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The impact of building-integrated photovoltaics on the energy demand of multi-family dwellings in Brazil

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Abstract

Brazil faces a continuous increase of energy demand and a decrease of available resources to expand the generation system. Residential buildings are responsible for 23% of the national electricity demand. Thus, it is necessary to search for new energy sources to both diversify and complement the energy mix. Building-integrated photovoltaic (BIPV) is building momentum worldwide and can be an interesting alternative for Brazil due its solar radiation characteristics. This work analyses the potential of seven BIPV technologies implemented in a residential prototype simulated in three different cities in Brazil (Natal, Brasília and Florianópolis). Simulations were performed using the software tool *EnergyPlus* to integrate PV power supply with building energy demand (domestic equipment and HVAC systems). The building model is a typical low-cost residential building for middle-class families, as massively constructed all over the country. Architectural input and heat gain schedules are defined from statistical data (*Instituto Brasileiro de Geografia e Estatística*—Brazilian Institute for Geography and Statistics (IBGE) and *Sistema de Informações de Posses de Eletrodomésticos e Hábitos de Consumo*—Consumer Habits and Appliance Ownership Information System (SIMPHA)). BIPV is considered in all opaque surfaces of the envelope. Results present an interesting potential for decentralized PV power supply even for vertical surfaces at low-latitude sites. In each façade, BIPV power supply can be directly linked to local climatic conditions. In general, for 30% of the year photovoltaic systems generate more energy than building demand, i.e., during this period it could be supplying the energy excess to the public electricity grid. Contrary to the common belief that vertical integration of PV is only suitable for high latitude countries, we show that there is a considerable amount of energy to be harvested from vertical façades at the sites investigated.

Keywords: Photovoltaic generation; Building energy simulation; Brazilian dwelling

1. Introduction

In recent years, Brazil has been experiencing a growing electricity demand due to both population growth, and per capita energy intensity, fueled by economic growth, access to cheaper electrical appliances that have only recently become available, and information technology [1–3]. Meanwhile, financing the considerable lump sums involved in large-scale hydropower projects, and overcoming the growing environmental barriers and opposition to such projects is becoming more and more difficult to justify. In this context, distributed alternative/renewable energy sources, especially building-integrated photovoltaics (BIPV), are likely to play a more significant role, if their costs decline as a result of economies of scale, and their distributed-nature benefits are translated in financial terms.

Brazil is a large-area and low-latitude country, with a large solar radiation resource and a low variability of the solar energy distribution content [4], which leads to a considerable potential for BIPV [5]. Residential, commercial and public buildings in urban areas correspond to over 45.2% of the electricity demand in the country, with residential dwellings being responsible for 22.3% [6]. In this article, we study the impact of integrating photovoltaics to the envelope of a hypothetical multi-family

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residential building, located in three different climatic regions, and analyze the potential of grid-connected BIPV on the energy these buildings demand from the public grid.

Most of the commercially available BIPV systems are either façade- or roof-integrated [7], with PV modules based on different technologies, which include the market-dominant crystalline silicon (c-Si), three thin-film technologies based on amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS), and a heterojunction comprised of a thin a-Si PV cell on top of a c-Si cell (HIT) [8].

The different light-to-electricity conversion efficiencies and operating temperature behaviors of these PV technologies should be taken into account in the design of a BIPV system. Nominal (nameplate) PV module output characteristics are given at the so-called Standard Test Conditions (STC),[1] and especially in warm climates and BIPV applications, where back-of-module ventilation is hindered and PV modules can reach considerably high temperatures [9], the temperature coefficient of power should be used to correct the expected operating efficiency. The only exception relates to the a-Si technology, for which the stabilized performance can be regarded as inert to temperature effects [10,11].

The integration of PV elements to the building envelope is an ideal application of PV generation, since PV modules can double as a power generation plant and a building element that can add value to urban architecture [12]. Running simulations of BIPV projects spanning from Brazil to Japan, it has been shown that over 50% of residential and commercial buildings' electricity needs can be supplied by wall, window and roof-integrated photovoltaic elements [13,14].

In Brazil, the economic viability of BIPV will be closely related to incentives, not yet in place, which has to be attractive enough for investors to become interested. The social, economic and industrial development potential associated with PV in Brazil will only eventuate if the large-scale nature of grid-connected photovoltaics is explored [15]. The first grid-connected, building-integrated PV system in the country was installed in 1997 as a retrofit to LABSOLAR's building, in Florianópolis [16,9]. The latitude-tilted (27° South), 40 m^2 installation uses thin-film, semi-transparent and opaque, unframed glass–glass PV laminates is been used to demonstrate the potential of solar modules as an energy-generating building element. This 2 kWp PV installation is fully monitored, logging temperature (ambient and module), radiation (horizontal and tilted) and electrical parameters continuously at 4 min intervals.

The extensive operational experience gathered in assessing the performance of this system, together with satellite-derived solar radiation data obtained from the United Nations-funded Solar and Wind Energy Resource Assessment (SWERA) project, were used in this work to study the effects of BIPV on the energy demand of multi-family residential buildings in three different climatic and geographic conditions in Brazil.

[1] STC: irradiation intensity of 1000 W/m^2, operating cell temperature of 25 °C, and spectral distribution of solar radiation equal to AM1.5.

2. Modeling and simulation

Computer simulation processes have developed a great deal in recent years, and are being extensively used, especially in the assessment of energy efficiency in buildings. In this work, we use the US Department of Energy's *EnergyPlus* software, which allows for the analysis of energy demand and flow, heating and cooling systems and loads, ventilation and lighting among others [17].

To run simulations on the application of PV systems, *EnergyPlus* (*version 1.2.1.o22*) allows for three mathematical model options to estimate the energy output of solar electric installations. In this work, we used the *Simple* model, which allows for the input of a fixed, arbitrary PV cell efficiency value. The other two model options use empirical relations to forecast a PV system operational behavior under different ambient temperatures [18]. We also used different PV technologies in our study, which present different performance behaviors with temperature; to account for temperature effects on PV module efficiency, we used the nominal operating cell temperature (NOCT).[2] Building geometry and solar incidence, as well as reflection and shading effects were also considered.

2.1. Modeling of the building

The building geometry selected was a typical middle-class Brazilian residential model. Floor plan, number of floors, building materials and internal heat loads were defined as per *Instituto Brasileiro de Geografia e Estatística*—Brazilian Institute for Geography and Statistics (IBGE) and *Sistema de Informações de Posses de Eletrodomésticos e Hábitos de Consumo*—Consumer Habits and Appliance Ownership Information System (SIMPHA) data. This prototype represents 15% of the middle-class residential flats in the country, with a growing share in the regions under analysis [19].

The prototype building has a 16 m × 19 m floor plan and four floors 2.8 m high each, with four apartments per floor. Each apartment has a 20 m^2 living room, two 12 m^2 bedrooms, a 10 m^2 kitchen and a 5 m^2 bathroom. Window to wall ratio (WWR) is 18% for living room and bedrooms.

In order to minimize simulation run times, the architectural model was translated into a thermal zone model. This adaptation was carried out considering the same temperature set point, internal heat gains generation, schedules and orientation for all rooms. As shown in Fig. 1, each floor was thus divided in five thermal zones: two living rooms (Lv) at 80 m^2 each, two bedrooms (Bd) at 96 m^2 each and a 132 m^2 common service area (Cm). Passageway areas were included in the common service area thermal zone.[3] Inside wall thermal inertia were considered in the simulations using a specific

[2] NOCT is the estimated temperature of a solar PV module when it is operating under 800 W/m^2 irradiance, 20 °C ambient temperature and a wind speed of 1 m/s. NOCT is used to estimate the nominal operating temperature of a module in the field.

[3] Since internal walls are made with concrete blocks, its thermal mass was considered.

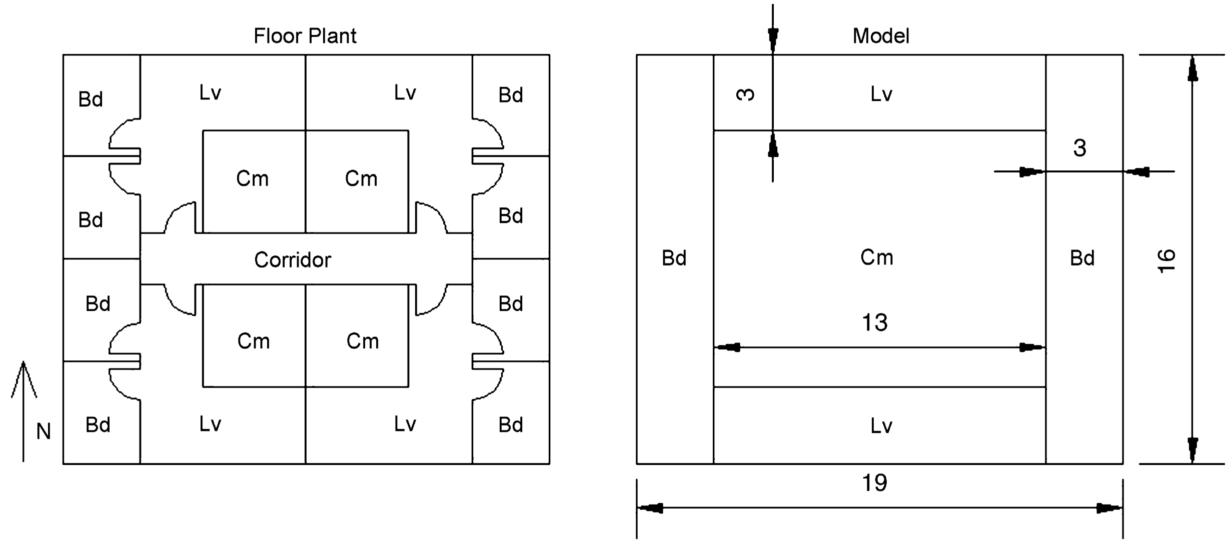

Fig. 1. Architectural plant and thermal zone model for residential prototype (dimensions are in meters, without scale).

software tool. *EnergyPlus* allows these elements to be described as ''Internal Mass'', and they contribute to the thermal balance area were they have been defined. A further assumption is that intermediary floors present the same thermal performance and can be modeled as a single floor with average height, carrying out thermal exchanges with the ground and top floors. Fig. 2 presents the 3D model of the building thermal model. Table 1 summarizes the geometrical characteristics of each thermal zone, and Table 2 shows the thermophysical properties of all materials used in the definition of building envelope. WWR is 18% for all building considering a 3 mm clear glass.

Each apartment occupation schedule was considered from early afternoon to early morning, with the first period running from 2 to 10 p.m. in the living room, and the second period running from 10 p.m. to 7 a.m. in the bedrooms. The maximum and minimum HVAC set point temperatures (23 and 18 °C) were used exclusively during occupation scheduled hours. Air exchange due to infiltration was set at 1.5 air change per hour (ACH), 24 h a day all over the year. Ventilation was set at 5 ACH during periods outside occupation-scheduled hours.

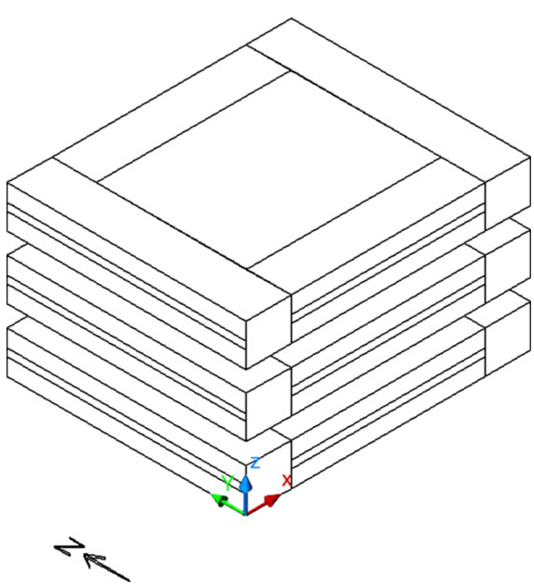

Fig. 2. 3D view of the thermal model for residential prototype.

Fig. 3 presents the occupation schedules of each thermal zone, identifying thermal loads as persons, lighting and equipment, as well as the HVAC running schedule.

2.2. Choice of photovoltaic technologies

Among the commercially available PV technologies, six different types of PV modules were selected, representing single silicon (m-Si), poly-silicon (p-Si) and amorphous silicon, as well as cadmium telluride, copper indium diselenide (CIS), and the highest efficiency heterojunction with intrinsic thin layer. Table 3 shows nominal power, module areas and STC efficiencies for the six particular module types selected. The lowest and highest efficiencies are typical of thin-film a-Si (6.3%) and HIT (17.0%), respectively. Module efficiency translates the actual share of incoming solar radiation that PV cells are able to convert to electricity, and is stated by manufacturers under standard test conditions that are hardly ever obtained in the field. Under real operating conditions and at 1000 W/m^2 solar radiation levels (typical of a clear day at noon), a dark-colored PV module will most likely be at temperatures considerably higher than the 25 °C defined as STC temperature, especially in warm climates like in Brazil.

Table 1
Geothermic characteristics of the thermal zones

	Area (m^2)	Volume (m^3)	Façade/ floor (%)	Window/ façade (%)	Window/ floor (%)
Room	80	224.0	93.3	13.0	16.7
Bedroom	96	268.8	128.3	17.9	16.7
Common	132	369.6	0.0	0.0	0.0
Floor	308	862.4	64.5	15.5	9.5

Table 2
Thermophysical properties of the materials used to define the components of the prototype

Layers	Thickness (mm)	Thermal capacity (kJ/(m^2 K))	Thermal resistance (m^2 K/W)
Wall			
Mortar	25	50.0	0.021
Concrete block	190	176.4	0.178
Mortar	25	50.0	0.021
Floor/slab			
Mortar	25	50.0	0.021
Concrete/clay slab	95	95.0	0.090
Mortar	25	50.0	0.021
Ceramic	10	14.7	0.011
Roofing			
Fiber–cement tile	7	11.2	0.007
Air space	–	–	0.210
EPS	50	1.8	1.250
Wood	10	13.8	0.071
Window			
Transparent glass	3	–	0.003

We routinely measure operating temperatures higher than 65 °C at our BIPV test site in Florianópolis [9], and would expect even higher operating temperatures in the Northeast. Except for a-Si, which has a negligible temperature coefficient of power ($T_{\mathrm{coeff},P_{\max}}$) after stabilization of the Staebler–Wronski effect [20,21] all PV technologies drop in power output with increasing operating temperatures. Table 3 also shows $T_{\mathrm{coeff},P_{\max}}$ for all PV technologies considered in this work. To account for operating temperatures higher than the STC 25 °C, we adopted a NOCT temperature of 45 °C, which, together with the application of the respective $T_{\mathrm{coeff},P_{\max}}$ for each PV technology, led to the correspondent temperature-corrected efficiencies ($\mathrm{EFF}_{\mathrm{NOCT}}$), for the 20 °C temperature difference (ΔT), as calculated by Eq. (1). Table 3 also shows the final $\mathrm{EFF}_{\mathrm{NOCT}}$, which were used as input data for *EnergyPlus* to calculate PV generation. To account for inverter, wiring and other losses related to STC nameplate DC rating to real AC output, we used a performance rate (ratio of actual to expected, STC-based performance) of 80%.

$$\mathrm{EFF}_{\mathrm{NOCT}} = \mathrm{EFF}_{\mathrm{STC}}\left\{\frac{100-(|T_{\mathrm{coeff},P_{\max}}|\,\Delta T)}{100}\right\} \tag{1}$$

Table 4
Geographical positioning of the cities [24]

City	Latitude	Longitude	Altitude (m)	Region
Natal	05°55′ (N)	35°15′ (W)	49	Northeast
Brasília	15°52′ (S)	47°55′ (W)	1.060	Middle West
Florianópolis	27°40′ (S)	48°33′ (W)	7	South

The simulation model considered PV modules applied to 95% of the roof area and to 95% of all opaque sections of external walls excluding window areas. No considerations are made as to PV module distribution patterns or installation details. PV-covered surface areas for the roof, North-, South-, East- and West-facing walls correspond, respectively, to 288.80, 177.46, 177.46, 139.84 and 139.84 m^2.

2.3. Weather and geography data

In this work, we present simulations developed for three Brazilian capital cities, namely Natal, Brasília and Florianópolis. These cities were selected based on their geographic location and climate differences. Brazil is a large country, with a total area of over 8.5 million km^2, and is divided into five macro-regions (North, Northeast, Central-west, Southeast and South), with latitudes spanning from 5°N to 33°S. Table 4 gives some details on the geography of the selected sites.

Fig. 4 shows the annual behavior of the minimum, average and maximum temperature monthly means for the three sites. Natal presents the highest annual averages, always around 25 °C, with the lowest range between maxima and minima (approximately 15 °C). Brasília and Florianópolis, on the other hand, show very stable average temperatures along the year, always around 20 °C. In winter months (July–September), however, Florianópolis presents lower minima than Brasília, with temperatures as low as 2 °C. Monthly maximum and minimum temperatures in Brasília and Florianópolis also show a larger range than in Natal. It is also interesting to note that maximum temperatures for the three sites are similar, between 30 and 35 °C.

Turning now to global solar radiation levels, Fig. 5 shows that the three sites are not only at considerable distances from each other, but they also present considerably different isolation

Table 3
Characteristics of PV panels technologies

Technology	Manufacturer	Power (W)	Module area (m^2)	$\mathrm{EFF}_{\mathrm{STC}}$ (%)	T_{coeff} (%)	$\mathrm{EFF}_{\mathrm{NOCT}}$ (%)
m-Si	BP Solar	170	1.26	13.50	–0.40[a]	12.42
a-Si	Bekaert ECD Solar Systems	64	1.12	6.30	0.00[a]	6.30
p-Si	BP Solar	75	0.64	11.60	–0.40[b]	10.67
CdTe	First Solar	50	0.72	6.90	–0.20[b]	6.62
CIS	Würth Solar	60	0.73	8.20	–0.45[b]	7.46
HIT	Sanyo	180	1.18	17.00	–0.33[c]	15.88

NOCT = 45 °C.
[a] Efficiency value (T_{coeff}) [21].
[b] Efficiency value (T_{coeff}) [22].
[c] Efficiency value (T_{coeff}) [23].

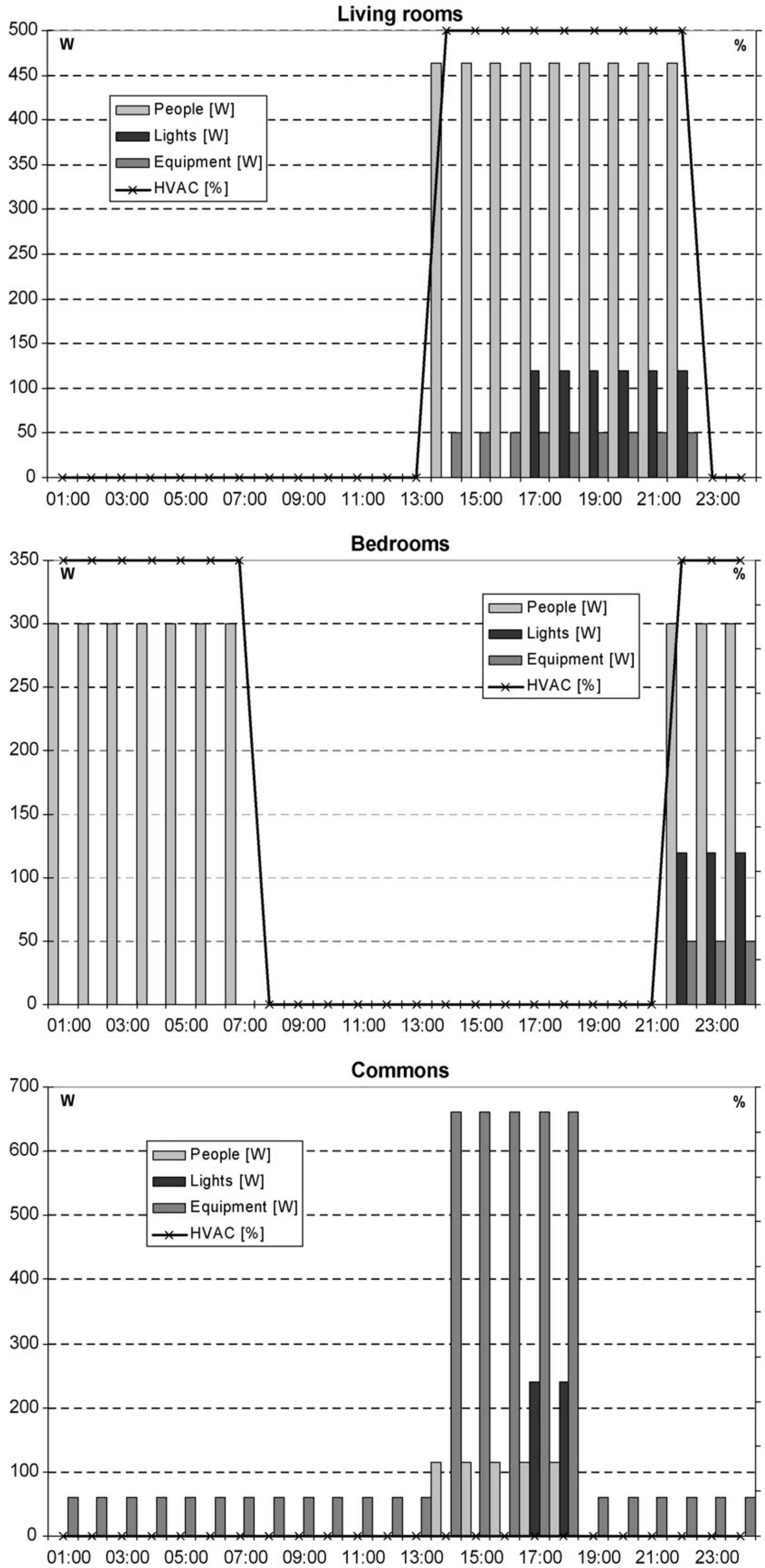

Fig. 3. Patterns of use, load components and HVAC system availability for each thermal zone.

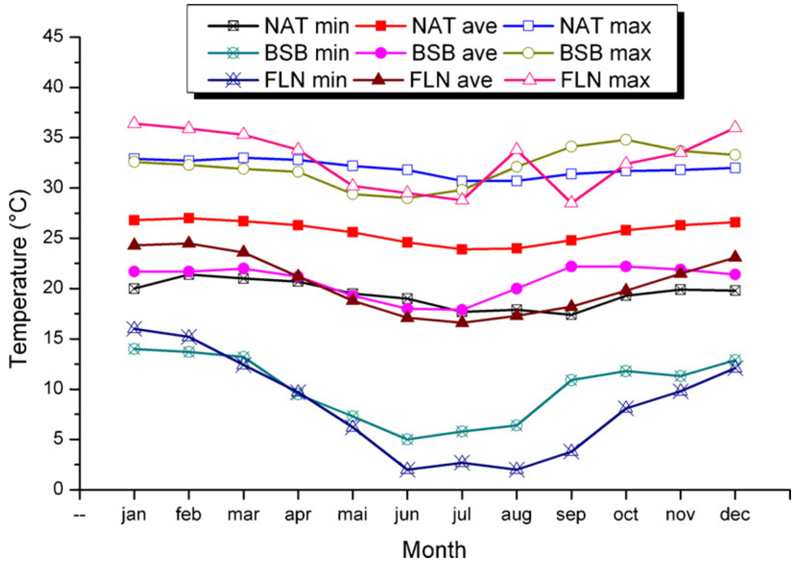

Fig. 4. Variation of the minimum, average and maximum temperatures for the cities of Natal (NAT), Brasília (BSB) and Florianópolis (FLN) throughout the year [23].

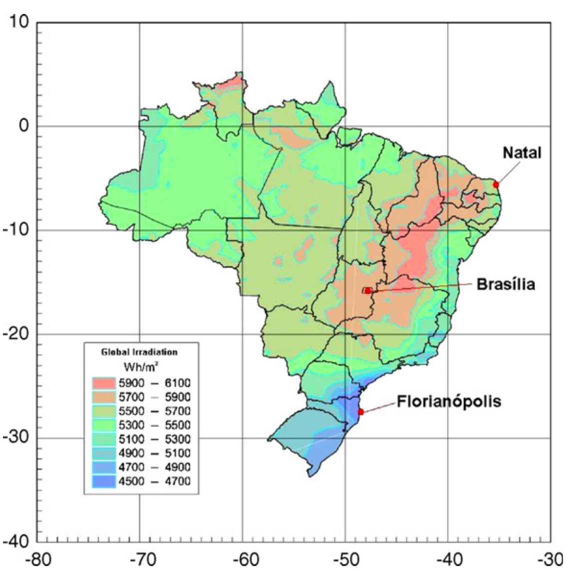

Fig. 5. Brazilian solar Atlas—annual average of the daily total global radiation incident on the horizontal plane [4].

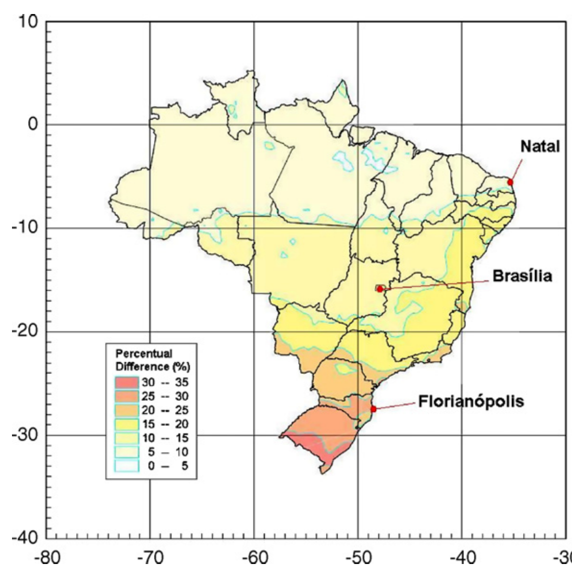

Fig. 6. Map of variability of the Brazilian solar Atlas—annual average of the percentage variation of global radiation on the horizontal plane [4].

intensities. Brasília is located at the Brazilian central plane, receiving over 6.0 kWh/m^2/day, one of the highest irradiation levels in the country. Natal, on the Northeast coast, ranges between 5.3 and 5.5 kWh/m^2/day, and Florianópolis, on the Southern coast, presents one of the lowest levels of solar radiation, ranging between 4.5 and 4.7 kWh/m^2/day. Fig. 6 shows the annual variability of the incoming global solar radiation on the horizontal plane. Natal is the most stable of the three sites, with deviations in the 5–10% range; Brasília presents a slightly higher variability, around 15%, and Florianópolis shows the highest seasonal fluctuations, ranging from 25 to 30%.

In the simulation process, Test Reference Year (TRY) files were used for each site. TRY files are compiled based on average data, excluding extreme high and low temperatures. TRY for Natal, Brasília and Florianópolis were, respectively, 1954, 1962 and 1963.[4]

3. Results

3.1. Building electricity demands

The simulation process revealed that for all three sites studied, the weeks with the highest electricity demands occur during the summer months (in the Southern Hemisphere) of January and February. It is also during summer that the highest irradiation levels are experienced, with solar energy

[4] Available for free download at www.labeee.ufsc.br.

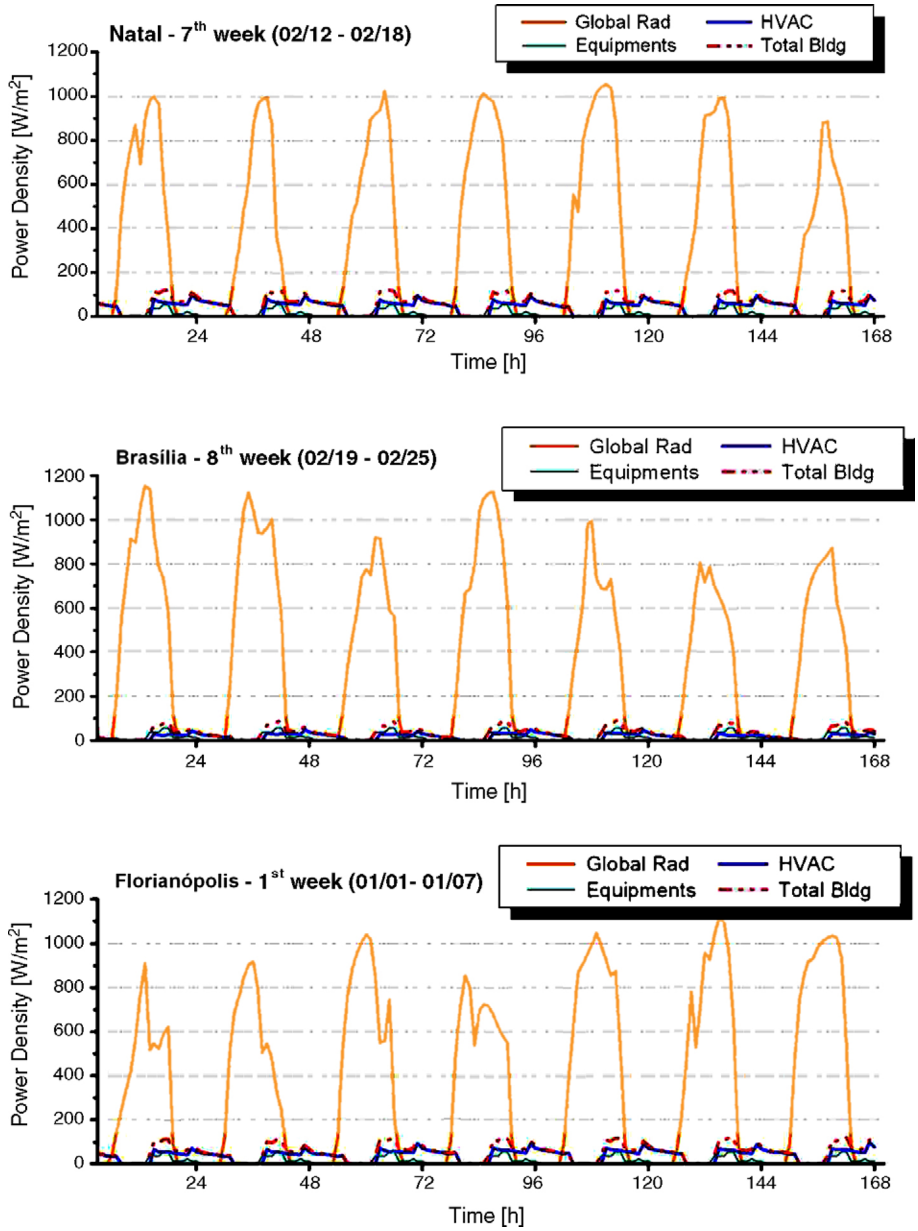

Fig. 7. Maximum demand week graphics for Natal, Brasília and Florianópolis.

available for some 12 h daily from around 7:00 a.m. to 6:00 p.m.

Fig. 7 presents the building's specific power demand (W/m^2 per ground projected area) compared with solar radiation (W/m^2 per ground projected area) availability for the three sites for the week with the highest demand (critical week). The dark-colored curve (Global Rad) presents the global horizontal solar radiation level; the grey-colored curve (Total Bldg) presents the total building's power demand per floor area, which results from the sum of HVAC and equipment loads including lighting. Over the critical week, HVAC and equipment represents on average, respectively, 75 and 25% of the building's power demand for Natal, 55 and 45% for Brasília, and 73 and 27% for Florianópolis.

Table 5
Average of demands and global radiation levels for building peak load hours on the critical week

City	Building demand (W/m^2)	Global radiation on the horizontal plane (W/m^2)	Percentage between global demand and global radiation
Natal	119.7	712.9	17
Brasília	84.9	545.9	16
Florianópolis	117.2	639.6	18

Table 6
Analysis of consumption and available solar energy throughout the critical week

City	Solar[a] energy (kWh/m^2)	Building consumption (kWh/m^2)			Percentage between total building consumption and solar energy	Percentage between building consumption and solar energy from 7 a.m. to 6 p.m.
		Total	During the hours with solar radiation incidence (7 a.m.–6 p.m.)	During the hours without solar incidence		
Natal	56.1	9.9	3.9	5.9	18	7
Brasília	59.1	5.4	2.7	2.7	9	4
Florianópolis	61.8	9.1	3.8	5.3	15	6
Average	59.0	8.1	3.4	4.6	14	6

[a] Horizontal plane.

Table 5 shows peak power demand averages per m^2 during the critical week for the three sites, as well as the corresponding average solar irradiation levels. It is interesting to note that during peak times, buildings in Natal, Brasília and Florianópolis operate at energy densities of 17, 16 and 18% of the incoming solar radiation, respectively. Integrating the curves in Fig. 7 we can compare quantitatively the building's total specific energy demands with the total incoming solar radiation during the critical week. On average, the total energy demands of our modeled buildings per m^2, summed over the day, are about seven times smaller (14%) than the available solar radiation per m^2 on the horizontal plane. However, only less than half (42.6%) of the building's power demands take place during the day. The same comparison for daytime hours (7 a.m.–6 p.m.) only reveals that on average the building's power density is some 16 times smaller (6%) than the available solar radiation. Table 6 shows these figures for the three sites selected in this study.

During the simulations it was also observed that for the weeks studied there were considerable radiation level shortfalls along the day, even during times when solar radiation was supposed to peak. These results from using simulations that runs on TRY files, which take into account the possibility of overcast portions of any day of the year.

Brazil is a country with a predominantly tropical climate and mild winters. The three cities analyzed in this study show very small HVAC loads during winter, and only for Florianópolis was there a need for heating during 2 days of the year. Since during winter the incoming solar radiation reaches minimum levels, it is important to also estimate the corresponding power demands for the week with the lowest irradiation level. Fig. 8 shows the building's demand per m^2, as well as the solar radiation incident on the horizontal plane for the week with the lowest irradiation integral for Natal, Brasília and Florianópolis. During that week the amount of solar energy available is some 62% lower than the available irradiation during the week with the highest electricity demand. The building's total demand is also some 59% lower than during the critical week, indicating a good match between solar energy availability and building loads. Even during the week with the lowest irradiation levels, the average building's electricity demand per m^2 is approximately six times lower (15%) than the available solar energy density on the horizontal plane.

Taking into account only the period between 7 a.m. and 6 p.m., demand is 11 times lower (9%) than the available solar energy density. Table 7 shows results for the irradiation density and the buildings' electricity demand during the week with the lowest amount of available solar radiation for the three cities considered in this study.

These results demonstrate the considerable potential of solar energy at the sites studied. Even under the worst possible local conditions (week with the highest energy demand and week with the lowest solar radiation availability), all the buildings' electricity demands per m^2 were considerably lower than the available solar radiation per m^2. This aspect can be better visualized in terms of hourly averages, where energy demand ranges from 6 to 10 kWh/m^2, and solar radiation availability lies between 164 and 211 kWh/m^2.

3.2. Photovoltaic generation

Table 8 shows the forecasted PV energy production (kWh/year) that each façade and PV technology can yield annually. In

Table 7
Analysis of consumption and solar energy throughout the lowest radiation availability week

City	Solar[a] energy (kWh/m^2)	Building consumption (kWh/m^2)			Percentage between total building consumption and solar energy	Percentage between building consumption and solar energy from 7 a.m. to 6 p.m.
		Total	During the hours with solar radiation incidence (7 a.m.–6 p.m.)	During the hours without solar incidence		
Natal	27.5	5.0	2.7	2.3	18	10
Brasília	27.0	2.6	1.8	0.8	10	7
Florianópolis	12.9	2.4	1.7	0.7	19	13
Average	22.4	3.3	2.1	1.3	15	9

[a] Horizontal plane.

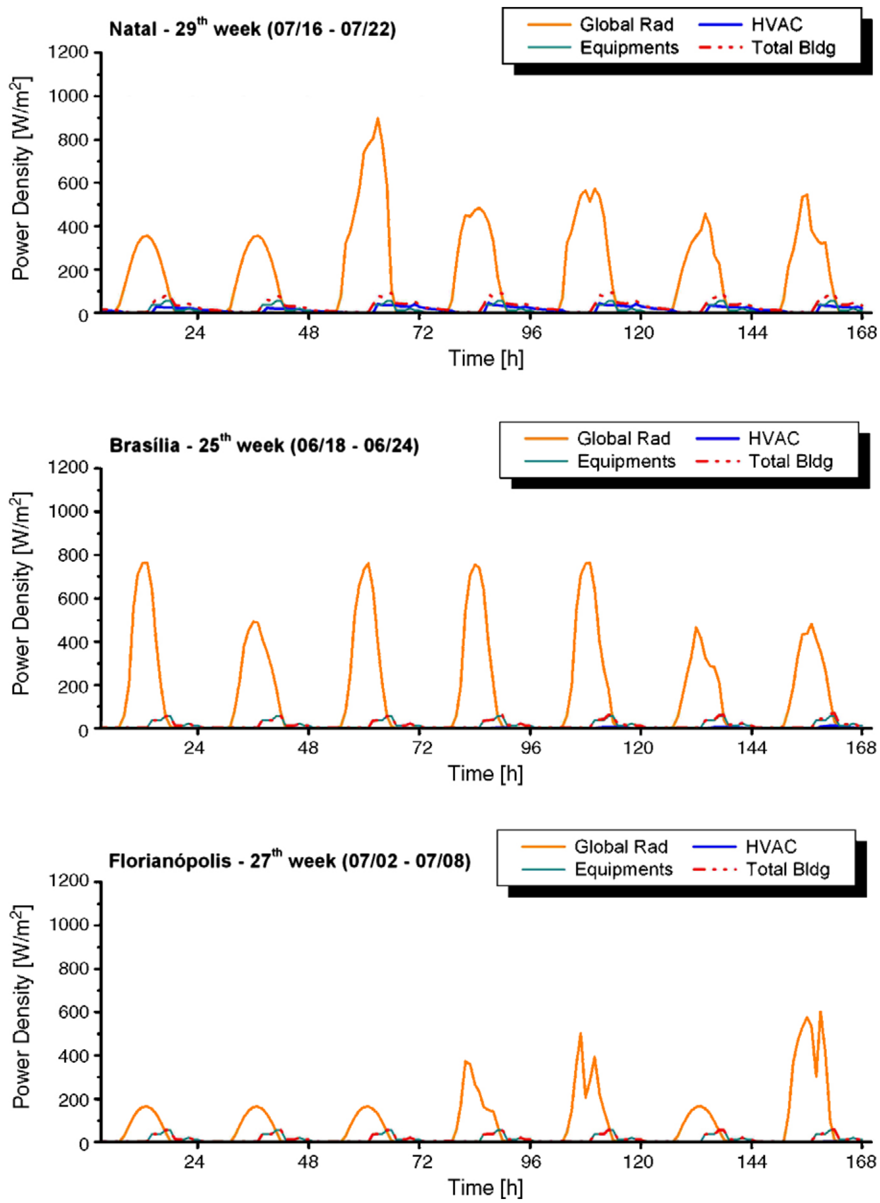

Fig. 8. Minimum demand week graphics for Natal, Brasília and Florianópolis.

all cases and as expected, PV systems installed on each building's rooftop yield more energy than on any of the vertical façades. It is important to note, however, that the building model has a PV-suitable roof area of 288 m^2, and vertical façades of 139 m^2 (N and S orientation) and 177 m^2 (E and W orientation). Among vertical façades, N orientation results in the highest yields for all sites and PV technologies. As expected, PV technologies with the highest efficiencies yield the largest amounts of energy. We will present further studies taking into consideration the a-Si and HIT PV technologies, which present, respectively, the lowest and highest conversion efficiencies.

For the a-Si and HIT PV technologies, and for each of the three cities considered, Fig. 9 shows the annual energy generation density (kWh/m^2/year) for each façade and roof. The horizontal axis shows the daily maximum solar radiation level on the horizontal plane (W/m^2), and the horizontal axis presents the PV-generated energy densities for each day (kWh/m^2). Therefore, all 8760 h are represented in each graphic.

Fig. 9 also shows that for N and S orientations at the highest latitude sites (Brasília and Florianópolis), generation profiles are different, because the N façade (facing the equator) receives more irradiation along the year. In overcast days, when the fraction of diffuse radiation is maximum, both orientations receive similar solar radiation levels. However, when horizontal global radiation exceeds 400 W/m^2, the N surface generates more energy, peaking when horizontal irradiation reaches intermediate levels (600–800 W/m^2 for Florianópolis, and 800–1000 W/m^2 for Brasília), during winter months when the sun is lower in the sky and with a more N-oriented path. For Natal, on the other hand, both N and S walls present a similar behavior, which follows that of the available horizontal solar radiation.

E and W façades generate similar amounts of energy both in Brasília and Florianópolis, with the W orientation yielding

Table 8
PV output and percentage of consumption met by the PV generation within each façade

	Wall—N		Wall—S		Wall—E		Wall—W		Roof		Total		Consume [MWh]
	MWh	%	MWh	%	MWh	%	MWh	%	MWh	%	MWh	%	
Natal													
a-Si	7.1	8.2	6.5	7.5	6.7	7.8	8.0	9.2	28.0	32.3	56.3	65.0	86.6
CdTe	7.5	8.7	6.8	7.9	7.1	8.2	8.4	9.7	29.4	33.9	59.2	68.3	
CIS	8.5	9.8	7.7	8.9	8.0	9.2	9.4	10.9	33.1	38.2	66.7	77.0	
HIT	18.3	21.1	16.7	19.2	17.3	20.0	20.4	23.6	71.7	82.8	144.5	166.8	
m-Si	14.1	16.2	12.8	14.8	13.3	15.4	15.7	18.1	55.1	63.7	111.0	128.2	
p-Si	12.1	14.0	11.0	12.7	11.4	13.2	13.5	15.6	47.4	54.7	95.4	110.1	
Brasília													
a-Si	8.1	15.6	5.5	10.5	7.2	13.8	7.3	14.0	27.5	52.9	55.5	106.8	51.9
CdTe	8.5	16.4	5.7	11.0	7.5	14.5	7.6	14.7	28.9	55.6	58.3	112.3	
CIS	9.6	18.5	6.5	12.4	8.5	16.4	8.6	16.6	32.5	62.6	65.7	126.5	
HIT	20.8	40.0	14.0	26.9	18.4	35.5	18.7	35.9	70.5	135.7	142.3	274.0	
m-Si	16.0	30.8	10.7	20.7	14.2	27.3	14.3	27.6	54.2	104.3	109.4	210.6	
p-Si	13.7	26.4	9.2	17.8	12.2	23.4	12.3	23.7	46.5	89.6	94.0	180.9	
Florianópolis													
a-Si	7.4	13.6	4.2	7.7	5.5	10.0	5.5	10.1	20.0	36.6	42.6	78.1	54.6
CdTe	7.8	14.3	4.4	8.1	5.8	10.5	5.8	10.6	21.0	38.5	44.8	82.0	
CIS	8.8	16.1	5.0	9.1	6.5	11.9	6.6	12.0	23.7	43.4	50.5	92.4	
HIT	19.0	34.8	10.8	19.8	14.0	25.7	14.2	26.0	51.3	94.0	109.4	200.2	
m-Si	14.6	26.8	8.3	15.2	10.8	19.7	10.9	20.0	39.5	72.2	84.1	153.9	
p-Si	12.6	23.0	7.1	13.1	9.3	17.0	9.4	17.2	33.9	62.0	72.2	132.2	

1.4% more energy than the E wall. In Natal, the W orientation presents a considerably higher generation level than the E orientation (some 18% higher on average), which can be traced back to different cloud cover behaviors between morning and afternoon at the site along the year, as demonstrated in Fig. 10.

3.3. Energy demand versus PV generation

Fig. 11 shows the relation between the buildings' energy demand (kW) and the PV-generated power for the year's 8760 h at each site for all the PV technologies considered in this study. The cloud of points spans through a wide range of energy demand and PV generation situations, the most unfavorable of which being the case for high air-conditioning demand in the evening (with no PV generation), i.e., the highest demand point in the horizontal axis, and the most favorable case being represented by points where demand is minimum, and PV generation is maximum. It can be seen that in each of the six combinations shown, the most favorable situation leads to PV power being generated in excess of the energy demanded in the least favorable case.

The 1:1 line in each graph shows a considerable number of points above the line, indicating a considerable amount of hours when PV-generated power is higher than the building's electricity demand. Table 9 lists the percentage of hours in which the building would be feeding electricity to the public power grid. Considering that the PV modules cover 95% of the opaque wall and roof areas, the installation would be exporting energy to the grid 30% of the time.

Table 9
Hour percentage in which the PV systems supply the grid with energy

	a-Si (%)	HIT (%)
Natal	30.4	42.2
Brasília	36.8	44.9
Florianópolis	30.9	42.2

Table 8 also presents the total energy supplied by each case of the façades and roof, and the corresponding fraction of the building's total energy demand. It can be seen that in all cases and for all PV technologies, the total annual PV generation exceeds 65% of the total building's energy demand (the worst case being represented by the a-Si technology in Florianópolis), reaching over 274% of the demand for the HIT technology installed in Brasília.

Fig. 12 shows, for the a-Si and HIT PV technologies, the contribution of each façade and the roof to the total annual PV generation in each of the three sites. For the specific building modeled, the largest amount of energy (>45%) will be produced in all cases on the rooftop portion of the PV installation. As far as the façades are concerned, in the case of Natal, Florianópolis and Brasília, the largest generation fraction comes from the N-oriented wall (12.7, 17.4 and 14.6%, respectively), and the lowest generation occurs on the S façade (11.5, 9.9 and 9.8%, respectively). For the E and W façades at both Brasília and Florianópolis, the contribution is around 13%. In Natal, however, the contribution of the façade orientations leads to a different spread of contributions, with the main share coming from the W-facing wall (14.1%), and the lowest contribution from the E orientation (12.0%).

It can thus be concluded that even at low latitudes like in most sites in Brazil, the PV generation potential of vertical surfaces is considerable. Contrary to the common belief that vertical integration of PV is only suitable for high latitude countries, it has recently been shown [25] that a N-oriented

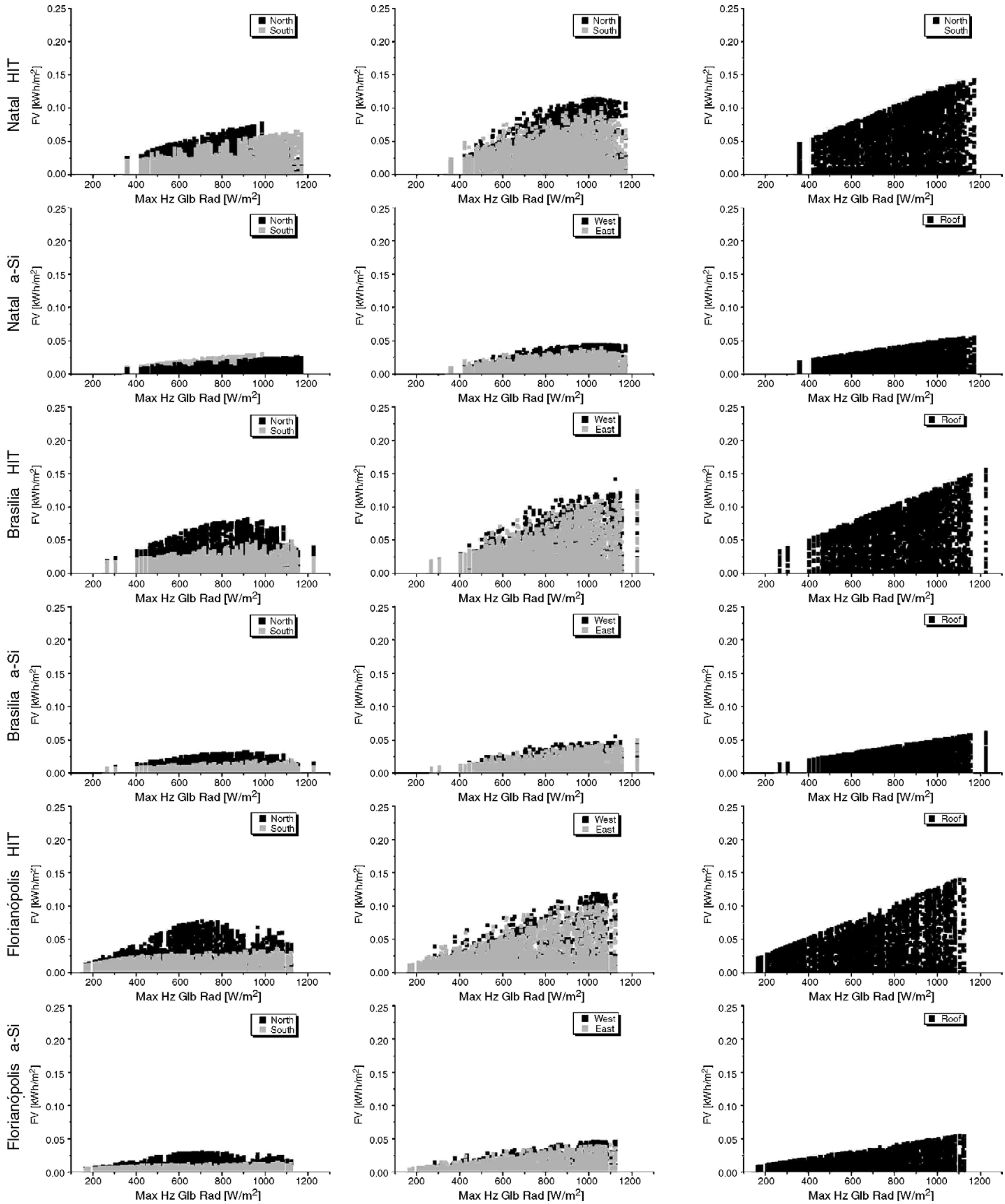

Fig. 9. Annual graphics for PV output for each surface and a-Si and HIT technologies for Natal, Brasília and Florianópolis.

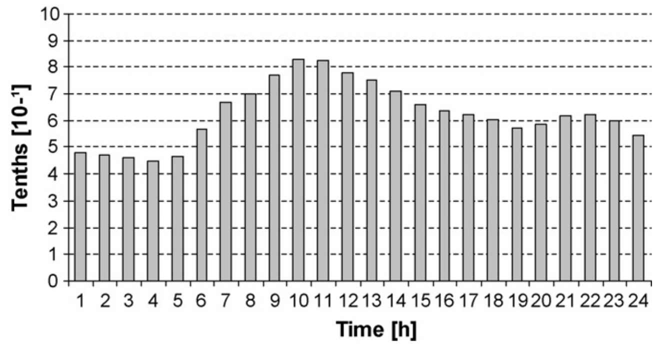

Fig. 10. Average of total sky cover (tenths) to Natal presents in TRY file [23].

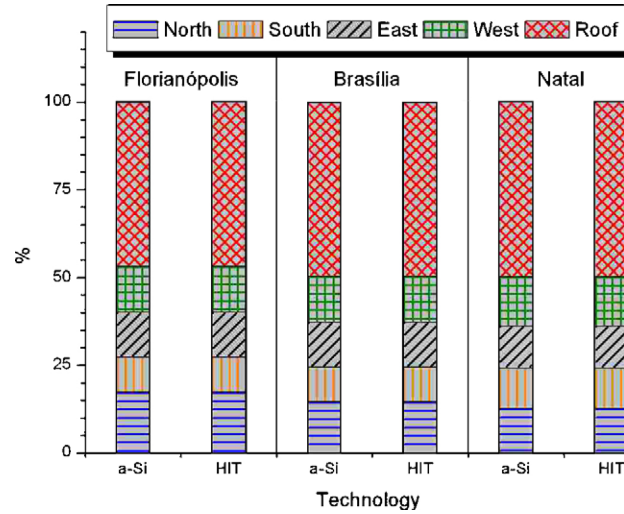

Fig. 12. Distribution by surface of PV generation annual for a-Si and HIT technologies for Natal, Brasília and Florianópolis.

vertical façade in Florianópolis (one of the sites in Brazil with the lowest irradiation levels in the country) receives some 10% more solar radiation than a S-oriented vertical façade in Freiburg (48°N, one of the sunniest sites in Germany). For the typical building model simulated in this study, comparing the PV generation on the roof (288 m^2) with that resulting from the sum of similar wall areas oriented W and E (total of 280 m^2) leads to the combined W and E walls yielding on average some 50% of energy produced by the roof in all cases. It should be noted, however, that these results assume no shading effects from adjacent buildings, which will only be possible in well-planned situations, and impossible in densely built urban centers.

We now extend this analysis to a more general scope. Fig. 13 shows, for the HIT and a-Si PV technologies, respectively, the yearly PV generation per m^2 (PV generation density) for the roof and façades. With these figures we can show the potential of each surface independent of surface area.

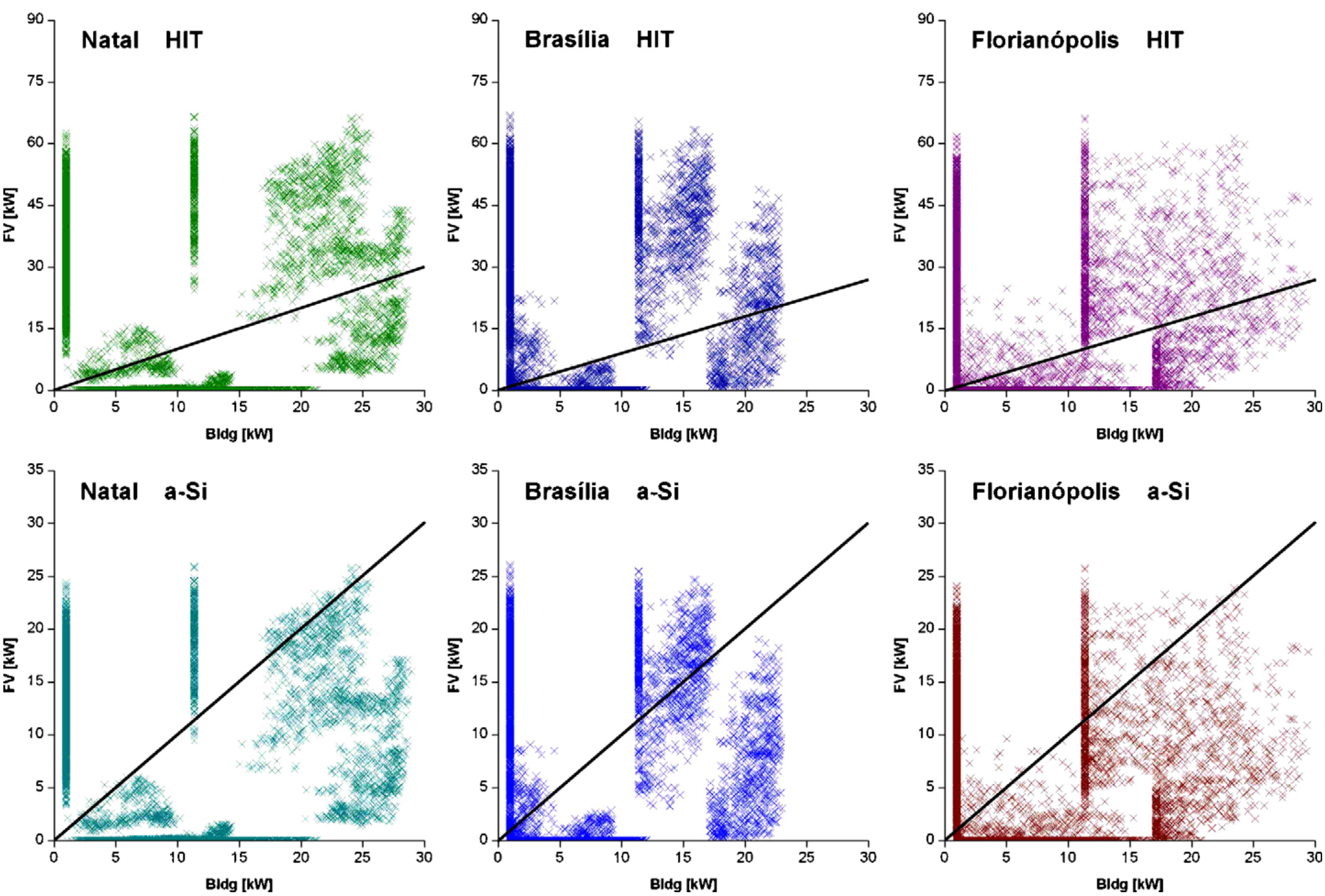

Fig. 11. Annual relation between building demand and PV power output for a-Si and HIT technologies for Natal, Brasília and Florianópolis.

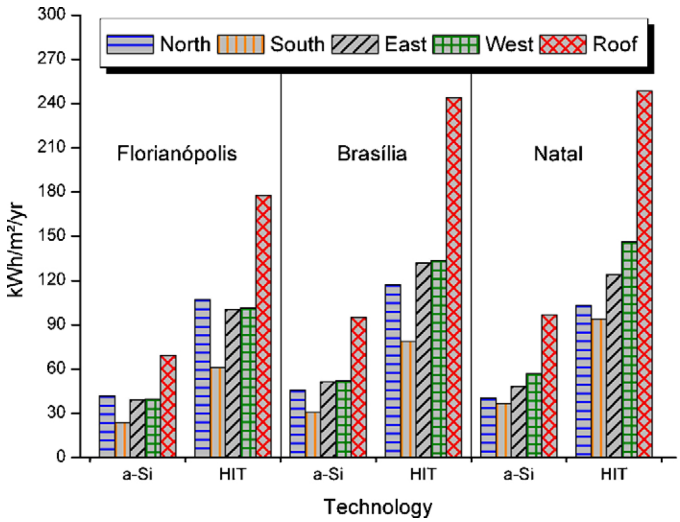

Fig. 13. Density generation by surface for Natal, Brasília and Florianópolis (a-Si and HIT technology).

In all cities the largest amount of energy is generated on the roof areas, but vertical surfaces show significant generation potential. In Florianópolis, N-oriented walls yield some 60% of the amount that can be generated on the roof, and E and W orientations can also yield 56% of the roof production each.

Brasília reveals that each of the W and E surfaces lead to 54% of the energy yield of the roof area, and the N façade can generate 48% of the energy that can be harvested from the roof.

Natal shows a different behavior, with the W façade yielding the highest generation levels among all vertical surfaces, reaching 59% of the energy yielded by the roof. N and L surfaces lead to 42 and 50%, respectively, of the roof potential. The higher potential observed for the W façade can be directly linked to a local climatic condition, where the largest amount of solar radiation is available in the afternoon period due to clearer skies in the afternoon, as shown in Fig. 10.

A common feature of the three sites is that S-facing walls receive the least amount of energy, yielding about one third of the energy that can be harvested from the roof per m^2.

4. Conclusions

We have shown that even though the use of BIPV systems in Brazil is not yet considerable, this technology presents an interesting potential for decentralized generation in urban areas in sunny countries, even when considering vertical façades at low latitudes.

The *EnergyPlus* software is useful tool for analyzing BIPV installations associated with HVAC systems in thermo-energetic analyzes. The main difficulty in its use is related to the establishment of a building model which translates reality as close as possible, so that the simulations can be regarded representative.

Despite the myriad of different architectural topologies of buildings in Brazil, the model selected for this study was simplified as much as possible to account for the main characteristics of Brazilian residential buildings. The same strategy was used when establishing the buildings' energy use patterns. As far as PV technologies are concerned, it should be noted that Brazil is a tropical country, and operating temperatures of these dark-colored PV surfaces under full sun can reach 65 °C and over [20]. The strong negative coefficient of power of some of the PV technologies shown should be taken into consideration in the choice of technologies and in the sizing of PV systems.

Our results demonstrate that at the three sites studied there is a considerable potential for solar energy generation. Even during the worst possible scenarios (highest energy demand week and lowest irradiation week), energy demand per m^2 was only a fraction of the incoming radiation available. Using hourly averages of energy demand and irradiation, the buildings studies showed average energy demands in the range from 6 to 10 kWh/m^2, while global horizontal irradiation ranged from 195 to 268 kWh/m^2.

A further hourly analysis demonstrated that along the year there is a considerable amount of hours when the PV system generates more energy than the building demands. For the particular building model selected, some 30% of the time the building is feeding energy to the public grid.

It was demonstrated that the integration of PV elements to vertical façades in Brazil, even at low-latitude sites, is not negligible and should always be considered. In some instances, local climatic conditions can lead to considerable deviations in the expected solar energy distribution, resulting in unexpected contributions from the various surface orientations in a building.

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