations consists of a Variable-Air-Volume (VAV) heat pump. It mainly consists of a Direct Expansion (DX)-oriented Outdoor Air Processing (OAP) unit, VAV boxes (terminal unit), supply fan, dumper and air duct. The advantages of VAV compared to other air systems include more precise control of temperature and air flow rate and lower power consumption. The outdoor air conditioned by the OAP unit is supplied to the building by the supply fan (either draw-through) through the VAV boxes. The VAV box regulates the conditioned outdoor air flow based on demand-controlled ventilation strategy corresponding to CO_2 contaminant concentration for maintaining indoor air quality (IAQ) [20]. In VAV systems, the supply air temperature and the supply air flow depend on the heat gains or losses within the thermal zone served and the zone air temperature. A room controller controls the air flow to the room by measuring the zone air temperature and the supply air flow. The amount of cooling is matched to the load by dampers in the supply air duct that vary the air volume flow rate of being supplied to the zone, while maintaining a constant supply air temperature (12.8 °C setpoint for cooling coil) until the zone comfort temperature is reached. When heating is required, the VAV system becomes a constant volume flow rate system with a variable supply air temperature. In order to reduce HVAC load, the indoor air temperature was kept between 22.5 °C and 25.5 °C in summer and from 21 °C to 23.5 °C in winter, based on ASHRAE comfort zone [21]. Two speed DX cooling coil was set employing a separate single speed model at high speed (full load) and low speed (minimum load) and interpolates between these 2 states to obtain the needed cooling output [22]. The model considered a supply fan total efficiency of 70% and outdoor air flow rate of 34 m^3/h per person.

The electricity for Domestic Hot Water (DHW) represents a high portion on residential buildings demand and the “electric shower” in Brazil (afternoon and evening showers using electrical power are commonly used) has great impact on the monthly consumption. By profiting the high degree of on-site generation allied with low house energy consumption and to represent a typical Brazilian residential building, an electrical boiler of 2 kW nominal operating

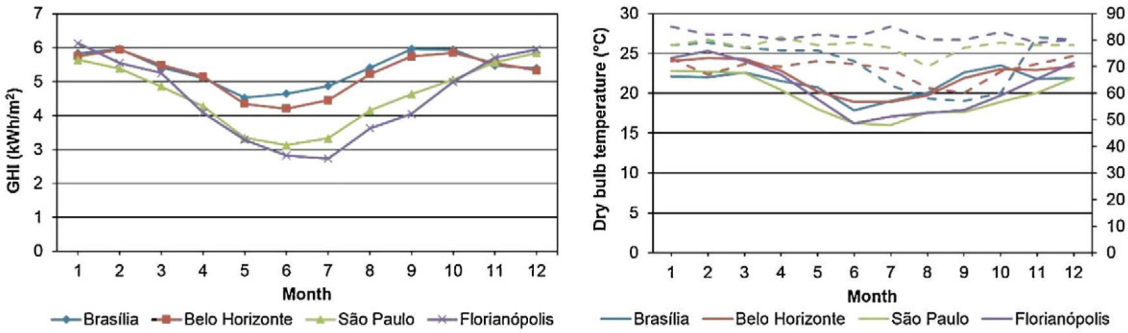

Fig. 2. Distribution profile of daily average of GHI (left) and dry bulb temperature (continuous lines) and relative humidity (dashed lines) (right) for locations under investigation.

capacity was modeled with nominal thermal efficiency of 90%. The water temperature setpoint was set to 42 °C.

2.5. *Photovoltaic solar system*

The PV array covers the entire roof and it was built with 11.04 kW_p (61 m^2 of monocrystalline silicon PV modules of 230 W nominal power each and 18.5% efficiency) focused on high energy generation, considering that surplus should power at least one additional family [16]. By virtue of the limitations of PV installed power with respect to the grid connection capacity, according to the Brazilian DG regulation, and taking into account the house annual electrical demand and the associated LCOE and payback time, different PV array capacities were analyzed, as explained in Section 3.1.

The PV generator is expressed by a mathematical model of Sandia from EnergyPlus software [22–24]. The Sandia model consists of a series of empirical relationships with coefficients and involves I–V curves adjustment to define polynomial equations that describe the PV array behaviour according to temperature and solar radiation [22]. Electrical, thermal, solar spectral and optical effects for PV modules are included in the model. To determine the house electricity distribution the "Track electrical" scheme was used, where the PV generator tries to meet all building electrical demand. The inverter was simulated with Look Up Table model, where efficiency is interpolated using a look up Table and the power production is normalized by the inverter input power in DC. It was assumed that the house was not surrounded by any object that can provide shading in the façade or in the solar modules on the roof area. This assumption is realistic in urban environments in Brazil where are dominated by single-family houses that have low height and which are not significantly affected by shading acquired from other buildings.

2.6. *Evaluation equations*

In order to evaluate the electrical energy performance, several equations were employed to determine electricity flows in the house electrical system as well as LMGI indicators. New parameters were also defined to characterize the interaction between the NPEB and the power grid. Fig. 3 summarizes an electrical diagram of the Ekó house case study with an overview of the relevant nomenclature used in the equations. In this configuration, the PV system is considered to be connected in "self-consumption" mode, that is, inside the building electrical installation. The building is connected to the power grid by means of a single feeder where bidirectional power flows can occur. It should be noted that, although such possibility is often not applied in countries with "net metering" billing schemes, it provides the highest energy efficiency (on-site generation being closest to local demand) and should be considered the most desirable connection mode in future, increasingly smart and sustainable electricity systems. It should be also considered that, even under the alternative mode, where the PV system is connected to the power distribution grid through a dedicated feeder independent from the building electrical installation one, the results presented in this work remain valid, due to the physical proximity between both feeders.

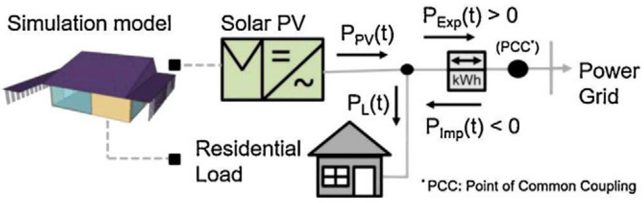

Fig. 3. Ekó House electrical system topology under investigation.

The electricity used to supply the consumption, $P_L(t)$, over an evaluation period between τ_1 and τ_2, can be calculated according to Eq. (1), in which, $P_{PV\to L}(t)$ is the electricity produced by the PV system and directly consumed by the load and $P_{Imp}(t)$ is the electricity imported from the grid. The energy balances are the integral of the measured power flows during 5 min period of time, typically found in readings of electricity meters.

$$\int_{\tau_1}^{\tau_2} P_L(t)\,dt = \int_{\tau_1}^{\tau_2} P_{PV\to L}(t)\,dt + \int_{\tau_1}^{\tau_2} P_{Imp}(t)\,dt \qquad (1)$$

During periods when the solar generator power is not sufficient to supply the load demand, electricity is imported from the grid. When the PV generator produces enough power to supply the loads, there is no grid requirement, and the surplus electricity is considered to be exported to the grid. Thus, the grid behaves as a backup for the system and the electricity injected into the grid is credited for the building.

The electricity generated by the PV system, $P_{PV}(t)$, can be decomposed into two dependent variables of solar generation concerning load supply and electricity exported to the grid:

$$\int_{\tau_1}^{\tau_2} P_{PV}(t)\,dt = \int_{\tau_1}^{\tau_2} P_{PV\to L}(t)\,dt + \int_{\tau_1}^{\tau_2} P_{Exp}(t)\,dt \qquad (2)$$

Table 3
Annual simulation results of energy indicators for Brazilian State Capitals.

Annual simulations	Brasília	Belo Horiz.	São Paulo	Florianóp.
PV installed power, P_0 (kW_p)	3.68	3.68	4.14	4.14
Inverter AC rated power (kW)	3.68	3.68	4.0	4.0
Performance Ratio, PR (%)	80.85	79.90	82.00	82.15
PV electricity, E_{PV} (kWh)	6088	5979	6010	6021
Imported electricity, E_{Imp} (kWh)	1958	1920	2535	2386
Exported electricity, E_{Exp} (kWh)	4393	4322	4216	4289
PV-electricity consumed by the house, $E_{PV\to L}$ (kWh)	1695	1657	1795	1732
Electrical load electricity, EL (kWh)	3653	3576	4330	4118
Of which: Cooling space (%)	24.16	23.78	18.52	23.76
Heating space (%)	2.64	2.70	2.23	2.49
DHW (%)	9.34	8.30	23.00	13.56
Lighting and Appliances (%)	63.86	65.22	56.25	60.19

where $P_{Exp}(t)$ is the electricity exported to the grid which can be combined into two fractions of electricity of interest under typical "net metering" regulatory schemes [4]:

$$\int_{\tau_1}^{\tau_2} P_{Exp}(t)\,dt = \int_{\tau_1}^{\tau_2} P_{Comp}(t)\,dt + \int_{\tau_1}^{\tau_2} P_{Surplus}(t)\,dt \tag{3}$$

where $P_{comp}(t)$ is the electricity feed-in to the grid to offset the electricity imported from the grid when the solar PV system is not available and $P_{Surplus}(t)$ is the electricity excess produced by the PV system over the building demand.

In order to analyze the utilization degree of the on-site PV generation related to the local building demand the following load matching indicators are proposed. The Load Cover Factor, $ʒ_L$, defined by [25], represents the percentage of the electrical demand covered by the PV system. It is evident that $ʒ_L = 0$ implies that there is no local generation, and with $ʒ_L$ closer or equal to one the local generation matches the local consumption. The Supply Cover Factor, $ʒ_G$, described in [26], is related to the PV-generated electricity that supplies the loads with respect to the total generated electricity. A system operating with $ʒ_G$ values closer to unit is a system that does not export large amounts of energy to the grid and the correlation between $P_{PV}(t)$ and $P_L(t)$ (P_{PV}-P_L correlation) is suitable to improve the self-consumption capability.

$$ʒ_L = \frac{\int_{\tau_1}^{\tau_2} P_{PV\to L}(t)dt}{\int_{\tau_1}^{\tau_2} P_L(t)dt} \quad ; (4)$$

$$ʒ_G = \frac{\int_{\tau_1}^{\tau_2} P_{PV\to L}(t)dt}{\int_{\tau_1}^{\tau_2} P_{PV}(t)dt} \tag{5}$$

In this sense, the Behavior Ratio (BR) represents the ability of a PV system to match in real-time the consumption. For low values of BR either the building holds a large excess of PV electricity, the consumption is too high for the PV installed peak power or the consumption does not match the generated electricity [26].

$$BR = ʒ_L \cdot ʒ_G \tag{6}$$

In addition to the parameters previously described, it is necessary to add to the analysis new variables that bring information about the electrical exchanges with the external power grid, the so-called grid interaction. Grid interaction parameters take into account the unmatched parts of generated or load profiles (e.g. peak powers injected into power grid) [27]. The Dimensioning Rate (DR) is defined as the peak power exchange over the connection capacity [28]. This parameter gives information about the daily highest peak, without detailing the amount of peaks or the duration of the peaks [28]. Under the assumption of "self-consumption" connection mode, it is useful to define a Dimensioning Rate as the minimum value of net imported electricity from the grid (DR_{Imp}). When considering the PV excess electricity over the grid connection capacity, DR_{Exp} is defined as the maximum value of the net exported electricity into the grid. The net values of DR_{Imp} and DR_{Exp} should never exceed the unit for a "grid-friendly" operation.

$$DR_{Imp} = \frac{\min\left(P_{Imp}\right)}{P_{GCC}} < 0; P_{Imp} < 0 \quad (7);$$

$$DR_{Exp} = \frac{\max\left(P_{Exp}\right)}{P_{GCC}} > 0; P_{Exp} > 0 \tag{8}$$

in which, P_{GCC} is the power of grid connection capacity representing the nominal connection capacity between the building and the power grid.

In addition, two grid interaction indicators were proposed: the Power Grid Imports Factor (F_{Imp}) and the Power Grid Exports Factor (F_{Exp}), that represent the imported power from the grid and the

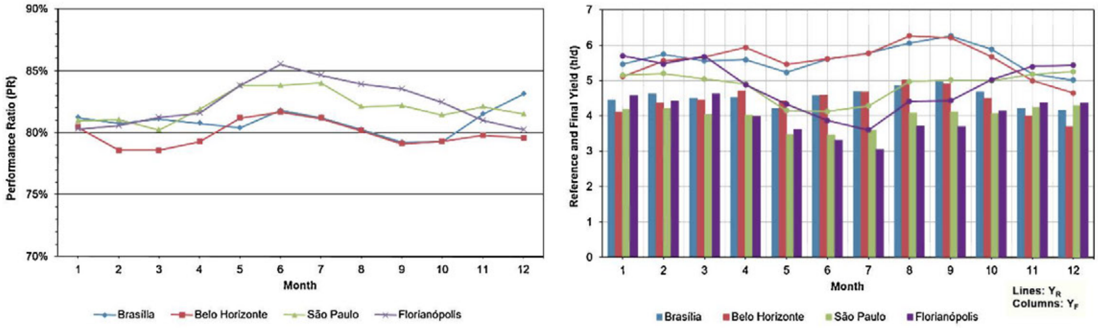

Fig. 4. Daily mean distribution profile for reference and final yields (left) and for performance ratio (right).

exported power to the grid, respectively, expressed as a function of the nominal connection capacity:

$$F_{Imp} = \frac{P_{Imp}(t)}{P_{GCC}} < 0 \tag{9}$$

$$F_{Exp} = \frac{P_{Exp}(t)}{P_{GCC}} > 0 \tag{10}$$

The reasoning in defining these parameters is the possibility to compare power flows with the grid with available PV electricity in normalized terms (equivalent hours of rated power grid use). If F_{Imp} is smaller than −1, the building has exceeded the limits of the grid imports connection capacity and in most cases a penalty is imposed by the power utility. If F_{Exp} is larger than one, the power exported is larger than the maximum allowed limit which can lead to undesirable voltage rise in the point of common coupling (PCC) between the PV array and the grid.

In this research, the evaluation of the effective PV system performance was conducted by calculating the overall system performance indices including the Final Yield (Y_F), Reference Yield (Y_R), Performance Ratio (PR), and Capacity Factor (CF) over reference periods as defined by the IEC Standard 61724 [29]. The final yield is defined as the annual, monthly or daily net PV energy output divided by the PV installed capacity (P_0) at standard test conditions (STC) of 1000 W/m^2 solar irradiance and 25 °C cell temperature.

$$Y_F = \frac{E_{PV}[kWh_{AC}]}{P_0[kW_{DC}]} \tag{11}$$

The reference yield is the total in-plane solar irradiation H_t (kWh/m^2) divided by the reference irradiance (1 kW/m^2); therefore, the reference yield measures the solar resource of the location.

$$Y_R = \frac{H_t[kWh/m^2]}{1kW/m^2} \tag{12}$$

The performance ratio is the final yield divided by the reference yield and represents the total losses of the PV system, including losses on the DC–AC conversion, soiling, module degradation, cabling losses, inverter inefficiency, mismatch losses, system failure or shutdown.

$$PR = \frac{Y_F}{Y_R} \tag{13}$$

Finally, the capacity factor (CF) is defined as the ratio of the actual annual energy output to the amount of energy the PV array would produce if it operated at full rated installed power for 24 h per day for a year [30].

$$CF = \frac{Y_F}{8760} = \frac{E_{PV,anual}[kWh_{AC}]}{P_0[kW_{DC}].8760} \tag{14}$$

2.7. Economic assessment criteria

The Levelized Cost Of Electricity (LCOE) is the cost of generating electricity at the point of connection to a load or electricity grid during the PV system lifetime and covers all system initial investments and operation and maintenance costs (O&M), including the replacement of PV system components when necessary. The analysis of LCOE allows comparing generation costs in PV systems differing in size, solar cell technology and location. Typically, PV solar systems have large capital investment costs (CAPEX) and low operating costs (OPEX). Thus, the CAPEX of the system is usually the dominant expense, and the method used to characterize this expense has a large impact on the average cost of energy. The LCOE (R$/kWh) is given by Eq. (15):

$$\mathrm{LCOE} = CAPEX \times (CRF + OPEX) \times \left(CRF \times \sum_{k=1}^{n} \frac{E_k}{(1+\rho_t)^k} \right)^{-1} \tag{15}$$

Where, CRF is the Capital Recovery Factor in the year k and represents the amortization cost of the system, E_k is the energy produced in the kth year and ρ_t is the annual discount rate. In this paper, the annual net present electricity cost was assumed during 30 years period, which represents the expected PV generator lifetime (n) currently considered in profitability analyses [9]. The annual cost of operation and maintenance (OPEX) was 1% and the PV yield decay caused by crystalline silicon solar cells efficiency losses was − 0.5% per year [31].The Net Present Value (NPV) is the most widely used parameter to estimate the profitability of an investment and it is the optimal method to deduce the time at which the initial investment begins to generate economic benefits (payback time). To calculate the NPV, it was considered as annual incomes the savings that the house achieves using PV energy compensation system compared to the savings without DG, including expenses for O&M.

3. Simulation results

3.1. PV system performance

By virtue of the limitation of PV installed power with respect to the grid connection capacity, according to Brazilian regulations, the PV capacity at each location was designed equal to the maximum annual load demand ($P_{L,Max}$), considering a margin of 20% for cases where the load power exceeds the maximum values assigned by the simulations. Taking into account the load profiles in the Brazilian capitals, two scenarios were defined based on the same PV module type: 3.68 kW$_p$ for Brasília and Belo Horiz. and 4.14 kW$_p$ for São Paulo and Florianópolis. The modules were simulated with the same electrical characteristics from those installed in the house. The grid connection capacity P_{GCC} is equal to the inverter AC rated power that represents the maximum power that could be injected into the grid during periods of solar generation above the local demand, as indicated by Table 3. Belo Horiz. and Brasília are the cities that need less nominal connection capacity due to lower annual consumption and high levels of solar generation, and São Paulo and Florianopolis demand more energy from the grid.

PV performance parameters for Brazilian state capitals are depicted in Fig. 4, including the solar resource, PV system yield and compound losses (respectively Y_R, Y_F and PR). The monthly daily mean Y_R is minimum in July in Florianópolis (3.6 h/d) and maximum in September in Brasília (6.26 h/d). The annual daily mean Y_R is higher in Brasília and Belo Horiz. (5.6 h/d) than in São Paulo and Florianópolis (4.85 h/d). PV final yield suffers a significant influence of the daily solar resource and ambient temperature and, as indicated in Fig. 4, the best cases of Y_F are in August and September in Belo Horiz. and Brasilia reaching values from 4.95 to 5.0 h/d. São Paulo and Florianópolis show better results for Y_F during the summer from November to March. PR shows the total effect of system losses and failures and may be used to identify operational problems. In this study PR can be used as straightforward indicator to compare the PV system operation in different locations with different designed PV system capacities. The temperature has great influence on PR because increases losses on PV modules output. In warmer climates, as in the case of Brasília and Belo Horizonte, PR is lower when compared to cooler climates such as São Paulo and Florianópolis. In the investigated locations, PR values range from 78.5 to 85.5% which is comparable with well-engineered systems [32].

Table 3 shows annual simulation results of energy indicators for Brazilian State Capitals. Brasília is the city that feeds into the grid more amount of electricity, and in São Paulo the house requests more electricity from the grid to meet the demand for DHW due to lower temperatures throughout the year. The results show that in the Brazilian territory annual values of PR can be around 80%. In the

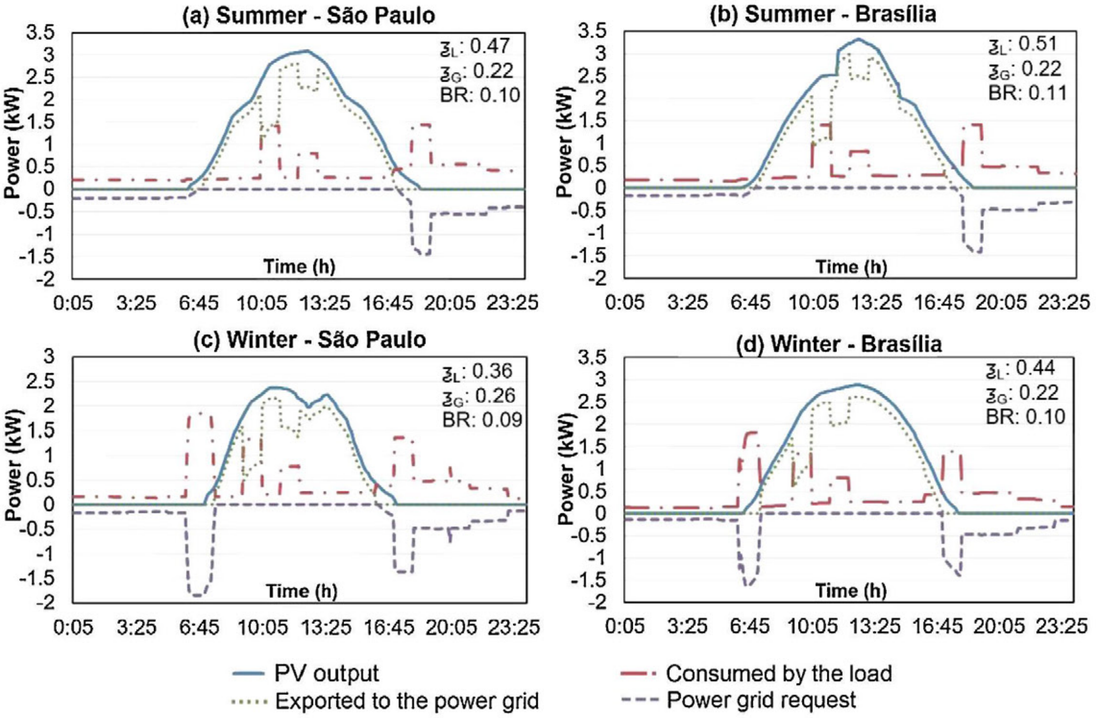

Fig. 5. Ekó house electricity flows in São Paulo ($P_0 = 4.14\,kW_p$) and Brasília ($P_0 = 3.68\,kW_p$) for summer and winter typical days.

reviewed of annual simulations the results show that the balance among E_{Exp} and E_{Imp} is always positive ($E_{Exp} > E_{Imp}$) for the studied locations and in this way the house performs as a NPEB.

3.2. Load matching parameters

It has been considered weather file meteorological data of each location to simulate the electrical consumption of HVAC system and electrical boiler. The contribution of appliances and lighting over load consumption was simulated through an annual schedule representing the operation hours of these loads. The simulations have been performed for complete years using 5 min time step interval. Fig. 5(a,b) present the electricity flows in the house on typical summer days in São Paulo and Brasília (summer season from 21st December to 21st March) with space cooling as the main influence on electricity demand. The highest imported electricity

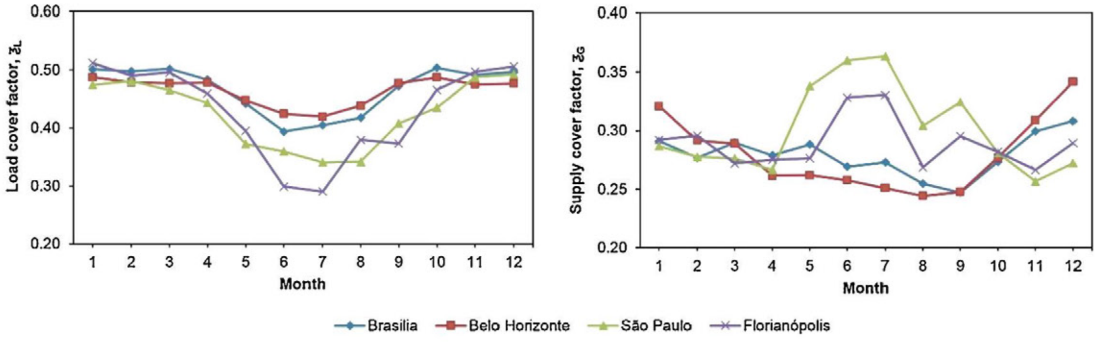

Fig. 6. Annual daily mean response of load cover factor (left) and supply cover factor (right) for four Brazilian state capitals.

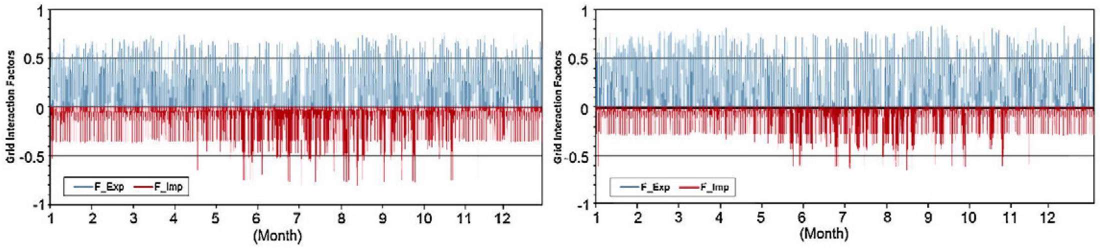

Fig. 7. Grid impact factors for São Paulo: Left: 4.14 kW_p PV installed capacity and 4 kW grid connection capacity. Right: 5.52 kW_p PV installed capacity and 5 kW grid connection capacity.

request starts at 6:00 pm and accounts for the operation of the HVAC system, appliances and lighting. The 4.14 kW_p PV system easily covers the demand of space cooling, appliances and lighting from 6:35 am to 5:30 pm. In Brasília city, cooling consumption is greater than in São Paulo in the afternoon due to higher temperatures and thus more percentage of the demand is covered by the PV (daily $ʒ_L$ is 51% in Brasília and 47% in São Paulo). This effect is also pronounced by $ʒ_G$ parameter where the daily mean generated electricity that is directly consumed by the loads is in general greater in Brasília. The surplus electricity fed into the power grid and not used by the load is converted in energy credits (kWh) to be used by the building, reducing substantially the purchased electricity from the grid.

Typical winter days (winter season from 21st June to 23rd September) are depicted in Fig. 5(c,d). In Brazilian climate, heating request is very low and the space heating does not account for a significant demand. There is a peak energy demand of the boiler from 6:00 to 7:00 am that the PV array does not supply and São Paulo needs more power to reach water setpoint temperature. From 5:00 to 6:00 pm a peak demand of appliances occurs, and in São Paulo, for a short period at night the boiler demands electricity to keep water warm. From 7:30 am to 4:25 pm the consumption of appliances and lighting is completely supplied by the PV system and thereafter the house requires electricity from the grid since the local generation drops to zero. By virtue of the reduction of cooling consumption in Brasília winter, associated with higher PV generation, $ʒ_L$ increases ($ʒ_L$ = 44% compared to 36% in São Paulo) and consequently the P_{PV}-P_L correlation gets smaller. In São Paulo, the on-site generation gets smaller, the P_{PV}-P_L correlation is slightly better ($ʒ_G$ grows from 22 to 26%) and there is less excess of PV electricity. During summer there are around two hours more Sun than winter and the Sun path is higher across the sky. In this way, the PV generator surface captures more solar energy, the PV system covers more percentage of daily total demand and $ʒ_L$ grows 11% in São Paulo and 7% in Brasília.

Fig. 6 shows the annual results of $ʒ_L$ and $ʒ_G$ for the Brazilian state capitals. The monthly daily mean load cover factor ($ʒ_L$) and supply cover factor ($ʒ_G$) range respectively, from 29 to 51% and from 24 to 36%, corresponding to typical values for residential buildings without batteries and Demand Side Management (DSM) implementation. There are significant seasonal variations of $ʒ_L$ and $ʒ_G$ for the studied locations. These variations are more pronounced in winter where the electricity consumption profiles change due to different temperatures in the Brazilian territory. In Florianópolis and São Paulo, from April to July less PV electricity is produced, cooling load decreases, boiler demands power before sunset and there is around two hours less of Sun. In this way, $ʒ_L$ decreases to below 40% because the PV array supplies less percentage of daily electrical demand. On these periods the supply cover factor $ʒ_G$ increases up to 10% in São Paulo and up to 6% in Florianópolis because the on-site generation gets smaller and the house profits more PV electricity during the day. On the contrary trend, from September to March, when there is highest need for electricity in the summer of Brasília and Belo Horiz. due to space cooling needs, the PV system shows high levels of generation. Consequently, the PV system covers more percentage of electricity demand, less amount of electricity is fed-in to the grid and $ʒ_L$ and $ʒ_G$ rates present highest annual levels. The results for $ʒ_G$ evidence that the load and generation profiles are not well correlated, there is a great excess of electricity and BR should be increased to improve self-consumption rates.

The results show that the house performs as a NPEB on an annual basis, however it should be kept in mind that the evaluations are aggregated values over a year and the time of demand and supply do not necessarily match. As shown by Figs. 5 and 6, $ʒ_L$ factor is typically below 50% due to the fact that no specific plan on the demand side was considered and one way to improve load-generation matching is to include an energy storage system allied with DSM strategies that would be able to enhance the house self-consumption potential, to reduce power grid requirements and also to complement PV electricity during low irradiance periods [25].

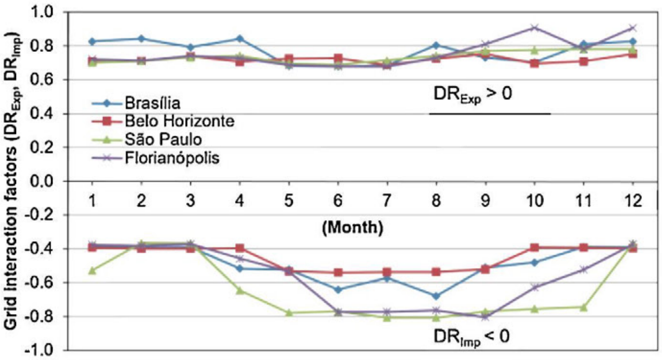

Fig. 8. Dimensioning rate of net imported electricity (DR_{Imp}) and net exported electricity (DR_{Exp}) for the Brazilian State Capitals.

3.3. Grid interaction parameters

One of the major requirements for DG is that the house demand does not exceed the grid connection capacity and the PV system contributes to the electrical demand supply. The results for São Paulo of the annual distribution of F_{Imp} and F_{Exp} presented in Fig. 7 show the magnitude of rated power grid use. It can be seen in Fig. 7 (left) the power grid exports factor (F_{Exp}) presents seasonal variations with less exported power magnitude from May to August. From January to April exhibits intermittent values of 0.7 and in some spring and summer days can surpass 0.8 scale, indicating the PV surplus does not surpass the connection capacity limits. The results of power grid imports factor (F_{Imp}) show that the imported power represents a quite constant fraction of an equivalent nominal connection capacity and the grid connection does not exceed the allowed limit. The demand associated to space cooling in summer generates F_{Imp} close to − 0.4. Due to the early morning load demand in winter associated to DHW demand, when no or little PV generation is available (see Fig. 5(c)), F_{Imp} factor can reach down to − 0.8.

In order to verify the grid interaction with different connection capacities, as an example, Fig. 7 (right) displays simulations for São Paulo with 5.52 kW_p PV installed capacity connected to an inverter of 5 kW (P_{GCC} = 5 kW). In this case, the exported power magnitude grows and F_{Exp} surpasses 0.8 in around 10 h of the year (equivalent to 0.11% of the yearly simulation interval) and the new grid connection capacity decreases F_{Imp} to below −0.6. This is due to the fact that the grid connection capacity is now considerably higher than the house peak demand and the new profile of PV system generation is able to mitigate the imported power with higher levels than the previous case.

Results of monthly values of Dimensioning Rate of net imported power (DR_{Imp}) and net exported power (DR_{Exp}) are shown in Fig. 8, considering the P_{GCC} values equal to inverter AC power as displayed in Table 3. As can be seen, the peak effects of exported and imported power vary fairly with the seasons for each studied location. Daily plotted results showed that for sunny days in Brazil the PV system feeds into the grid most of the generated power and as a result the DR_{Exp} parameter is high (annual mean DR_{Exp} is around 0.7 in the analyzed zones). For example, for the system operating in Florianópolis the peak effects of exported energy are notably significant in October and December with DR_{Exp} close to unit. The PV system

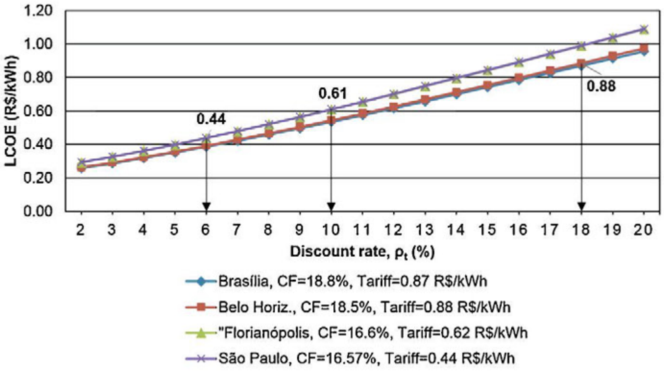

Fig. 9. Levelized cost of solar energy generation (LCOE) in 2015.

operating in Brasilia shows higher peaks in summer and for seven months DR_{Exp} values are around 0.8 due to the favorable solar conditions. In this sense, but considering large-scale DG penetration situations into the grid, taking into account exported power peaks over the grid that is not profited by the load, reverse power flows in the distribution lines can appear, which are a matter of concern for distribution utilities and the main reasons for limiting the capacity (active power) of nondispatchable DG that can be connected to the power grid, such as photovoltaics. The lower temperatures in São Paulo from May to November bring on significant increases of imported power due to DHW needs, and then on these periods DR_{Imp} varies between −0.74 and −0.81. In Florianópolis, the ambient temperature rises from September to December, the DHW load is reduced, the PV increases production and then DR_{Imp} decreases from −0.8 to −0.4. By virtue of the PV contribution on the afternoon cooling power peaks, DR_{Imp} is in general smaller in Brasília and Belo Horiz., thus in the sunniest months DR_{Imp} is only − 0.4. On the other hand, in the absence of PV system P_{Imp} corresponds to P_{Load} and the imported peaks are remarkable. For example, in Florianópolis during December DR_{Imp} decreases from −0.37 (with PV system) to −0.80 (without PV) by virtue of P_{Imp} is not mitigated by P_{PV}. To conclude, the dimensioning rate can give information about the expected peak power over the grid for different solar energy distributions, as well as the purchased power from the grid and the grid connection capacity can be reduced with rooftop PV system.

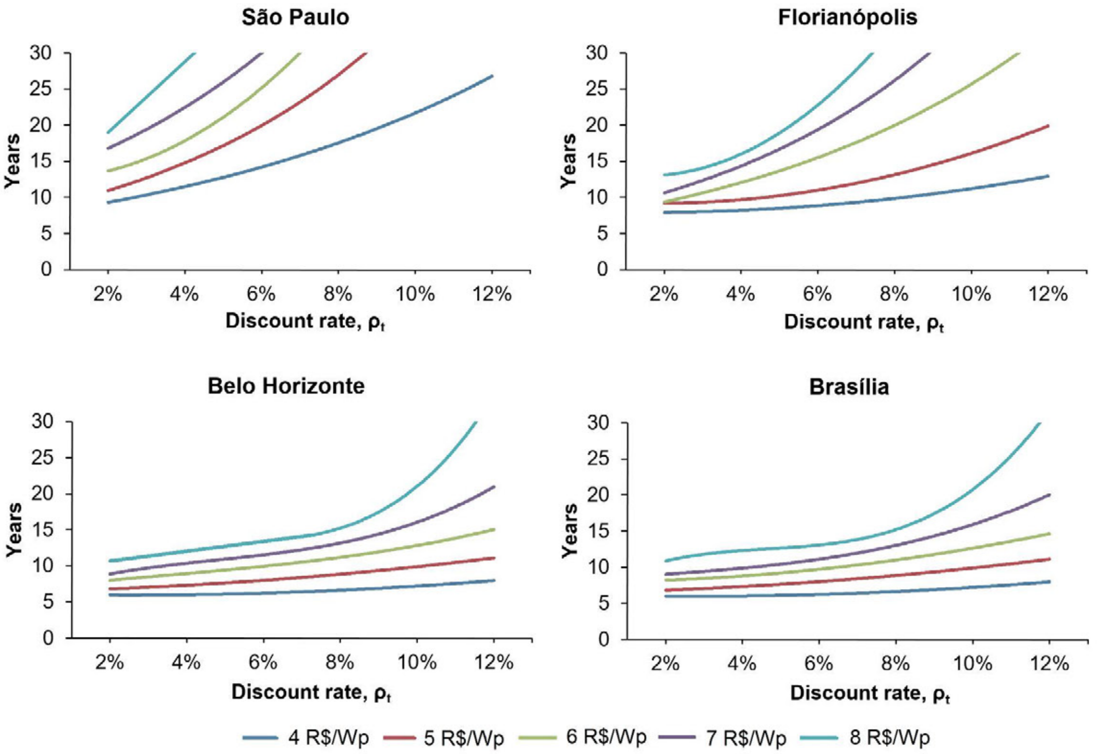

Fig. 10. Payback time for the Brazilian State Capitals as a function of the discount rate for different investment costs of residential PV systems.

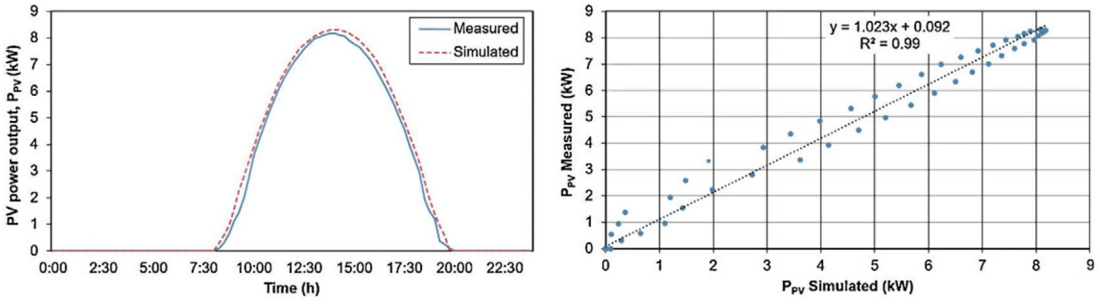

Fig. 11. Left: Daily comparisons of measured PV power output with simulated results. Measured data are given for each 15 min on 19th September of 2012 during Solar Decathlon Europe 2012 competition in Madrid. Right: Linear regression for measured and simulated PV power output. P_0: 11.04 kW_p.

3.4. *Cost of PV-generated electricity and payback time*

The investigations were performed considering the cost of PV modules and inverter obtained from typical Brazilian PV solar system installed in early 2015 [33]. The investment cost is 2.51 R$/W$_p$ for the PV modules, 1.55 R$/W$_p$ for the inverter and 3.26 R$/W$_p$ for the Balancing of System (BOS) costs, which represents the average price per unit of the rated output power. Considering added taxes and national taxes the investment cost is 7.32 R$ per Watt peak installed (equivalent to 2.35 €/W$_p$). Fig. 9 presents results of LCOE in function of discount rate variations of each state capital indicating when the LCOE is set equal to the electricity tariff in order to achieve grid parity. The distinct locations cover a range of solar radiation levels, capacity factors (CF), discount rates (ρ_t) and full power utility tariffs for the residential sector. The power utility tariffs include different tax levels among Federal States in Brazil, which have contributed to the existing regional tariff disparities [34]. In the last years, a 10% discount rate represented a mature market in Brazil. However, the rates can vary a lot, depending on variations in compound discount rates offered by Brazilian banks to private individuals for the acquisition of goods. The results show the investment on PV can be attractive in Brazil for low annual discount rates. The discount rate must be around 6% in São Paulo and 10% in Florianópolis, for the PV system to be profitable under the current residential buildings tariffs. In Belo Horizonte and Brasília, where the electricity tariffs are higher, the scenario changes, and around 18% discount rate the system achieves grid parity. As can be seen in Fig. 9, the LCOE decreases with increasing capacity factor, which means that the PV system operation is more feasible in regions with better solar generation panorama. Although, it was also observed the LCOE decreases with the CAPEX, which means that changes in the investment cost of the system have the highest impact on the LCOE.

For each Brazilian state, the annual savings obtained by using the energy credits produced by the PV surplus electricity injected into the grid, is directly related to the power utility tariffs and the financial incentives. In addition, the higher the credits are, the higher the annual savings will be, leading to shorter payback time of the PV investment. Whereas the discount rate is a variable difficult to predict, the price of PV technology is in constant reduction. This suggests the convenience to perform simulations to assess the NPV with ρ_t ranging from 2% to 12% and CAPEX ranging between 4 R$/W$_p$ and 8 R$/W$_p$, assuming a moderate increase in the average annual electricity tariff of 3%. Fig. 10 shows how the best situations for payback time are in scenarios with lower CAPEX and lower discount rates. Considering the current investment cost of 7.32 R$/W$_p$ the payback range from 13 to 31 years in Florianópolis, but adopting an optimistic scenario with CAPEX of 4 R$/W$_p$ the return of investment range from 8 to 13 years. Assuming São Paulo utility tariff, which is lower than in the other capitals, the annual savings are smaller and the payback is larger. In this scenario, for discount rates up to 6% and high CAPEX (> 7 R$/W$_p$), the payback approaches or is above the PV generator lifetime, which means that it would only be profitable to invest in scenarios with low ρ_t and low CAPEX. It can be noted that the cities of Belo Horizonte and Brasilia, having similarities in PV generation, exported electricity to the grid and electricity tariff, present coincident responses of return on investment. With higher electricity tariffs and more potential for PV generation (> CF), the payback time is shorter in these locations, because the prosumer saves more money (arising from PV generation locally consumed and the excess exported to the grid) than the other cities. For example, adopting 6% of discount rate, the payback time varies from 6 to 14 years according to CAPEX variations. Considering the same previous financial conditions ($\rho_t = 6\%$, annual tariff increment = 3%), with actual CAPEX of 7.32 R$/W$_p$, the net present value (NPV) at the end of PV lifetime can reach around R$ 25.000 in these locations.

4. Conclusions

The present work studied the performance of a NPEB analyzed in terms of PV system operation, LMGI indicators and economic assessment under Brazilian conditions. In this research, nearly 20 performance parameters were identified and the paper made a major contribution finding the advantages of applying analyzed indexes, indicating which cities of Brazil they are most suitable for. Daily and annual variations of the indexes have been presented highlighting the effectiveness in providing realistic simulations analysis. The first analyses indicated higher Y_R and Y_F in the zones with hottest climate and higher daily mean GHI, noticeably in Brasília and Belo Horizonte. Although, these zones presented higher losses assigned by the temperature effect on the PV modules power output. This study considered the importance of studying LMGI parameters to design PV arrays and electrical installations towards to self-sufficient houses. Daily electricity flows in the house was able to show the comparisons of the consumption, generation and exchanges with the grid in two cities, indicating there are no general rules for self-consumption because it depends of decoupled factors. The results showed the PV system installed in Brasília and Belo Horiz. have more potential to cover the demand, expressed by ʒ$_L$ factor, by virtue of the higher Y_R allied with higher cooling load requirement in summer, when the PV production is higher, and lower consumption in winter, when PV production is lower. According to the analyzed consumption profile, the statistics of ʒ$_G$ showed the smaller the on-site generation was more PV electricity was profited by the house and less excess of PV-origin electricity was noted, according to the results of São Paulo and Florianópolis, and the P_{PV}-P_L correlation grew with cooling load increases, according to the summer of Brasília and Belo Horizonte.

The seasonal variations of peak effects for each location was investigated. By growing the PV capacity to 5.52 kW$_p$ the magnitude of the exported power increased, as expressed by Fig. 7 (right). The study indicated the building injects high power peaks over the grid and thus DR_{Exp} margins are high in Brazil, with annual mean DR_{Exp} around 0.7. It was noticed in Brasília summer the values reached 0.8 in around seven months of the year. The results demonstrated the net imported power and the grid connection capacity can be reduced with rooftop PV system and the imported peak effects were more pronounced in the lowest solar radiation periods or in the periods the PV was not able to mitigate load consumption, as the early morning boiler power peaks exhibited in São Paulo.

Stimulated by increasing electricity tariffs imposed by distribution utilities, at a profitable LCOE, NPEB was set to achieve grid parity in the state capitals from discount rates of 6%, in the best case, to 18%, in the worst case. The results showed the Brazilian PV energy compensation system is remarkably profitable for prosumers in Brazil. The payback time showed to be shorter in Brasília and Belo Horiz. due to higher electricity tariffs allied to the high CF. The study demonstrated the economic scenarios vary from each location, depending on the electricity tariffs and applicable discount rates, and it should keep low CAPEX and low discount rates in order to reduce payback time. The feasibility of investment evidenced to be promising, however it should be kept financial incentives in correspondence with the annual prices reduction of PV technology.

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2. Appendix

The PV system operation in the competition Solar Decathlon Europe 2012 was simulated in EnergyPlus in order to quantify simulation model accuracy. It was used an Actual Meteorological Year (AMY) weather file from coincident year (2012) to measured data performed in the house. The weather file was taken from Weather Analytics[2] weather station placed in Madrid (around 2 km from competition site). The PV modules were oriented to the south with a 15° tilt angle. The reason for the low tilt angle is to increase the output in the summer offsetting periods of lower solar radiation. As a sample, daily profile comparison of PV power output with measured data is shown in Fig. 11. Differences between results can occur due the fact the simulation compiled through the weather file may vary fairly depending on the solar radiation sensors spectral responses due to weather changes and the real PV power output depends of the temperature effect on the module's efficiency, inverter thermal losses, shading, and other factors that is not ever quantified in the simulations.