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Solar energy scenarios in Brazil. Part two: Photovoltaics applications

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ABSTRACT

This paper discusses some energy scenarios for photovoltaic applications in Brazil engendered by using SWERA database in order to demonstrate its potential for feasibility analysis and application in the energy planning for electricity generation. It discusses two major different markets: hybrid PV–Diesel installations in mini-grids of the off-grid Brazilian electricity system in the Amazon region, and grid-connected PV in urban areas of the interconnected Brazilian electricity system. The potential for using PV is huge, and can be estimated in tens to hundreds of MWp in the Amazon region alone, even if only a fraction of the existing Diesel-fired plants with a total installed capacity of over 620 MVA would fit to run in an optimum Diesel/PV mix. Most of the major cities in Brazil present greater electricity demand in summertime with the demand peak happening in the daytime period. This energy profile match the actual solar resource assessment provided by SWERA Data Archive, enabling grid-connected PV systems to provide an important contribution to the utility's capacity.

1. Introduction

Currently, two issues are imperative in the energy sector: the energy security and the environmental damage due to the consumption of the conventional sources of energy. In addition, the requirement of supplying electricity to remote communities, that currently do not have access to it, is a vital issue in developing countries in order to improve the country's socio-economic condition and the capacity to compete in the global market.

In most of the large countries of the developing world, it is widely acknowledged that distributed energy resources are the only way of making electricity available to the billions of people that presently do not have access to it. There is no capital available and it is not cost-effective to deliver electricity power in the traditional way. Long distances and relatively small energy demands make electricity transmission and distribution costs prohibitive. Mini-grids fed by small to medium Diesel generator sets are commonly used to supply electricity to most of these remote communities and small towns. While this might be a least-cost alternative to extending the public electricity grid in terms of investment, running costs are high (and reliability and service quality are low), and it is important not to neglect the environmental costs associated with greenhouse gases emission due to the Diesel consumption.

The plant life-cycle equation will often show there are better options than fossil fuel plants, like the hybrid Diesel/photovoltaic (PV) power plant systems without storage, where PV systems are added to existing Diesel thermal plants in the Amazon region, for example. Besides offsetting Diesel consumption during daytime hours, these systems have prospects of future conversion to fuel cell/PV hybrid configurations, in which case energy generation would rely 100% on PV. It can be argued that in the short-term hybrid Diesel/PV and in the medium-term hybrid fuel cell/PV plants feeding mini-grids can represent real markets for PV, creating demands that can lead to large-scale PV manufacturing in Brazil, leading to the necessary cost reductions for PV to become a real player in this country. Grid-connected, building-integrated PV systems in the urban environment can also have an important role to play especially in sunny areas of the Central-West and Northeast Brazil, where high annual energy yields make PV generation more competitive.

2. PV in the world

Grid-connected PV is presently the fastest growing energy technology in the world, which grew in existing capacity by 55% per year from 2000 to 2005 (Mints, 2006). Second is wind power, which grew by 28% per year (Martinot, 2005). On the other hand, PV conversion of solar energy to electricity is currently one of the most costly energy generation alternatives commercially

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available. Hence, maximizing the benefits of this decentralized, modular, silent and clean renewable energy technology is of fundamental importance to improve its economic value when compared with more traditional energy technologies (Denholm and Margolis, 2007).

The establishment of national incentive programs in many regions worldwide, especially in Japan, Germany, Spain, and the USA, has led to the impressive growth rates shown in Fig. 1, and the installation of some 2.5 GWp of PV in 2006. More than 80% of the new installations were grid-connected PV systems (Mints, 2006). Table 1 shows the regional PV demand growth, both in terms of installed capacity and percentage of total, and the evolution of the PV market from 2000 to 2005. Fig. 2 shows the forecast of this booming market for the next 10 years, on a business as usual (BAU) and accelerated (ACC) scenario (Mints, 2006).

Despite the huge solar energy resource availability and the potential of using PV in a variety of grid-connected and stand alone applications, Latin America has been responsible for a very small fraction of the worldwide PV market, shrinking from some 4% (11 MWp) in 2000 to about 1% (20 MWp) in 2005, as shown in Table 2. This slowing demand in Latin American countries could mean that PV is preferred less than other renewables for many reasons including cost and the lack of technological awareness, or that conventional energy sources are more preferred. It could also mean that financial resources for off-grid PV systems for solar home systems, which are the most common application of PV in the region (68% as shown in Table 2), are stalled, or that programs

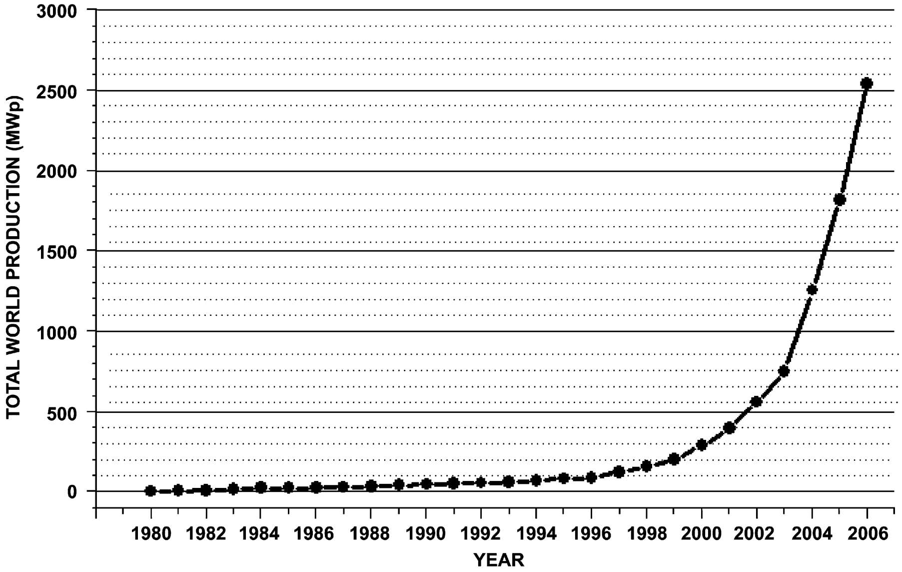

Fig. 1. Evolution of the global photovoltaic market including all technologies and manufacturers. (*Source*: Photon International, 2007).

Table 1
Major photovoltaic market categories

Market category	Status–valuation–reliability	Customer description
Remote industrial	• Earliest commercial market • High credit for economic value • Reliability required: high urgent	• Most-sophisticated customer • Requires detailed specifications but lesser systems support
Remote habitation	• Second market entered in volume • Medium value and reliability • PV is life-cycle-competitive now	• Least sophisticated customer, in developing countries • Most systems support required
Consumer power	• Established niche markets • Novelty, portability, and independence from conventional power are key	• More sophisticated customer in industrialized countries • Little customer support required
Grid-connected	• Market penetration continuing, driven by incentive schemes • Low credit for economic value • System reliability required: high • Lifetime required: long	• Industrial country consumer • Education needed to raise perception of value • Ongoing support structure required • Beginning of interest from building industry
Consumer indoor	• 1980s-market entry and saturation • Economic value: non-issue • Reliability, life required: low	• Broad, global customer base • Little customer support required • Short lifetime expected

Source: Adapted from Mints (2006).

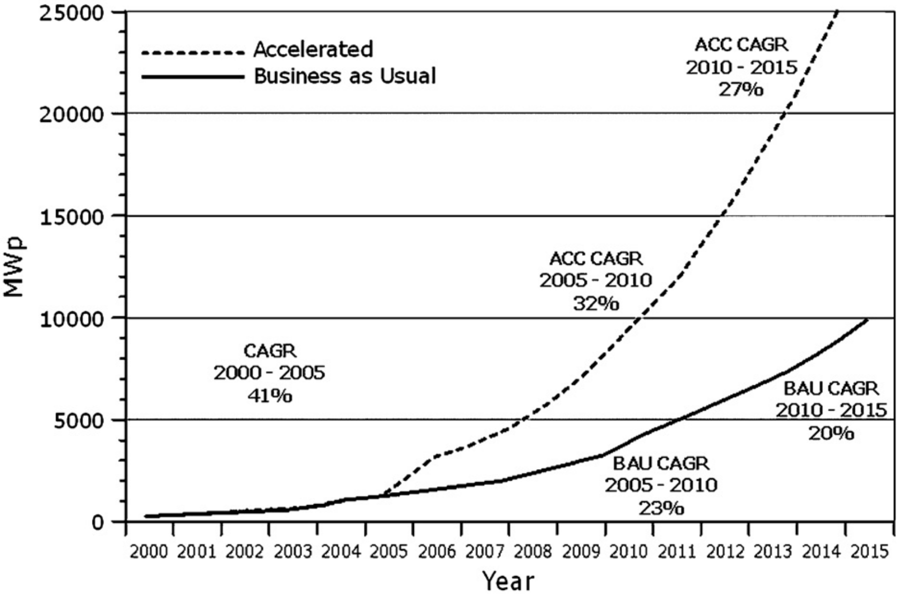

Fig. 2. Projected photovoltaic industry growth in the business as usual (BAU), and accelerated (ACC) scenarios, with compound annual growth rates (CAGR). (*Source*: Mints, 2006).

Table 2
Regional demand growth of the photovoltaic market. Source: Adapted from Mints (2006)

Region	2000	2001	2002	2003	2004	2005	CAGR 2000–2005 (%)
Europe	74.1	119.9	172.6	232.6	472.4	667.4	55
Percent total	29	34	34	34	45	48	
Asia	83.3	117.4	187.1	262.7	341.5	448.0	40
Percent total	33	33	37	39	33	32	
North America	36.8	46.2	61.9	77.6	105.0	139.0	30
Percent total	15	13	12	11	10	10	
West Asia	15.1	18.4	23.5	28.3	42.0	48.6	28
Percent total	6	5	5	4	4	3	
Latin America	11.3	13.2	15.5	18.6	21.0	20.8	13
Percent total	4	4	3	3	2	1	
Oceania	9.3	11.7	14.4	19.6	22.1	20.8	18
Percent total	4	3	3	3	2	1	
Southeast Asia	6.1	7.2	8.8	11.0	15.8	19.5	26
Percent total	2	2	2	2	2	1	
Central/Southern Africa	10.1	12.0	13.3	15.7	18.9	18.1	12
Percent total	4	3	3	2	2	1	
Middle East	2.6	3.1	3.4	4.1	4.9	5.6	16
Percent total	1	1	1	1	<1	<1	
North Africa	3.3	3.8	4.4	5.1	6.3	1.8	−11
Percent total	1	1	1	1	1	<1	
Total	252.0	352.9	504.9	675.3	1049.8	1389.5	41

CAGR stands for compound annual growth rate.

are poorly administered (Mints, 2006). Although government incentives for displacing the use of fossil fuels in thermal generation by the use of renewables like solar, wind and biomass are already running in Brazil, these incentives are not attractive enough to justify their adoption by private enterprises.

In addition to the government incentives, detailed knowledge of the solar energy resource availability, with increased space and time resolution, is of extreme value in order to reduce the uncertainties associated with PV system performance and energy generation forecasting (Colle et al., 2004). Economic analysis of PV generation systems using life-cycle cost analysis over periods of 20–30 years can only be performed with an acceptable confidence level, if accurate and high-resolution information on the solar resource is available, and in this context is that the SWERA project represents a valuable asset for energy planners and investors (Martins et al., 2008).

Table 3 shows an overview of the traditional PV industry application segments. Each of these segments presents peculiarities in the way PV systems are designed and installed, and might also differ in who will be the user of the solar radiation data necessary to size the installation or application. Except for consumer power and consumer indoor applications, the quality and reliability of solar radiation database is a major issue. The confidence on the solar radiation data is critical for remote industrial applications like communication systems, water pumping, village power or rural lighting.

Table 3
Breakdown of the photovoltaic market by region and application segment

Region	2005 total MWP	% Grid residential	% Grid commercial	% Grid utility	% Off grid industrial	% Off grid habitation	% consumer power	% consumer indoor
North America	139.0	35	28	<1	16	15	4	0
Latin America	20.8	0	<1	4	27	68	1	0
Europe	667.4	54	43	<1	1	1	<1	0
Middle East	5.6	0	1	4	55	35	5	0
North Africa	1.8	0	2	0	58	35	5	0
Central Southern Africa	18.1	0	0	3	28	65	4	0
West Asia	48.6	0	4	7	44	39	5	<1
Asia	448.0	85	2	0	4	4	2	2
Southeast Asia	19.5	2	<1	0	29	56	7	5
Oceania	20.8	9	1	1	44	36	9	0
Global total	1389.5	57	25	1	7	8	2	1

Source: Adapted from Mints (2006).

High-quality solar radiation data are also required for life-cycle analysis in remote area applications. If credit mechanisms, training and maintenance issues and solar radiation information were properly dealt with, growth in the segment of remote area applications would accelerate.

Despite the fact most of the grid-connected applications growth is taking place in the developed world, it is expected that with declining costs the benefits of the distributed nature of grid-connected PV will extend a more widespread adoption of this application worldwide. Since life-cycle cost analysis is current practice in the establishment of the incentive programs (in both the public and private sector) related to this segment, data quality is critical and of great value.

This paper will show the potential of PV in Brazil in two distinct and considerably different markets, namely hybrid PV–Diesel installations in mini-grids of the isolated Brazilian electricity system in the Amazon region, and grid-connected PV in urban areas of the interconnected Brazilian electricity system.

3. SWERA Data Archive

The scenarios presented here were prepared using the solar energy resource maps provided by radiative transfer model BRASIL-SR, developed by CPTEC/INPE together with LABSOLAR/UFSC. All solar radiation data are available for public access at the United Nation Environment Program (UNEP) website (http://swera.unep.net/). The data archive is a result of the SWERA project, sponsored by UNEP and GEF, and comprises an extensive high-quality database intended to support energy planning in developing countries making use of their solar and wind energy resources to meet their future energy demand (Martins et al., 2008).

Reliable solar resource data are of fundamental importance in assessing the technical and economic feasibility of using PV systems. Fig. 3 shows charts derived from the SWERA results of the annual and seasonal averages of the daily solar irradiation incident upon latitude-tilted planes for the entire Brazilian territory. The charts illustrate the potential of PV applications as well as its reliability demonstrated by the small seasonal variation of the solar irradiation throughout the year all over the country. Additional information on the variability of the solar irradiation is also necessary for feasibility studies in PV projects and the solar resource data on monthly basis are also available in the SWERA Data Archive. The reliability and confidence levels, as well as the resource variability, was discussed in the earlier paper submitted for this journal (Martins et al., 2008).

The tilt angle is a key factor for PV systems design. The yearly average maximum output power of a PV system is, in principle, achieved with tilt angle equals to the local latitude, which was used to produce the maps available in the SWERA Data Archive.

4. Photovoltaics scenarios in Brazil

We have identified two major applications for PV in Brazil, where there is a potential for large volumes, and for which the accurate knowledge of the solar resource distribution is critical. In the following sections, we describe these applications and show examples of SWERA products that can be directly employed to project design and economic viability assessment.

4.1. Hybrid diesel/PV systems in mini-grids in the Amazon region

By far most of the Brazilian Amazon region is not connected to the Brazilian grid of electricity distribution as shown in the Fig. 4. Currently, energy supply to dispersed populations in this region assumes a number of configurations: no service at all, PV solar home systems with very limited coverage and service, and mini-grids supplied by Diesel generator sets are examples. There are hundreds of mini-grids operated by independent power producers (IPPs) or local state utilities in the Amazon, that cover the main share of this demand, which is, however, only a small fraction of the country's total energy consumption. Mini-grids extend over some 45% of the area, but they supply energy to only 3% of the population (Rüther et al., 2003). Most of the sites where they operate are not easily accessible, increasing cost and decreasing reliability of supply. The operators of these systems, however, all make use of a subsidy that covers 100% of the fuel, as long as they operate at or below the 0.34 l/kWh specific consumption limit. This government subsidy's life span has recently been extended for another 20 years until 2020. Utilities are allowed to include a surcharge to all urban and rural consumers of the national interconnected system to collect funds to subsidize consumers of these isolated systems. This surcharge system, and the funds collected, is directed to the so-called Isol-CCC account (fuels consumption account of the isolated systems), which subsidizes Diesel for the thermal plants in isolated mini-grids. IPPs willing to invest in renewable generation that displaces Diesel can claim the cost of the fuel consumption avoided, but so far this has not been attractive enough to encourage them to switch to renewables,

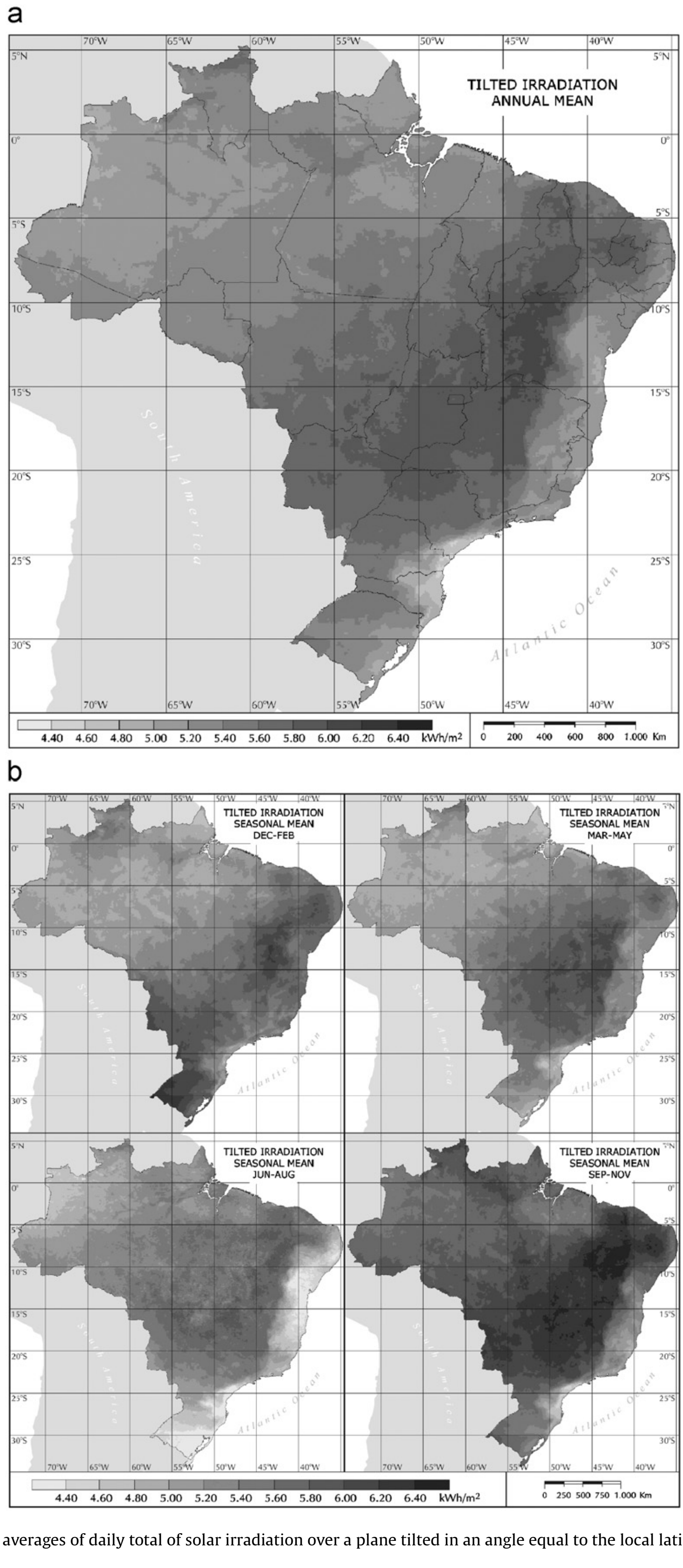

Fig. 3. The annual (a) and seasonal (b) averages of daily total of solar irradiation over a plane tilted in an angle equal to the local latitude in relation to the horizontal plane.

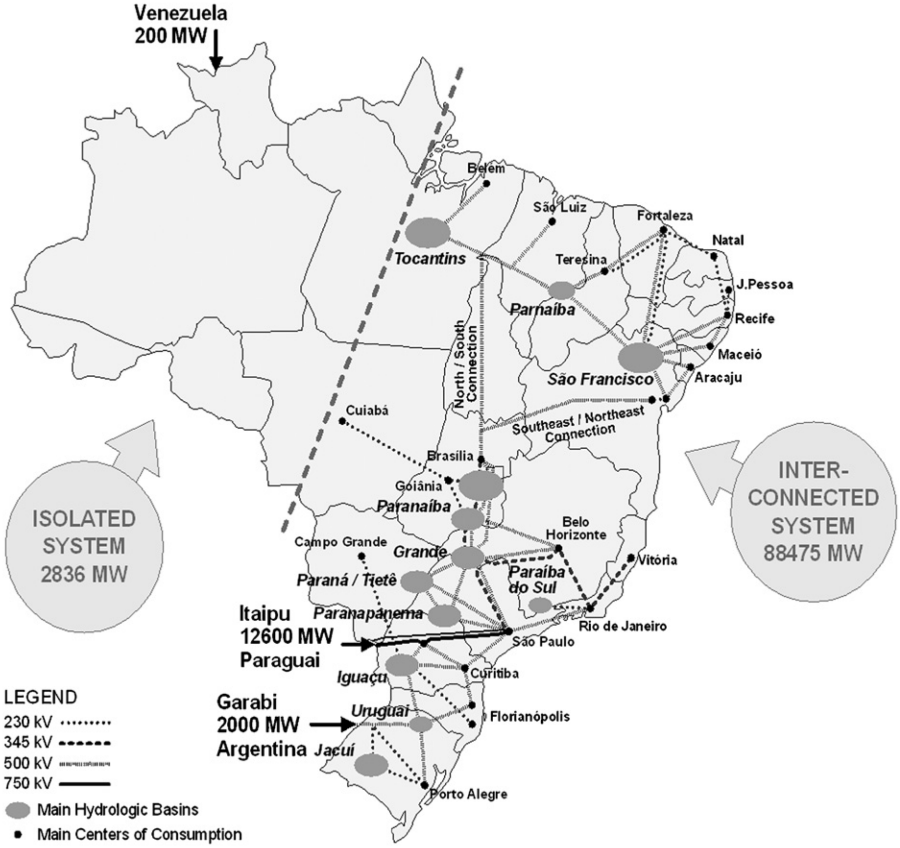

Fig. 4. Electricity distribution system in Brazil. *Source*: ANEEL (2005).

because the lack of mandatory targets and a typically short-term management strategy.

The potential for using PV, however, is huge, and can be estimated in tens to hundreds of MWp in the Amazon region alone, even if only a fraction of the 286 existing Diesel power plants with a total installed capacity of over 620 MVA would adopt some PV to an optimum Diesel/PV mix (Beyer et al., 2004). Furthermore, while the solar radiation resource distribution in Amazon region is considerable, and with a small seasonal variation, as demonstrated by the SWERA results (Martins et al., 2008), the wind resource distribution, on annual as well as on seasonal average, is very limited and not adequate to produce electricity as pointed out in "Brazilian Atlas for Wind Energy" (Camargo et al., 2002). Fig. 5 shows the annual average of wind speed in the Amazon region together with the location and size of Diesel-powered generation units.

Solar PV is one of the most viable renewable energy technologies currently available for the dispersed and relatively small energy density demands in the region. Fig. 6 shows, on an annual and on a seasonal average, SWERA results for the daily PV generation yields, in kWh/kWp, that can be expected for the amorphous silicon thin-film PV technology deployed at latitude-tilted arrays in the Amazon region, together with the location of villages/towns and Diesel-fired generation units in the region. The solar resource maps on a monthly basis should be employed in order to evaluate seasonal trends in more detail.

4.2. *Grid-connected PV systems in urban areas*

While most of the impressive growth in the PV market is related to grid-connected installations in developed countries, there is a huge potential for this application in sunny urban areas all over the world as well. Brazil is particularly well suited for the application of grid-connected PV due to both considerable solar resource availability, and to the high value that can be attributed to PV in commercial areas of urban centers (Rüther, 2004).

PV can contribute to a utility's capacity if the demand peak occurs in the daytime period. Commercial regions with high midday air-conditioning loads have normally a demand curve in a good synchronism with the solar irradiance (Knob et al., 2004; Perez et al., 2001). Another important factor in this analysis, is the comparison between the peak load values in summer and winter. The greater the demand in summertime in comparison with the demand in wintertime, the more closely the load is likely to match the actual solar resource. This is the typical picture of most capital cities in Brazil. Utility feeders in urban areas all over the country show distinct regions. While regions where commercial and office buildings dominate present daytime peak demand curves, in residential regions the peak demand values take place in the evening. To add value to the distributed nature of solar-generated electricity, it is important to know the PV capacity of the different regions of a city when installing a PV power plant, in order to select the feeder with the greatest capacity credit. In this context, the concept of the effective load-carrying capacity (ELCC) of PV was defined, to quantify the capacity credit of a strategically sited PV installation (Knob et al., 2004; Perez et al., 1996). Fig. 7 shows, for a typical daytime peaking utility feeder in an urban center, the peak-shaving effect of adding a small amount of PV to assist in reducing the load requirements of the feeder. To determine the capacity benefits of PV as shown in Fig. 7, knowledge of the solar radiation resource distribution on an hourly basis is necessary, and this information can be retrieved for the whole of the Brazilian territory through SWERA. The Fig. 7 shows the demand

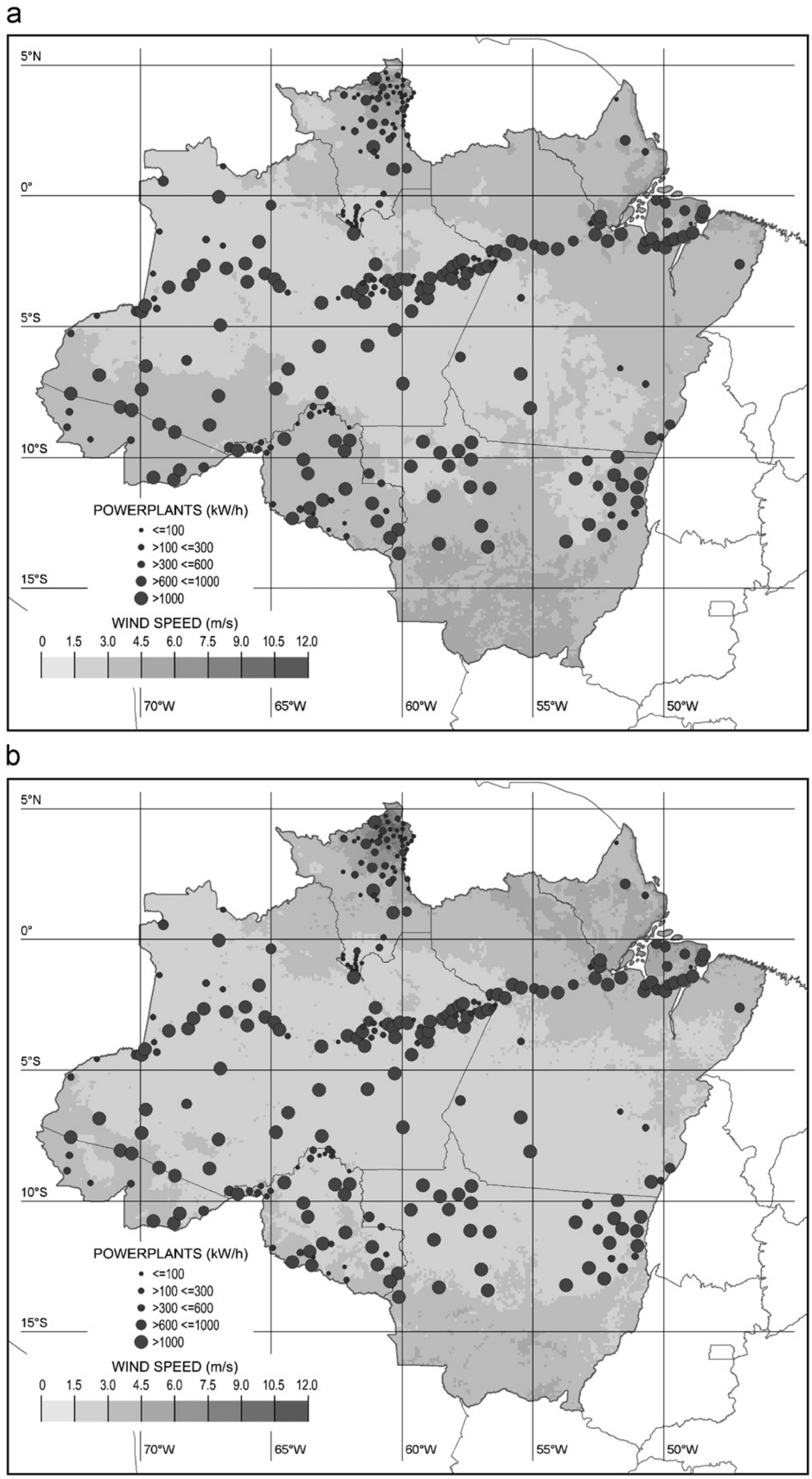

Fig. 5. Wind speed in the Amazon region together with the location and size of Diesel-powered generation units: (a) the annual average, (b) the winter average, (c) the spring average, (d) the summer average and (e) the autumn average.

behavior of a typical urban utility feeder serving a commercial/office building region in Brazil. It can be noted how the distributed nature of grid-connected PV can assist in peak shaving. The upper curves show the demand curve without PV; the lower curves show the PV generation profile for 3 consecutive days (partly overcast day, clear day and overcast day, respectively); and the

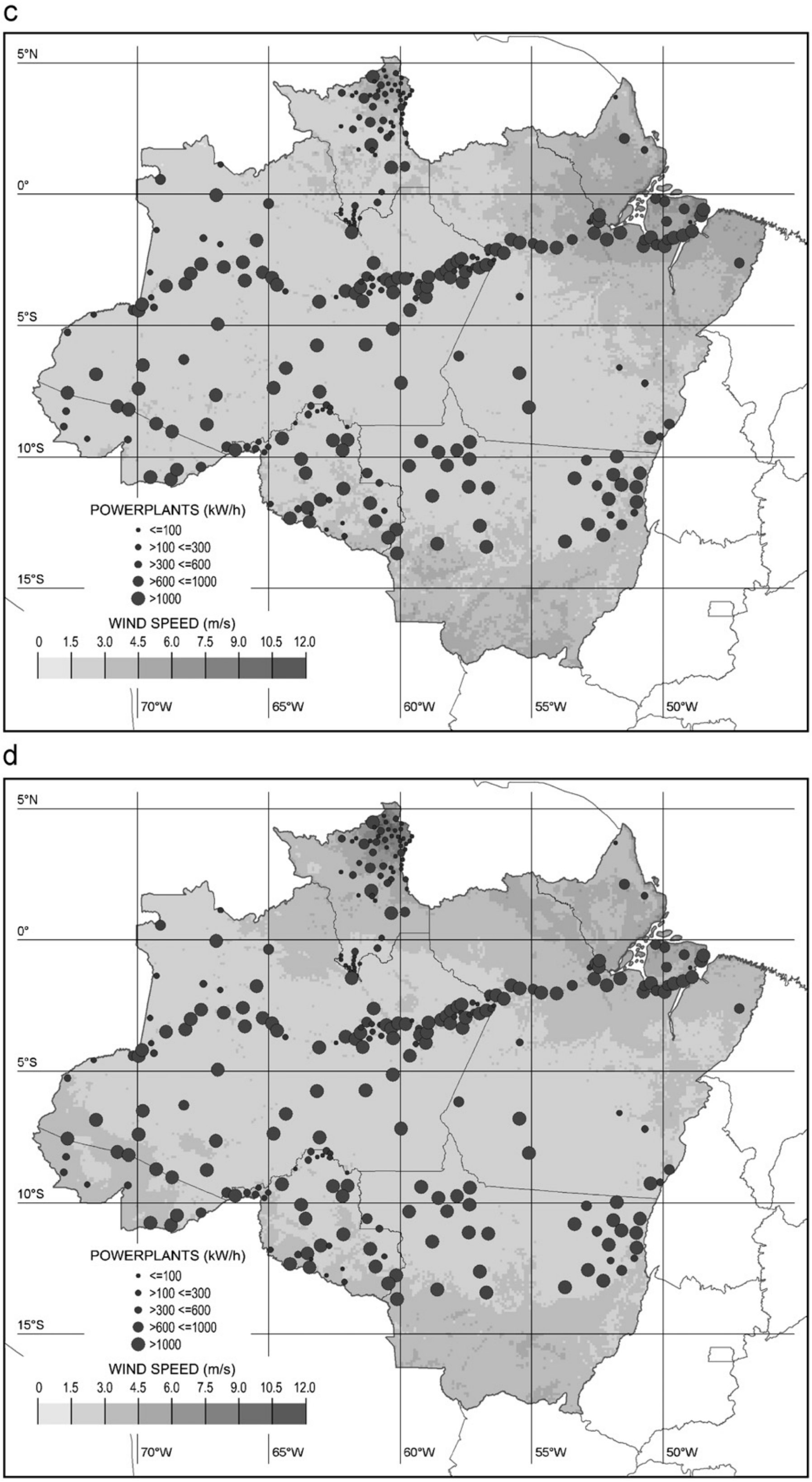

Fig. 5. (*Continued*)

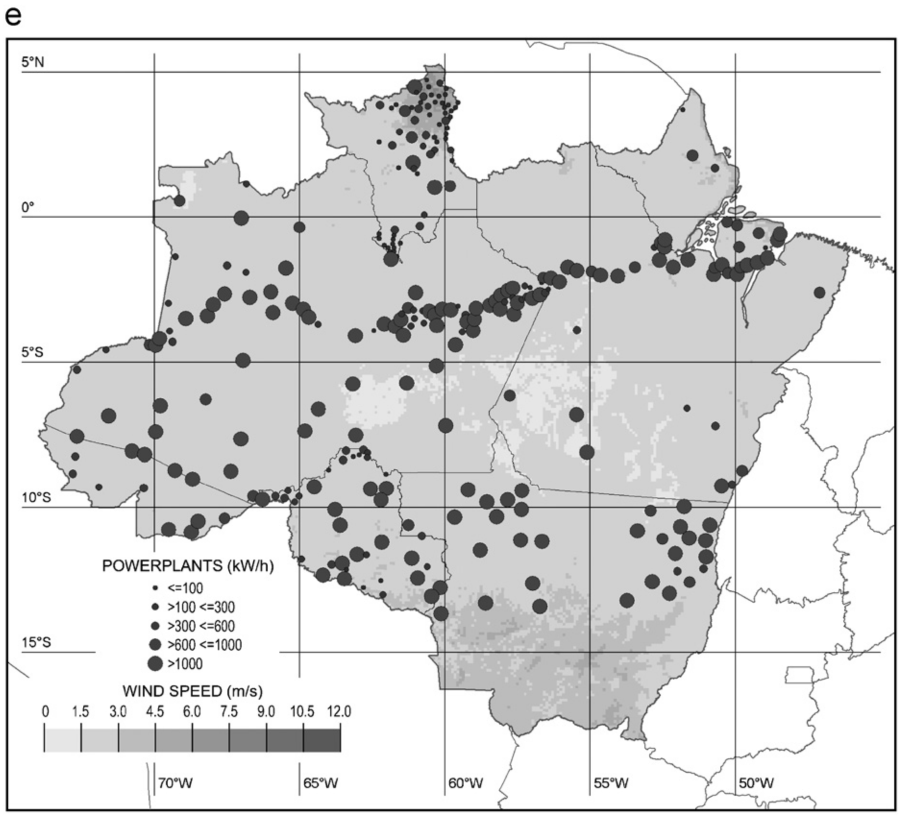

Fig. 5. (*Continued*)

intermediate curve shows the effect of adding a small fraction of PV to assist in peak load reduction.

In the near future, when the use of grid-connected PV becomes more widespread due to both cost reductions and the acknowledgment of the benefits of distributed PV, the assessment of ELCC will be of strategic value for utilities and investors.

5. Conclusions

This paper discusses some energy scenarios for PV applications in Brazil in order to demonstrate its potential to help in energy planning and viability analysis of its application on electricity generation. The scenarios presented here were prepared using the solar energy resource maps provided by radiative transfer model BRASIL-SR, developed by CPTEC/INPE together with LABSOLAR/UFSC. All solar radiation data are available in the SWERA Data Archive for public access at UNEP website (http://swera.unep.net/).

Two major applications for PV in Brazil are clearly identified, where there is a potential for large volumes, and for which the accurate knowledge of the solar resource distribution is critical: hybrid Diesel/PV systems in mini-grids to provide electricity to remote population in the Brazilian Amazon region; and grid-connected PV systems in urban areas of the interconnected electricity distribution system.

In the Brazilian Amazon region, electricity is typically produced by mini-grids Diesel generators providing the largest part of the electricity to dispersed populations in the Brazilian rainforest. Electricity production costs is high and reliability of the electricity supply is hindered by the difficulty to access most of these isolated communities. The potential for using PV in Amazon region is huge as pointed out in the daily PV generation yields (Fig. 6) and can be estimated in tens to hundreds of MWp, even if only a fraction of the existing Diesel power plants with a total installed capacity of over 620 MVA would adopt some PV to an optimum Diesel/PV mix. It is worth to mention that the wind resource in most of the Amazon region, on annual as well as on seasonal average, is very low and not adequate to electricity generation. Notwithstanding, the energy policy and government incentives need some adaptations to make investments in PV generation more attractive or mandatory, in order to displace Diesel consumption.

Brazil is particularly well suited for the application of grid-connected PV due to both considerable solar resource availability, and to the high value that can be attributed to PV in commercial areas of urban centers. Most of the major cities in Brazil present the demand peak happening in the daytime period and the largest electricity demand in summertime.

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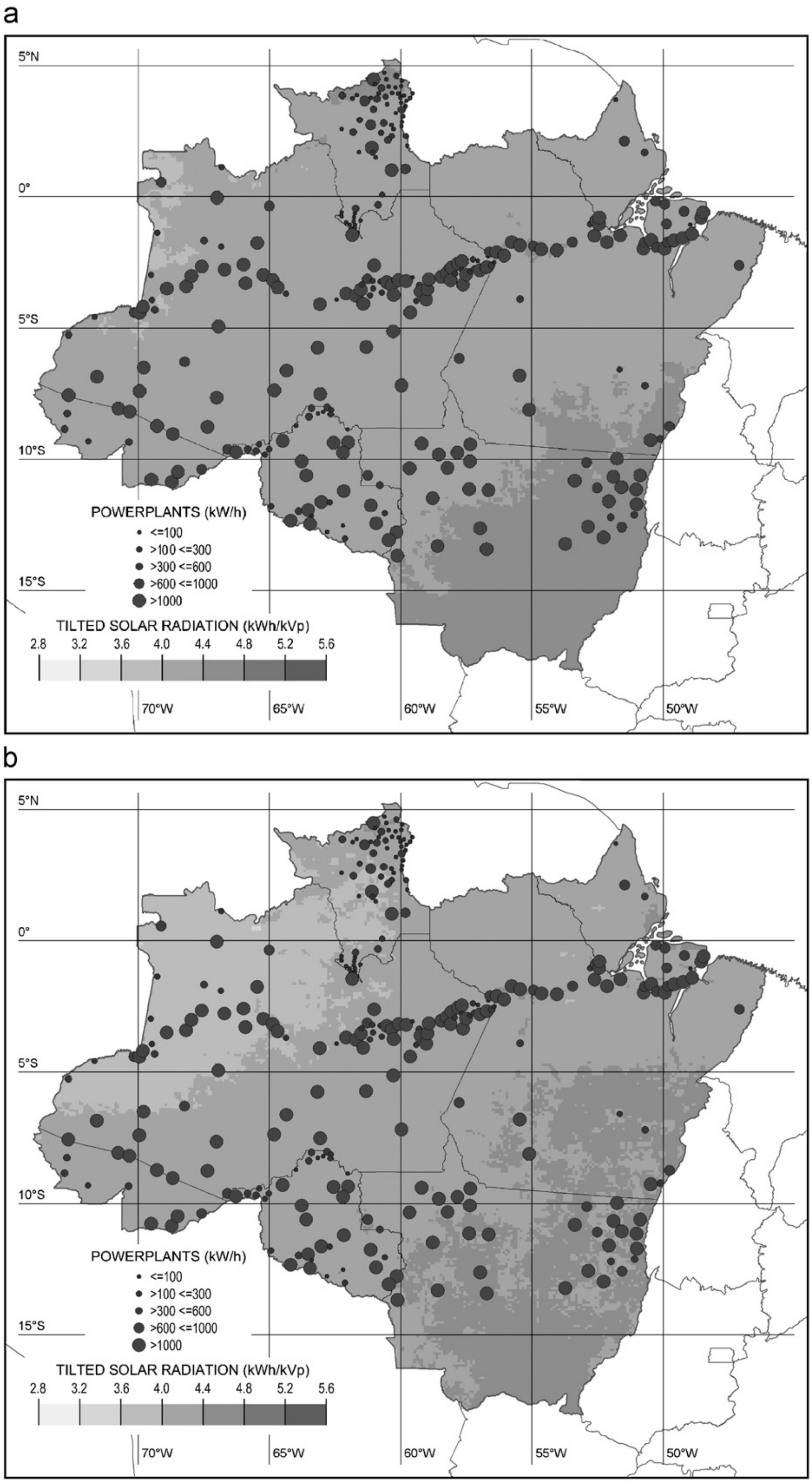

Fig. 6. The daily PV generation yields, in kWh/kWp, that can be expected for the amorphous silicon thin-film PV technology deployed at latitude-tilted arrays in the Amazon region, together with the location of villages/towns and Diesel-fired generation units: (a) the annual average, (b) the winter average, (c) the spring average, (d) the summer average and (e) the autumn average.

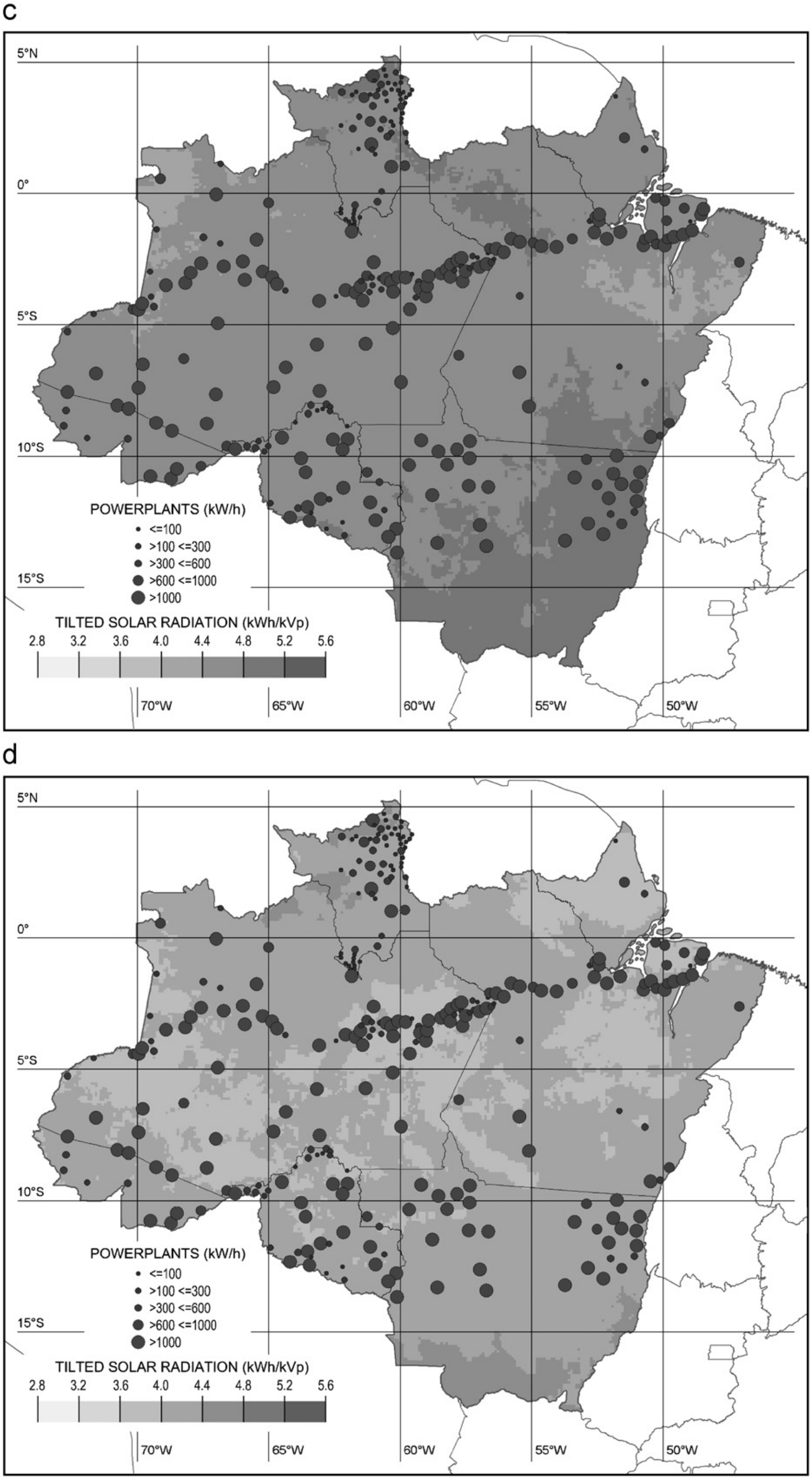

Fig. 6. (*Continued*)

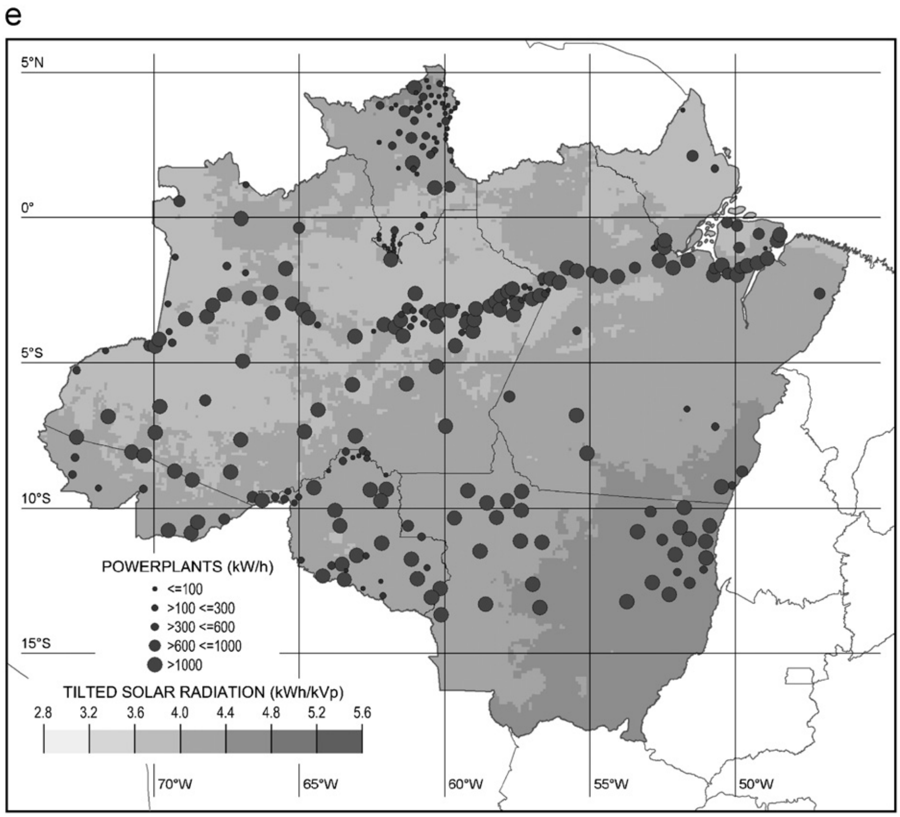

Fig. 6. (*Continued*)

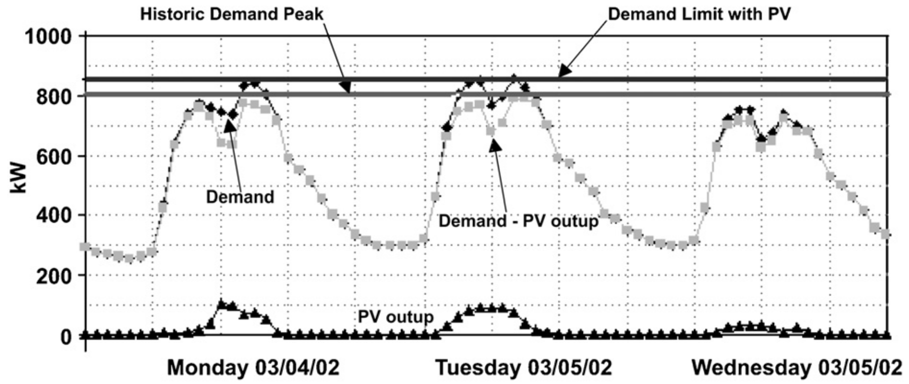

Fig. 7. Demand behavior of a typical urban utility feeder serving a commercial/office building region in Brazil, showing how the distributed nature of grid-connected PV can assist in peak shaving. The upper curves show the demand curve without PV; the lower curves show the PV generation profile for 3 consecutive days (partly overcast day, clear day and overcast day, respectively); and the intermediate curve shows the effect of adding a small fraction of PV to assist in peak load reduction. *Source*: Knob et al. (2004).

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